Integration of Heuristic Multi-Agent Protection System into Distribution Network Interconnected with Distributed Energy Resources

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People are asleep when they die they wake up.

Imam Ali (Peace Be Upon Him)

To my parents Farhad and Shamsi

Abstract

Power system operation is undergoing rapid changes due to market deregulations and interconnection of Distributed Energy Resources (DERs) such as wind power and solar panels. The power flow complexities arising from interconnection of DERs into the distribution network have adverse effect on protection systems which can degrade the reliability and power quality in power systems and lead to cascading failures or blackouts. However, with the prospect of integrating Information and Communication Technologies (ICT) infrastructures into power system operation, the ability to utilize advanced protection strategies has become realizable.

Given the size and complexities in operation of the future power systems the need for distributed and resilient protection system is inevitable to address the difficulties and inaccuracies introduced in protection settings. Multi-Agent Systems (MAS), as a branch of Distributed Artificial Intelligence (DAI) are capable to deal with complex and large scale systems such as power distribution networks. Moreover, in MAS agents can be deployed in power system to engage with interdependencies between various components while pursuing global goals through supervisory function or behaviours specific to each agent types.

In this research, a Multi-Agent Protection System (MAPS) consists of different agent types with certain tasks has been developed to effectively cooperate with other Intelligent Electronic Devices (IEDs) within the protection communication network. A heuristic approach based on exchanging information between different IEDs in the system is utilized to adjust the IED settings according to fault current level in the protected zone. Additionally, to validate the outcomes of the research under real-world scenario, an experiment setup based on Power Hardware in the Loop (PHIL) methodology has been developed to verify the outcomes of the research. The simulation results are discussed to emphasise MAS as a distributed and scalable approach to deal with complexities in future power systems and specifically in relation to protection systems which is crucial for reliability and efficiency of the interconnected distribution networks.

List of Publications

Journals

1. P.Peidaee, A.Kalam, J.Shi and P.Jimenez, “Fault Current Characteristics in Distribution Networks Interconnected with DFIG”, International Review of Electrical Engineering (IREE),Volume 10, No.5, pp 662-669, 2015.
2. P.Peidaee, A.Kalam, J.shi, “Integration of Heuristic Multi-Agent Protection System into Distribution Networks Interconnected with DER”, energies. Volume 13, No.20, 2020.
3. H.Reda, B.Ray, P.Peidaee, M.Abdun, A.Anwar and A.Kalam, “Vulnerability and Impact Analysis of the IEC 61850 GOOSE Protocol in Smart Grid”, Elsevier, Computers & Security. Submitted 30^{th} of May 2020-Manuscript ID:IJCIP-D-20-00078.

Conferences

1. P.Peidaee, A.Kalam and M. H. Moghaddam, "Developing a simulation framework for integrating multi-agent protection system into smart grids," in *2017 Australasian Universities Power Engineering Conference (AUPEC)*, 2017, pp. 1-6
2. P.Peidaee and A.Kalam “A Real-time Simulation Framework for system Protection in Smart Grids Application, AUPEC2018.

Awards

Winner (First Rank) of International Project Event of INNOTECH 2019- KIET Group of Institutions, Ghaziabad, India.

Technical Papers-Presented

1. P.Peidaee, A.Kalam and S.Amjadi , “Protection Challenges in Distribution Networks Interconnected with DFIG Systems” Australian Protection Symposium (APS), 2016 Melbourne, pp.21-27.
2. S.Gunasekera, P.Peidaee and A.Kalam, “Design and Development of Model Zone Substation Automation Laboratory for Research, Study and Testing IEC61850 Standard, Study Committee B5 Colloquium CIGRE2017, Auckland, New Zealand, September 11-15, 2017
3. P.Peidaee, A.Kalam, “ Developing Wide Area Monitoring and Protection System Based on IEC61850 Standard”, SEAPAC19, Sydney, Australia, March 19-20, 2019.

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Symbols	Names	
AI	Artificial Intelligence	
CB	Circuit Breaker	
CIM	Common Information Model	
CIN	Complex Interactive Network	
CT	Current Transformer	
DER	Distribution Energy Resources	
DFIG	Doubly-Fed Induction Generator	
DG	Diesel Generator	
EMS	Energy Management System	
EPRI	Electric Power Research Institute	
FCL	Fault Current Limiter	
FIPA	Foundation for Intelligent Physical Agents	
FOC	Field Oriented Control	
GOOSE	Generic Object Oriented Substation Event	
HIL	Hardware In the Loop	
ICT	Information and Communication Technology	
IED	Intelligent Electronic Device	
MAS	Multi Agent System	
NEM	National Electricity Market	
NERC	National Electric Reliability Council	
OOP	Object Oriented Programming	
RAS	Remedial Action Scheme	
SDLC	Software Development Life Cycle	
SG	Smart Grid	
SGAM	Smart Grid Architecture Model	
SO	System Operator	
SOS	System of Systems	
SPS	System Protection Scheme	
UML	Unified Modelling Language	
VT	Voltage Transformer	
WAMP	Wide Area Monitoring and Protection	

LIST OF SYMBOLS

symbol		symbol	
V_{as}	Stator voltage in phase a	L_{rr}	Rotor windings inductance without the leakage consideration H
V_{bs}	Stator voltage in phase b	L_{rs}	Mutual inductance of individual stator windings on each rotor
V_{br}	Rotor voltage in phase b	L_{sr}	Mutual inductance of individual rotor windings on each stator
V_{ar}	Rotor voltage in phase a	L_{ss}	Stator windings inductance without the leakage consideration H
R_r	Rotor resistance Ω	θ_r	Rotor angle (position) in three phase coordinate
I_{ds}	Stator current in d direction	ψ_{ar}	Rotor flux linkage in phase a
I_{cr}	Rotor current in phase c	ψ_{as}	Stator flux linkage in phase a
I_{qr}	Rotor current in q direction	ψ_{br}	Rotor flux linkage in phase b
I_{cs}	Stator current in phase c	ψ_{bs}	Stator flux linkage in phase b
I_{qs}	Stator current in q direction	ψ_{cr}	Rotor flux linkage in phase c
I_{dr}	Rotor current in d direction	ψ_{cs}	Stator flux linkage in phase c
I_{as}	Stator current in phase a	ψ_{dr}	Rotor flux linkage in d direction
I_{ar}	Rotor current in phase a	ψ_{ds}	Stator flux linkage in d direction
I_{bs}	Stator current in phase b	ψ_{qr}	Rotor flux linkage in q direction
I_{br}	Rotor current in phase b	ψ_{qs}	Stator flux linkage in q direction
V_{cs}	Stator voltage in phase c	ψ_s	Synchronously rotating stator flux
L_s	Stator inductance H	ω_r	Rotor angular speed in three-phase coordinate
L_r	Rotor inductance H	ω_s	Synchronous
C_{dc}	DC-Link Capacitance	I_{df}	d-component of the filter current in synchronous frame

V_{dc}	DC-Link Voltage	I_{qf}	q-component of the filter current in synchronous frame
I_{qg}	q-component of the grid current in synchronous frame	V_{df}	d-component of the filter voltage in synchronous frame
P_r	Rotor active power	V_{dg}	d-component of the grid voltage in synchronous frame
I_{dg}	d-component of the grid current in synchronous frame	V_{qf}	q-component of the filter voltage in synchronous frame
P_f	Filter active power	V_{qg}	q-component of the grid voltage in synchronous frame
V_{cr}	Rotor voltage in phase c	H	Inertia constant (s)
R_s	Stator resistance Ω	θ	d-q frame arbitrary angle
L_m	Magnetizing inductance H	ω	d-q frame arbitrary angular speed

Declaration of Originality

I Pejman Peidaee, declare that my PhD thesis entitled "Integration of heuristic Multi–Agent Protection System into Distribution network Interconnected with Distributed Energy Resources (DER)" is no more than 100,000 words in length including quotes and exclusive of tables, figures, appendices, bibliography, references and footnotes. Also, I confirm that this thesis contains no material that has been submitted previously, in part or as a whole, for the award of any other academic degree or diploma. Except where it has been indicated, this thesis is my own research work.

14.10.2020

Pejman Peidaee

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CHAPTER 1

INTRODUCTION

In this chapter, an overview of the thesis structure and underlying arguments related to research background and the adopted methodologies are discussed. Literature review is presented in Chapter 2, which mainly addresses new concepts regarding power system operation and protection requirements within the modern power system. Following that in Chapter 3, power system modelling for distribution network interconnected to Distributed Energy Resources (DERs) such as Doubly-Fed Induction Generator (DFIG) system and a Diesel Generator is developed. In Chapter 4, various operation scenarios are discussed to highlight variation of fault current behaviour under different operating condition of the power system and further to that conventional protection settings and their performance against in system protection. Development of a Multi-Agent System (MAS) and application of software program and integration of heuristic decision making approach for system protection in interconnected distribution network are explained in Chapter 5. Validation of the results for the proposed Multi-Agent Protection System (MAPS) is discussed in Chapter 6. Finally, Chapter 7 summarizes the outcomes of the thesis, advantages and challenges for developing MAPS are explained as well as suggestions for future research studies for system protection in smart grids are proposed. Also, separate sections have been added in appendices on supporting information, tables, plots or further details of implementation and programming codes for MAPS.

In the following sections a background on power system operation and protection systems are discussed. Later in this chapter, significance of the research and its objectives are addressed in context of the future power system operation. Accordingly, the adopted methodology and its limitations are investigated and presented. Finally, a summary of the chapter is presented.

1.1 Background

Electric power networks are large scale systems which transport and deliver electric power from remote power plants to consumers in geographically wide areas in urban regions. However, with the emerging challenges associated to sustainable development and environmental issues in the modern societies, the idea of bulk generation of the electricity by burning fossil fuels such as coal, natural gas or petroleum is not a viable option anymore. As a response to the current trend in power supply industry more sustainable and efficient power generation has been promoted through international treaties and conventions which are supported by governments of various countries. Thus, currently governments are taking actions to realize the prospect of a new era where electric power supply industry can meet the requirements for socio-economic benefits of a modern society [1]. Although transitioning of the power system has opened doors to previously unknown challenges, exploring the drivers of this transition can provide a realistic understanding about technical complexities in power system operation and address these challenges before any deployment planning [2]. In the following section, some of the main factors which drive the transition in power system operation are highlighted and accordingly technical challenges arising from that are briefly discussed, as it can further clarify the significance of the research thesis.

1.2 Power System Transition

The evolution in power systems operation is a multifaceted problem which depends on different factors related to economic, political and technical issues. Therefore, in order to understand the level of changes and complexities in operation of the future power system, identifying and exploring integrated frameworks which facilitate reliable functioning of the new modern power system are inevitable. Moreover, in relation to conducting research studies and addressing technical issues, a broader perspective on power system transition can be critical for adopting effective strategies both in short term and long term solutions. Among many factors participating in this transition, there are specific themes that have gained momentum and are expected to have a dominant role in the operation of the power system [3, 4]. In the following subsections, complexity and the role of each factor are highlighted [5, 6].

1.2.1. Market Deregulation

From economical point of view, electricity supply industry has been integrated within individual electricity utilities where extensive transmission and distribution networks are natural monopolies to deliver the generated electricity to consumers [7]. However, during the past decades, deregulation of the electricity supply industry has been a major theme to bring about competition and economic efficiency into the heavily regulated electricity industries. Thus unbundling of primary components of the electricity supply (Generation, Transmission and Distribution Networks) and non-discriminatory access to the electricity supply infrastructure has led to emergence of market places and actors operating in parallel to physical load flow power system. In Figure 1.1, the structure of a typical deregulated electricity supply industry has been illustrated where the connecting lines represent interaction between the electricity market and power system infrastructure. The operation and the extent of interaction between these elements are dependent on market policies in each energy market. Consequently, operation of the future power system is exposed to various uncertainties including prices of energy carriers, technological advancement in DERs, behaviour of competitors and etc., which can affect the development of power supply industry. Hence parallel interactions between actors acting in the electricity market and physical load flow complexities in operation of the future power system is emerging as a paradigm shift to electricity supply industry [8].

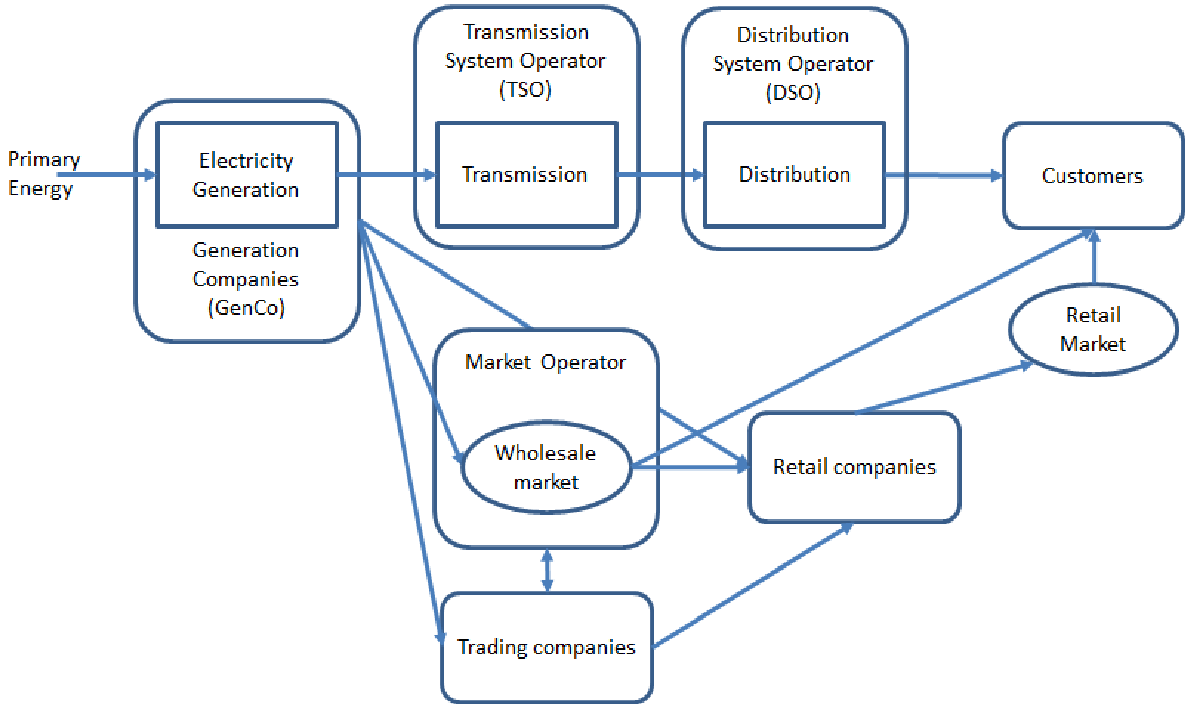

Figure 1.1 Interactions between the actors operating in deregulated electricity supply industry [8].

1.2.2. Distributed Energy Resources (DER) Technologies

In general, around 60% of the electricity generation is wasted in conventional power plants in form of heat before it delivers any useful energy to end users. However, as a promising means to address energy losses in power systems, DERs are becoming a viable solution for the energy crisis in electric power supply industry. From technical point of view, DERs are comprised of technologies, ranging from fuel cells and micro-turbines to renewable energies such as wind turbine and solar panels. There are many advantages for fuel-flexible and small-scale DERs against large-scale capital-intensive power plants which has attracted attention for future trends in supplying ever increasing electricity power demand. For example, the modular and small-scale DERs units can be used close to end users avoiding losses and congestion in transmission lines. Moreover, with the introduction of market deregulation in electricity supply industry, utilizing DERs such as wind turbine and solar panels becomes a viable option for both retailers and consumers to address price cuts in a competitive electricity market. In fact, departure from the conventional, centralized power system network has led to a new paradigm shift where retailers and end users can participate as power generation sources (as single sources of unit or aggregation of units). Given the advantages and potentials for a realistic scenario in operation of the future power systems, interconnection of the DERs into distribution network is inevitable. In Figure 1.2 the prospect of energy conversion chain for delivering electric power have been illustrated as the interconnection of DERs from retailers and end users are taken into account [9].

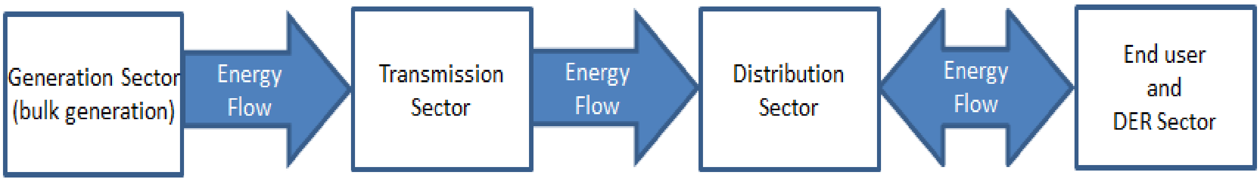

Figure 1.2 Prospect of energy conversion chain for electricity industry in presence of DER.

Despite the advantages discussed for connection of DERs, there are technical challenges that affect power quality in distribution networks. According to Electric Power Research Institute (EPRI) report [10] on power quality distributed generation, many generator applications are naturally benign; either they are small relative to the capability of the system or have other characteristics that make problems less likely depending on the size of DER or groups; more detailed studies including relay coordination, fault current analyses, load-flow studies and stability analysis is required [10].

1.2.3. Information and Communication Technology (ICT)

Although data communication is not new in utilities and System Operators (SO), as many utilities have used simple telephone lines, micro waves or fibre optics which only serves for a single purpose with limited bandwidth. The advent of the Intelligent Electronic Devices (IEDs) and their capabilities for exchanging information within a communication network has provided unique opportunities for utilities to integrate ICT infrastructures for addressing complexities arising from the transition of power systems.

The use of ICT infrastructure has an enabling role to envision transition in future power system operation and its potentials to provide reliable and affordable electricity power to all consumers. Accordingly, the term Smart Grid has been adopted to highlight the use of ICT infrastructures in operation of the modern power systems where information flow in parallel to power flow is utilized to improve efficiency of the power system [11]. For example, ICT infrastructure and communication network are the key technological factors which can bridge the gap for sharing information between DERs in single units or aggregated blocks with the demand side management. This implies that distributed providers of electricity services can be able to successfully compete and collaborate with centralized supply towards an efficient solution for electric power generations. Figure 1.3 illustrates the interactions involving DERs in electric power system operations and system operators utilizing ICT for exchanging information under the framework of electricity market [12].

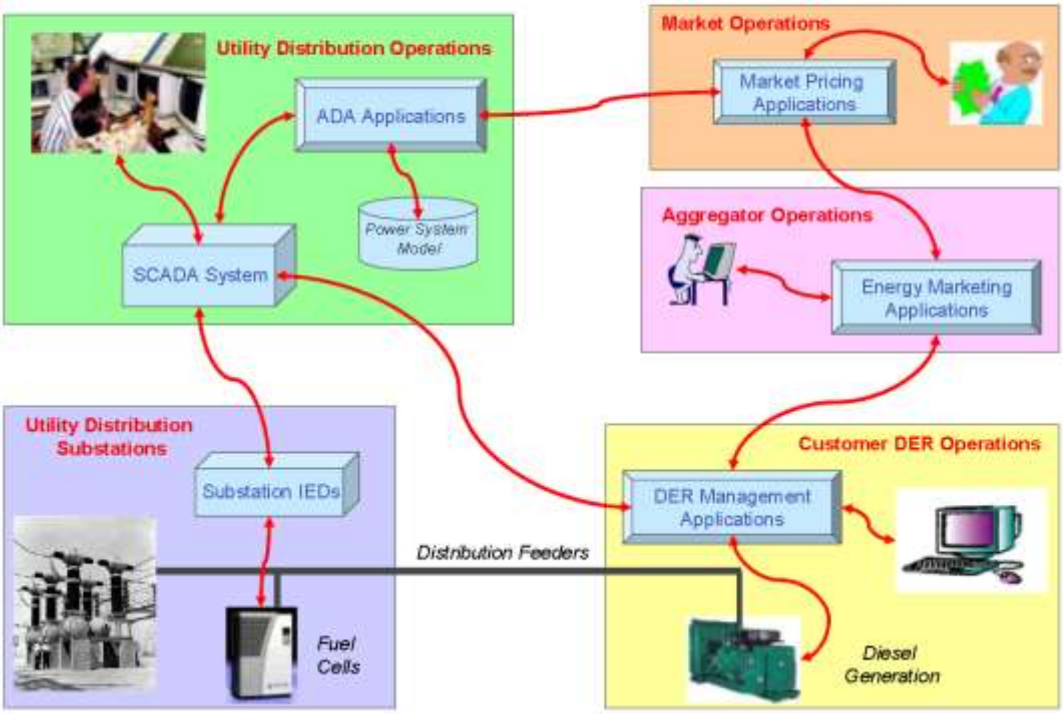

Figure 1.3 Interactive players involving DER and Power System Operator (PSO) [2].

Nowadays, utilities are deploying their sophisticated portfolio of communication technologies to realize their Smart Grid visions as a complex interactive networks (CINs) system of communication which has to be managed with the same rigor as the power delivery grid [13, 14]. Further, important features relying on ICT infrastructure is the introduction of standards such as Common Information Model (CIM)/IEC61970, IEC61968 and IEC61850 which promote interoperability between different layers of the power systems. In consequence, through literature advanced strategies such as self-healing, automated fault location, isolation, and service restoration (FLISR) and intelligent protection systems have been proposed which rely on embedded ICT infrastructures within Smart Grids paradigm [14].

1.3 Protection System

As a large scale networked system, electric power system networks are prone to disturbances due to failure of electric power components or external natural causes such as falling trees, lightning strikes etc. Thus, system protection is deployed to minimize the risks to people and assure continuity of the electric power supply during power system disturbances which are essential requirements for any power system network [15-17]. In general, functionality of the protection system is fulfilled through sub-tasks of detection and isolation of the faulty sections where protective equipment such as relays and circuit breakers are used to clear out the faults. In its simplified representations, fault detection process is a decision making algorithm embedded in protective relays, where voltages and currents of the system monitored as inputs and trip signals are decisions made to operate Circuit Breaker (CB). In Figure 1.4, a simplified block diagram for a typical protective relay and its basic components has been illustrated. It is worth mentioning that the configuration represented in Figure 1.4 highlights the interactions between the components of a protective relay to fulfil protection task, irrespective of protection schemes or any particular technology that is available in the field of power system protection technologies.

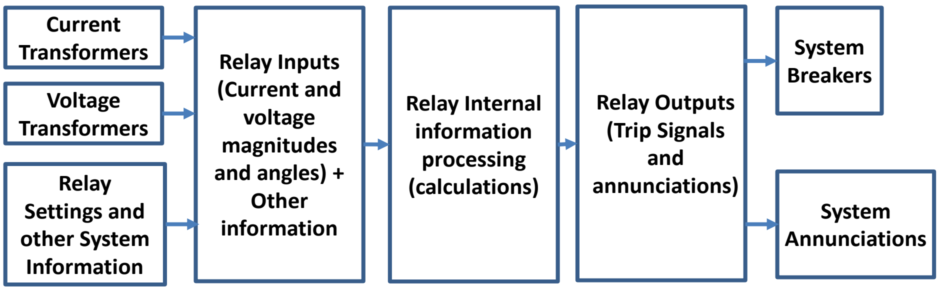

Figure 1.4 A simplified block diagram representation for protective relaying.

Having explained simple interactions and operations between protective relays and CBs, designing and establishment of protection and control systems have always been an important element in achieving reliable and efficient operation of the power system. However, in order to address desired functionalities for the protection system, there are some requirements and characteristics which are independent from the technology and application utilized in protective relays but it is essential to be taken into account for designing of the protection systems [18]. In the following subsection, requirements for power system protection are discussed.

1.3.1. Functionality Requirements

From technical point of view system protection plays a critical role for reliable and secure operation of the power system network, as failure to meet certain requirements in functionalities of the protection system can lead to catastrophic outcomes. Thus, it is important for any system protection to be assessed against desired response expected in case of any disturbance in power system networks. Consequently, the concept of reliability in power system protection is defined as acceptable response of the power system through the operation of power system network [19]. There are two main aspects for the reliability in protection systems which are:

- **Dependability**

It is a measure for system protection which refers to a degree of certainty that a protective relay detects the fault and trip the corresponding CBs when required. The dependability issue in power system is mainly concerned when any fault occurs in protection zones. Thus dependability means that when there is a fault in the protection zone, the fault should be detected and protective relay should operate the respective CB.

- **Security**

The security of the protection system is a measure which relates to the degree of certainty that a relay or protection system will not operate incorrectly. The security issue in protection system is mainly related to external fault out of the protection zone or unfaulty conditions which are normal operating conditions of the power system. Example of that can be transient behaviours due to load switching, or inrush current by loading transformers [19].

1.3.2. Performance Requirements

Aside from the functionality requirement for system protection which is essential for reliability of the power system operation, there are certain measures in designing of protection system which have to be considered in order to reduce the impact of failures in power system networks. Thus in context of power system protection, performance requirements are defined as characteristics to improve the reliability of protection system, where detailed analysis of the failure modes of the protection system components (relays plus CTs and …) and timings of the operation for protection relays are investigated. There are three main performance criteria which can be discussed for protection system as performance criteria:

- **Sensitivity**

It refers to operation of the relays or protection systems for a given condition where stronger propensity to operate the relays for that condition is desired. The sensitivity measure is used to ensure the magnitude and location of the fault on the protected power system components are seen strong enough to be detected by the relays. Usually, sensitivity measure is used to distinguish between remote faults and the fault close to protection relays within protection zones of the power systems.

- **Selectivity**

It is also known as timing coordination for the protection relays in which relays are intended to operate faster for certain operating conditions thus for a specific fault in the system one protection relay or one protection scheme should operate at a time. This coincides with the concept of backup protection, which is defined due to selectivity measure devised for protection relays within protection zones.

- **Speed**

Simply the role of speed in detection and isolation of the faults within power system network is a desirable characteristic for protection system. In fact the requirement for fast isolation of the faulty sections or lines within power system networks are essential for both minimizing the damages to power system equipment and mitigating stability issues arising from abnormal operating condition of the power system [19].

In summary, although it is important to take into account the performance requirements for designing system protection, many times it is impossible to meet the aforementioned measures at the same time where a compromise between the criteria should be met. In the following section, principles of agent technology are explored as a new approach to deal with complexities of future power systems.

1.4 Agent Technology

Generally, the advent of agent technology in software programming has been the result of evolution from both artificial intelligence (AI) and distributed computing where software programs can communicate with each other in a distributed manner. Although, various definitions have been provided regarding the agent and agency concept, there is hardly a universally accepted definition which can be agreed on by researchers in the field. In its definition Wooldridge et al. [20] expressed the agent software as an entity capable of autonomous action in which the concept of autonomy is presumed with minimized human action [21]. Through literature survey there are some basic properties for agent concept which has been denoted as follows:

- **Autonomy:** ability to control their own actions and make decisions without direct human interventions.
- **Social Ability:** allows agents to imitate human social behaviour by utilizing agent communication languages in which they can cooperate to do the task assigned for them.
- **Reactivity:** agents can respond to the changes with their environment as they detect or identify the changes.
- **Proactivity:** not only agents are able to respond to any changes in their environment where they have been placed, but they can initiatively take actions towards a specific goal or goals as a goal driven behaviour.

From the perspective of AI researchers, the aforementioned attributes are for an intelligent agent that can be conceptualized and implemented from human interactions or decision-making process [22]. Therefore, given the heuristic approach imitated from human intelligence and computational capabilities embedded in hardware/software modules, agent technology is looming to be an effective tool in dealing with complex tasks where cooperation between various components or subsystems is crucial. Thus far, applications of agent technology has been utilized in different domains of research including workflow management, electronic commerce and other new solutions [23]. However, in recent years agent technology has gained more attentions within the domain of power supply industry, as the requirement for intelligent and automated functionalities in operating of the power system have become the utmost concern for system operators (SO) [24, 25].

In fact, the prospect of power system networks evolving into a large cyber-physical systems with different levels of complexities and interdependencies between the elements of the power systems adopting of new strategies such as agent technology has become a hot topic for researchers in the field of power system engineering [25]. Actually, in a similar way to agent paradigm, system protection relay is a specialized control system which monitors the power system operation and detects faults or abnormal conditions by initiating actions to recover normal operation of the power system [26]. In Figure 1.5, the agent attributes within agent paradigm have been represented as an entity, which can interact with its environments towards a certain goal.

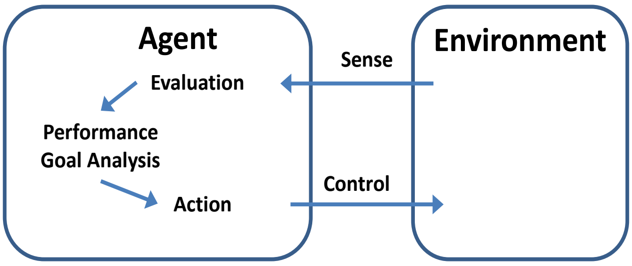

Figure 1.5 Agent paradigm attributes relevant to control and protection tasks.

For modern power system, protection relays are IEDs, hardware equipment with embedded ICT infrastructure and software codes, which can behave like an agent in a power system environment by taking actions to isolate fault section of the distribution lines. Thus, introduction of agent programming within protection system can promote unique capabilities and concepts which are suitable for addressing complexities of the protection tasks within the large-scale interdependent networks such as interconnected distribution network. On the other hand, with the emerging paradigm in Smart Grid operation and availability of advanced ICT infrastructure for integrating agent technology into power system operation, many research areas within the field of power system engineering have endorsed agent software standards relevant to power system domain applications. For example, with the growing use of agent programming and agent technology in power system applications, IEEE committee has adopted Foundation of Intelligent Physical Agents (FIPA) as a standard for integration and development of the agent systems into power systems operation. Consequently, as a core of the research study in this thesis, integration of MAS into protection system has been adopted to address the protection challenges of the future power systems [25, 27].

1.5 Research Methodology

In order to address the aims and objectives of the research study, a 6-steps methodology has been proposed which serves as a systematic procedure to identify and rank the steps for planning and development of the research phases. Figure 1.6 illustrates the sequence of phases and steps taken to cover different aspects of the proposed methodology. Although in cases where there are dependencies between the phases, some iterative planning is necessary by allowing the steps to be moved back and forth.

Figure 1.6 Steps and sequences of planning in adopted research methodology.

The research strategy is based on deductive approach which relies on drawing conclusions from premises and the proposition is defined in the research field. In this PhD research study, a MAS has been proposed to address protection challenges in a distribution network interconnected with DERs. The detailed approach for the adopted methodology is as follows:

1. ***Literature Review:*** As an initial stage to the research study, understanding and exploring the issues arising from the interconnection of the DER and the new paradigm in operation of the power system has been crucial for planning and development of a suitable solution to the protection challenges in the power systems. Due to iterative nature of literature review, the process is progressed towards the last stage of the research where search engines in different databases (IEEE Xplore, Scopus etc) and journals related to the field have been used continuously.
2. ***Workshops and Technical Conferences:*** Aside from academic resources and research publications, attending training workshops and technical conferences have been highlighted as an important factor to ensure the quality of the research and up to date understanding of the industry. As the outcomes of these activities, three technical papers have been presented and published in well-respected industrial events such as CIGRE-SEAPAC2019 and Australian Protection Symposium (APS2016).
3. ***Power System Modelling:*** A typical distribution network interconnected to DERs such as DFIG and Diesel Generator have been developed in MATLAB/SIMULINK. The analysis of the fault current under different operating condition of the DERs with embedded grid codes was considered as the real-world scenario to investigate for system protection challenges.
4. ***Establishment of MAPS:*** Application software based on agent technology has been developed to fulfil the protection tasks within the framework of MAS. Similar to Software Development Life Cycle (SDLC) technical details related to MAS such as agent communication, agent behaviours and software platform (middleware) have been addressed through analysis and design phase. Furthermore, an intelligent decision

making process which utilizes knowledge database and descriptive logic reasoning is integrated into MAS to enable adjustment for protection settings within the protection system of the interconnected distribution network.

5. ***Co-simulation Platform:*** Development of a laboratory setup to test the performance and applicability of the proposed MAPS system has been carried out by adopting PHIL methodology where a real-time digital simulator has been used to model the power system domain and interface the signals to external devices under the test. Moreover, the concept of the co-simulation was used to integrated MAPS into the power system protection system utilizing the synchronization between the different domain-specific software which is SIMULINK and JADE .
6. ***Results and Analysis:*** Validation of the MAPS has been investigated for various operating scenarios of the power system where 3-phase faults are applied in different locations and the protection system is able to isolate the faulty section correctly. The results have been compared and plotted to present the improvement of the system protection based on MAS technology.

1.6 Research Objectives

In this PhD research thesis, the main aim of the study is concerned with synergism and interconnectivity between power system and ICT elements which is used to improve protection tasks within future power system operation. However, as discussed earlier in section 1.1 due to multi-faceted complexities and interdisciplinary nature of the evolution within operation of the power systems, there are certain perspectives related to the establishment of the research objectives which has to be aligned in accordance with the research methodology. As a matter of fact, given the large-scale, distributed infrastructure and heterogeneity in components, future power system characterizes System of Systems (SOS) engineering [28] problem where analysis and identification of the system objectives rely on understanding of orderly interactions between elements of the system (subsystems) and their pre-determined objectives. For example, interfacing between the power system components and the ICT infrastructure can be defined as two separate but interdependent subsystems which have central objective, which is the establishment of the MAPS for interconnected distribution network. Thus, concepts such as inputs/outputs, system boundaries and interfacing between subsystems have to be considered to ensure feasibility of the assigned objectives for each subsystem while serving the central objective of the research. In the proposed MAPS there are multitude of objectives related to different domain of the study including time domain simulation of the power system network, development of the MAS enabling distributed interaction between protection IEDs and establishment of a decision making process based on knowledge database obtained by MAS. Therefore, the objectives defined for this PhD research project require knowledge in power system engineering, power system protection, software development methodologies and agent programming.

In this research study, literature review plays a crucial role to identify boundaries of the overall system and underlining the research objectives based on the current state of the domain knowledge. The research objectives are highlighted as follows:

- Development of a time-domain simulation for a typical distribution network interconnected with Distribution Energy Resources (DER) such as DFIG and DG.
- Analysis and investigation of fault currents variations in distribution network connected with DERs.
- Establishing a decentralized system protection strategy based on Multi-Agent System (MAS).
- Integration of heuristic Multi-Agent Protection System (MAPS) to accommodate higher penetration of the DERs into distribution network.
- Developing an experimental test-bed for verification and validation of the proposed protection scheme.

1.7 Research Significance

In general, there are two main aspects related to the significance of the research outcomes. One is concerned with technical knowledge and innovative approach for system protection for interconnected distribution network and the other one is associated with consequential or externality analysis which is associated to different stakeholders of the research project including economic and environmental issues. For technical aspects, implementation of MAPS and fulfilling protection tasks are highlighted as the core of the research outcome, while there are also different factors and elements effective in operation and performance of the protection system in modern future power systems which can be listed as contributions in the field of power system protection. The significance and improvement contributed by the proposed heuristic MAPS are:

- Establishment of technical feasibility and implementation of the adaptive protection settings within the context of modern power system.
- Introducing new distributed decision making process for power system protection based on human mind reasoning knowledge.
- Improving system protection reliability by preventing false tripping and mis-coordination (selectivity) within the interconnected distribution network.

- Proposing and adopting protection ontology to improve interoperability in system protection under new paradigm of the Smart Grid operation.
- Encouraging cost-effective solutions by introducing scalability in deployment of system protection based on specific agent types with pre-configured protection sub-tasks.

Aside from the abovementioned technical significances in the field of power system protection, there are external stakeholders to the operation of power system where the outcomes of the research can contribute to enhance performance for downstream effects in the chain of energy management system (EMS). In fact, protection system plays a crucial role for efficiency and security of the EMS where in the wider sense it can affect environmental and economical aspects of the power system operation. Some of the potential contributions assumed from the proposed protection system are highlighted as follows:

- Increasing competitiveness for the electricity price in a deregulated electricity market by allowing higher penetration of the DER into network which means cheaper power generation costs.
- Reducing the carbon emission as the higher penetration of the DER based on renewable energy can be possible which is a main concern of the new millennium.

1.8 Limitations

Generally, computer simulation models are powerful to evaluate alternative scenarios by varying different parameters of the systems. However, from system engineering point of view operation of Smart Grid relies on interactions between independent constituent systems which form a large-scale, distributed and complex heterogeneous system a.k.a SOSs engineering. Thus, in modelling and development of the Smart Grid operation there are important challenges within the SOS engineering framework, which are the foci of work in the field of system engineering [28]. In this research project, the proposed methodology for validation of the research outcomes have been addressed through integration of the MAS into power system protection, which is basically developed by interfacing various simulation domain to simulate overall behaviour of the system a.k.a co-simulation. Although the aforementioned concepts have been proven to be effective, there are boundaries related to both technical aspects such as interfacing between different simulation domains, data communications and management aspects including stakeholders which are limiting factors to gain confidence for system operation in terms of behavioural correctness or performance qualities. Some of the aspects that can affect the performance of the proposed MAPS within the real-world scenarios are defined in the following sections.

1.8.1. Data communication

In relation to data communication and exchanging real-time measurement data between the power system network and MAPS, a standard TCP/IP protocol has been used to establish a reliable and fast data exchange mechanism between the two entities (power system and protection agents). However, compared to real world scenario, measurement data can be received by protection agents through data streaming technologies, such as synchro-phasor measurement unit and Sampled Values which are utilized for hard real-time applications in protection and control systems. Therefore, issues related to data traffic and communication delays within TCP/IP protocol can be addressed during the implementation phase where communication bandwidth is devised to meet the requirement for protection system performance. Moreover, general Ethernet switches/Hubs for exchanging data can be another source of communication delays where in case of power system protection strict standard for configuring high speed ethernet switches are mandatory to avoid overloaded or any unnecessary data traffic in the communication network. Although, the focus of this research study is to address potential benefits in MAS and their communicative capabilities for introducing intelligent protection schemes. But, technical details for network configuration and communication delays are currently assumed as a solid knowledge field in the era of advanced ICT infrastructures.

1.8.2. Not Standard

As mentioned earlier in previous sections, power system operation is undergoing a transition period where interconnectivity between different levels/layers of the power system collaborate collectively to deliver a service, which in this case is electric power, in an efficient and cost-effective manner. Thus, according to SOS engineering framework and from the modelling perspectives, considering management aspects such as Energy Markets (EM) or hierarchical decision making within Smart Grid paradigm can introduce significant challenges related to communication standards, data modelling and interoperability between different layers of the Energy Management System (EMS) which can be impossible or even out of scope of this research topic. Consequently, with respect to the domain of study, interoperability and data communication between agents are the only context that FIPA standard for agent technology has been utilized as one of the objectives for the proposed MAPS to improve scalability within system protection of the interconnected distribution networks. It is also worth mentioning that data modelling which are used in MAPS as abstraction model for electric power components is based on object-oriented modelling paradigm and not intended to follow any existing standards for modelling power systems such as IEC61968 or Common Information Model (CIM). Therefore, defined process variables and object classes are considered to comply with ICT approaches within power system automation.

1.8.3. Simulation Environment

For simulation environment, a platform developed to integrate two different domains of continuous physical process of the power system and discrete event-based data communication infrastructure where MATLAB/SIMULINK and JADE are software tools used for power system and MAS respectively. Although, individually both simulation software (SIMULINK and JADE) have their own limitation related to their hardware such as CPU processing power for numerical computation, memory spaces and communication interfaces between the two software environments. Thus, the proposed methodology for co-simulation is capable to cater small-scale power systems which have to be balanced with the capability of each software packages individually.

1.9 Summary

In the first section, the thesis structure and scope of each chapter of the thesis have been highlighted. In the following section, two research background and transition of the power system operation have been explained where market deregulation, DER technologies and ICT infrastructures are highlighted as the driving force for the drastic changes in power system industry. Later in section three, system protection and its functionalities within power system networks are discussed. As the core of the research study, agent technology and its advantages for integration into power system protection have been explored by comparing agent paradigm interaction with human social behaviour such as cooperation and autonomy in decision makings. For research methodology, steps taken toward the research objectives have been discussed and illustrated by a continuous arrow process diagram. Objectives and significance of the research study have been pointed out enabling readers to evaluate and assess the contribution of the results in the context of the future feasibility and practicality of the power system industry. Limitations corresponding to the research study have been identified as hardware/software based limitations such as computational capacities, data communication traffic and data modelling standards for exchanging information between different hardware or devices.

As the final remark, chapter 1 highlights some of the main aspects related to the thesis title which will be discussed in later chapters further with technical and mathematical details.

CHAPTER 2

LITERATURE REVIEW

In this chapter, a thorough investigation on relevant literature and research studies related to system protection within the context of future power systems has been conducted. Initially, Smart Grid architecture and its importance as a reference model for conducting any research studies corresponding to future power systems are explained. In the second section, simulation of Smart Grid as a cyber-physical system has been investigated through various methodologies such as co-simulation and hardware in the loop (HIL). Moreover, to highlight the importance of the simulation platforms for developing research studies in cyber-physical systems, list of research studies adopting co-simulation and HIL approach has been provided. The third embarks on reviewing protection system tasks and protection challenges in distribution systems interconnected with DERs which are critical in designing and analysis of the system protection. Primarily, in the review process, background and technical details related to each protection approach are explained and research publications corresponded to that specific approach are investigated accordingly. There are four approaches adopted in devising system protection which have been discussed for fault current limiters (FCL), adaptive protection systems, graph theory application and agent based protection schemes. Finally, in the summary section, advantages and disadvantages for each protection approach are compared and concluding remarks on the adopted protection approach in this PhD research study are discussed. In the following section, architectural model referencing future power system operation and its layer-based interactions are discussed.

2.1 Future Power Grid Architecture

Understanding the operational complexities and interdependencies between various levels in the hierarchy of modern EMS plays a crucial role in designing and development of practical solutions for Smart Grid paradigm/applications [29]. In fact, given the interdisciplinary approach in expertise and solution scopes in Smart Grid applications, definition of a reference architecture that can be used to document various functional aspects of the Smart Grid is imperative to disseminate and achieve higher technology readiness level (TRL). Thus, in order to address the emerging technical standards and their applicability to Smart Grids, Smart Grid Architecture Model (SGAM) has been introduced as a tool to be referenced from system engineering perspectives [30]. In reference [30], a holistic approach based on integration of ICT infrastructure into EMS has been identified which defines a three dimensional multi-layer architecture including physical, communication and operational levels of the power system [30]. In Figure 2.1 the SGAM proposed by [29] has been illustrated where the three axis of domain, zone and system automation classify individual parts and data exchanged interfaces within the EMS landscape.

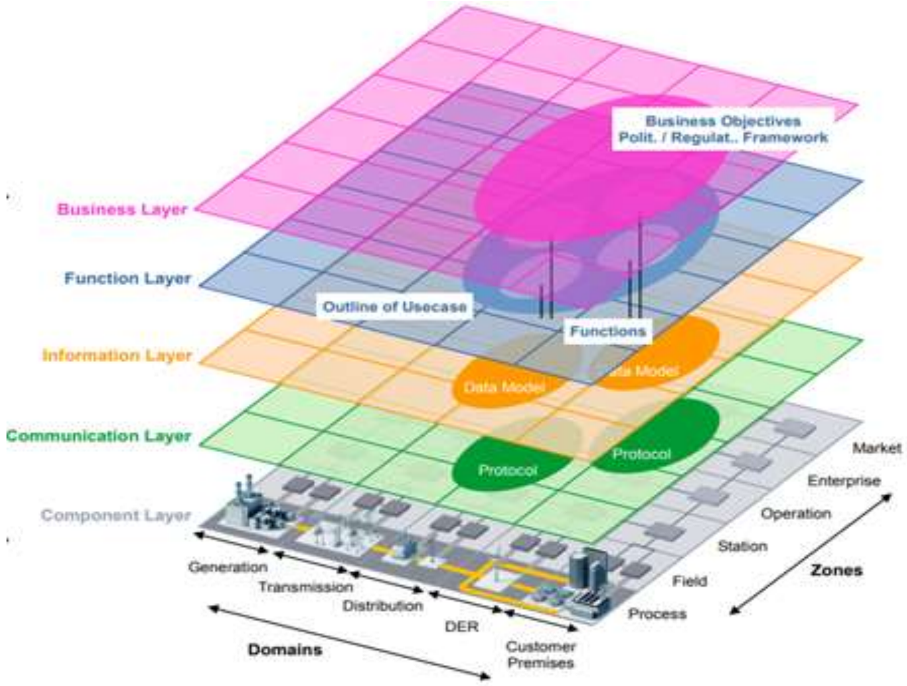

Figure 2.1 A multi-layer representation of SGAM to reference interactions in smart grids [30].

The aforementioned SGAM highlights some of the characteristics and operational services within the Smart Grid paradigm, which are the requirements during planning and development phases. For example, in SGAM architecture the domain axis shows physical connectivity between various power system components while specifications associated to data communications at each operational levels are given in the zone axis. In general, SGAM is considered as architectural development guide which assist both power system engineers and system integrator to include well-defined applications traverse utility network/industry [30]. Furthermore, defining SGAM can be used as a modern system modelling tool to manage complexity in developing simulation platforms to study Smart Grids operation which is discussed later in this chapter. In the following subsection, detailed explanations regarding the characteristics and functionalities corresponding to each of the three dimensions of SGAM are discussed.

2.1.1. Domain Specific model

Although SGAM has been adopted to represent different types of interactions and interdependencies within future power system through multidimensional or multilevel system architecture, power system itself is a large energy conversion chain, which can be partitioned into different domains providing certain capabilities to transport electric power over its infrastructures. Thus, according to the operational task for each specific domain and their involvement as physical infrastructure within the energy conversion process, different domain or levels are partitioned which can be highlighted or related to other dimensions of the Smart Grid architecture model such as information services and management infrastructures. The domains of the power system network as physical transportation medium have been defined as follows:

- **Generation:** It mainly includes the power generation units which are in bulk quantities such as fossil fuels, nuclear and hydro plants. Although large-scale wind farms which are connected to transmission lines, they can be partitioned as generation domain.
- **Transmission:** The physical infrastructure linking generation sources for transportation of the electricity power over long distances using high voltage levels.
- **Distribution:** Includes the infrastructures and organizations which directly distribute electricity between transmission line and the consumers.
- **DER:** Distributed local generation with different technologies, which are interconnected directly at the distribution levels.
- **Customer premises**: The end users consumers and producers which can be residential homes or commercial properties [29].

2.1.2. Operating Functionalities

Technically, in the literature study for System of Systems engineering (SOSs) Smart Grid is an illustrative example where reliance on operating services are essential to capture the physics of demand response and network behaviours for supplying reliable and secure electric power to consumers. Thus, from the perspectives of model-based approaches, operating services in Smart Grid are itemized into five layers as presented in Figure 2.1, to enable interconnectivity and automation functionalities via embedded ICT infrastructure. At the highest level operation services are associated with exchanging data providing a view at business level which focuses on economic and regulatory structure of the enterprise. For the functional layer services and use cases functionalities related to electric power transportation such as Voltage/VAR control, SCADA and DER control are implemented. The information and communication layer constitute the ICT infrastructure, which mainly includes communication protocols and standard data models facilitating data exchange between services in the functional layer. Finally, component layer which represents physical distribution of the power system equipment located at the process level. In fact, the proposed SGAM is used to determine interactions between different power system component distributed in the power system for functional requirements and ICT equipment for different power system components. This can be useful in developing research projects and simulation framework in which validity of the simulation results in real-world scenario is critical for Smart Grid applications [28, 31]. In the next subsection, the interoperability issues in the Smart Grid are explained.

2.1.3. Interoperability

As illustrated in Figure 2.1, the three layers of information and communication constitute the ICT infrastructure enabling information exchange between component layers to the highest level in enterprise management. Therefore, each component in power system has set of interfaces to the management level by utilizing interoperability between these layers. As a matter of fact, data modelling and communication protocol standards have been introduced for power system automation to harmonize data exchange between the layers of smart grid where data integration is performed according to functionality and tasks specified for each layer. Currently standards such as IEC60870 (SCADA), IEC61970 (CIM), IEC61850, IEC62541 (OPC UA) and DNP3 are defined for Smart Grid operation in different domains. Indeed, there are relevant technical requirements and standards for operating Smart Grid which is critical to be taken into account for compliancy in performance under real-world scenario. Consequently, according to SGAM, simulating Smart Grid operation based on available software tools if it is not impossible incurs high expenses for developing the software tool. Moreover, development of numerical solutions for multi-domain timescale simulations such as Smart Grids can be both technically and computationally intensive, requiring expensive software/hardware platforms. In the following section some of the methodologies and technical complexities associated to simulation of the Smart Grid operation has been discussed [32, 33].

2.2 Smart Grid Simulation

The advent of Smart Grid concept and notion of coupling ICT infrastructure into operation of the power systems have provided the opportunities for researchers to apply sophisticated and complex algorithms to address technical challenges, as mentioned earlier, in operation of the Smart Grids. However, in the context of engineering and system development, experiments on Smart Grids can be time consuming, expensive and often time restricted by the laboratory facilities [34].On the other hand and with respect to SGAM, simulation and modelling of Smart Grid requires special software tools and simulation framework which can address the heterogeneous nature of the subsystems in Smart Grids. The specific challenge in relation to simulating of Smart Grid operation is the tight coupling between power system, ICT infrastructures and Artificial Intelligence where operation of Smart Grid is coordinated. In Figure 2.2, the overlap of three different theories in the field of engineering and computer science for simulation of Smart Grid operation has been illustrated [35]. Therefore, considering the current scenario for Smart Grid studies, the importance of software tools and methods for simulating Smart Grid has been highlighted in many research studies [35, 36]. In the following subsection, some of the methods and simulation frameworks adopted for Smart Grids have been discussed.

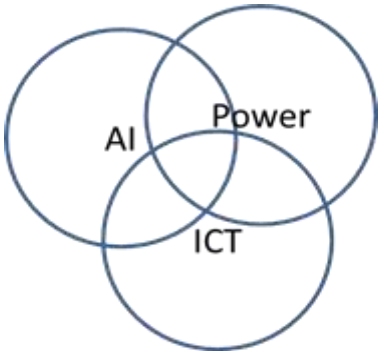

Figure 2.2 Overlaps in technology domains utilized in smart grid operation.

2.2.1. Multi-domain Simulation

The coupling between power system and other different systems has introduced Smart Grid as an entity comprising of wide range of subsystems which can be of an entirely different nature. For example, simulation methods in power system software tools adopt continuous-time integration of algebraic equations to simulate individual objects. Simulation environment for computer networks and ICT infrastructure utilizes discrete event-driven approach to model ICT-specific features such as communication network topology, protocols, bandwidth and latencies (information security, reliability issues), which intrinsically affect the behaviour of the power system [36] .Thus, according to SGAM reference architecture and interactions defined between the power system elements and ICT infrastructures, Smart Grid is a multi-domain system where monolithic single-domain simulators are not suitable to address reasonable detail and simulation speed. Moreover, single-domain algorithm have been developed and numerically optimized for specific domain of simulation extending such solvers for multi-domain systems can compromise the numerical stability of the simulation tools [34]. In the literature, the approach called co-simulation or cooperative simulation has been reported for multi-domain system simulations although initially it was used for single-domain simulation environment where large power system with different time-scale applications are distributed into separate simulation processes [34]. In Figure 2.3, time-scales for various applications in different power system domains has been illustrated where co-simulation can be applied to solve a multi-domain system within a monolithic continuous-time simulation. As a matter of fact modern power grids are becoming complex environment of system of systems (SOS) where data integration and communication interfaces for each individual device plays an important role to receive or provide operating services within the framework of the SGAM. The aforementioned requirement for multi-domain simulation systems have led to more advantageous and effective solutions to the problem of the co-simulation for smart grid applications.

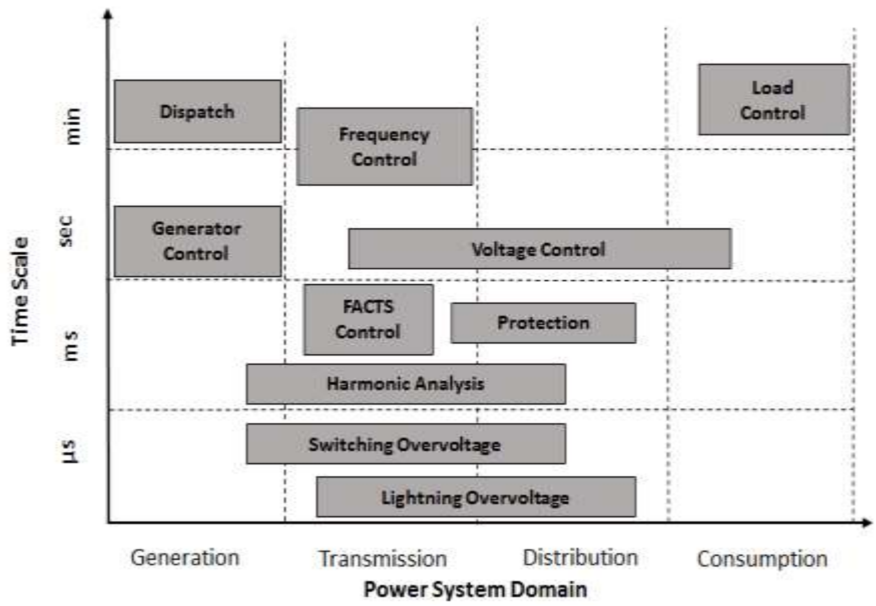

Figure 2.3 Time-scales for various applications in power system domain.

In [34], based on the potential flexibility in co-simulation method, various solvers are distributed entities which model power system elements with different time-scales as well as ICT infrastructures in power system operation. In the literature, there have been different approaches for co-simulation of the ICT infrastructures and power system components which has been highlighted below:

- Hardware in the Loop (HIL)
- Emulated ICT hardware
- Simulated ICT hardware
- Full simulation

Although the co-simulation has offered flexibility to incorporate multiple solvers in separate processors, interdependencies between the elements is relied on synchronization mechanism which is a dominating factor in the performance and accuracy of the simulation results. In the next section, the synchronization methods and their vital roles in developing co-simulation frameworks will be discussed.

2.2.2. Synchronization

One of the advantages of the integration of ICT infrastructures into power system is to enable the devices to interconnect and provide fine grained information about their behaviour [37]. However, to address this important aspect of the co-simulation method interaction between power system components and ICT infrastructure has to be coordinated using appropriate synchronization mechanism. Through literature, different synchronization methods based on the required functionality and real-time guarantee for exchanging information between the power system and ICT infrastructure simulation subsystems has been reported as:

- Point based;
- Event-driven; and
- Master-slave.

Generally, time synchronization for interfacing between continuous simulation for power system and discrete simulation for ICT infrastructures is dependent on the application and appropriate real-time guarantee for the functionality of power system operation. In Figure 2.4, real-time guarantees for various protocols used in different power system operation functionalities have been illustrated [38].

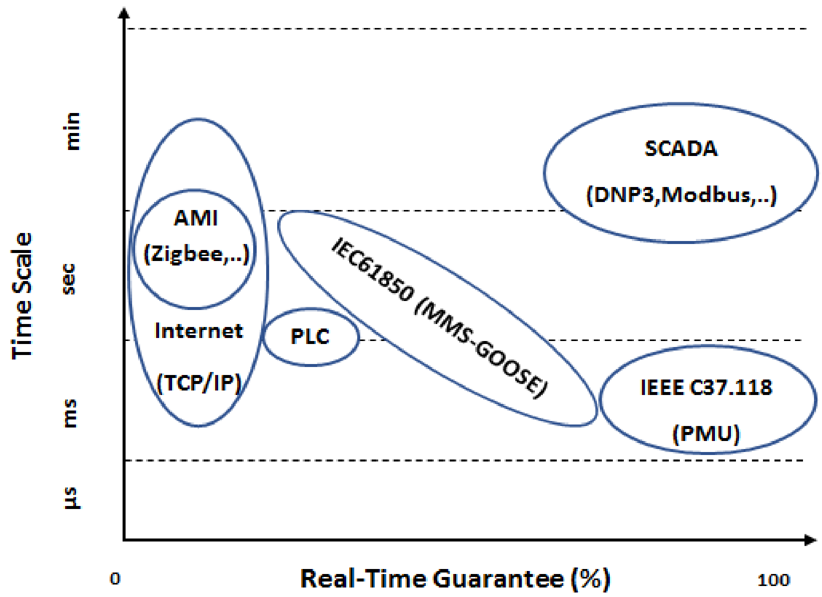

Figure 2.4 Real-time guarantees for various communication protocols in power system.

2.2.3. Co-simulation Platforms

In the last decade, evolution of simulation tools has been driven by the advancement in computing technologies where high performance processor with reduced costs which are utilized to solve complex problems in less times. However, with the introduction of Smart Grid paradigm and integration of the ICT infrastructure into power system, a transition in simulation tools for power systems are becoming inevitable [39]. Currently, application of co-simulation has been highlighted as a reliable and effective approach to address Smart Grid applications within different research fields [36]. Thus far, much of effort has been made to utilize co-simulation for coupling continuous power system simulators with discrete ICT infrastructure and communication network domains. In

Table 2-1, some of the co-simulation platforms have been listed in which various application domains and synchronization methods have been adopted[34].

Table 2-1 Examples of co-simulation of power systems and ICT infrastructure [34].

Name	Application	Components	Synchronization	Time-scale	Scalability
EPOCHS	Protection and control schemes	PSCAD/EMTDC, PSLF, and NS-2	points-based	microseconds to minutes	Suitable for large systems
OpenDSS & OMNet++	Wide area monitoring and control	OpenDSS, OMNet++	points-based	milliseconds to minutes	Medium
Adevs+NS-2	Wide area monitoring and control	Adevs, NS-2	Event-driven	Limited range	Suitable for large systems
GECO	Wide area protection and control	PSLF, NS-2	Event-driven	milliseconds to seconds	Suitable for large systems
Greenbench	Cyber security in distribution grid	PSCAD, OMNet++	Event-driven	N/A	Tested in small systems
PowerNet [29]	Monitoring power grid devices	Modelica, NS-2	Master-slave	N/A	Unsuitable for large systems
INSPIRE	Monitoring and control	DIgSILENT Power-Factory, OPNET	Master-slave	microseconds to minutes	Suitable for large systems
VPNET	Networked power converter system	VTB, OPNET	Master-slave	N/A	Unsuitable for large systems
OpenDSS and NS-2	Distributed energy resources integration	OpenDSS, NS-2	Not addressed	From milliseconds to seconds	Medium size
TASSCS	Cyber security of SCADA	PowerWorld, OPNET	N/A	Real-time in communication network	Suitable for large systems

As shown in Table 2-1, development of the co-simulation platforms is dependent on various factors related to Smart Grid operation such as application domain, simulation software, synchronization methods etc. Therefore, considerations for co-simulation require beyond the state of the art integration of refined domain-specific tools to investigate mutual interactions of ICT infrastructure and power systems [34]. In some applications, strict real-time constraints have to be met ensuring accurate comparison of the results similar to real-world scenario. The concept of Power Hardware in the Loop (PHIL) has been introduced to fulfil the real-time constraints and interactions between actual physical power system components and the co-simulation software. To implement PHIL simulation, a Real-Time Digital Simulator (RTDS) is required to compute the model of the power system as fast as a wall clock while the hardware under test is interfaced through signal converters such as Digital to Analogue Converters (DACs) or Analogue to Digital

Converters (ADCs) [36]. In Figure 2.5, the PHIL concept has been illustrated where signals from the simulated model in RTDS can be connected directly to the hardware under the test.

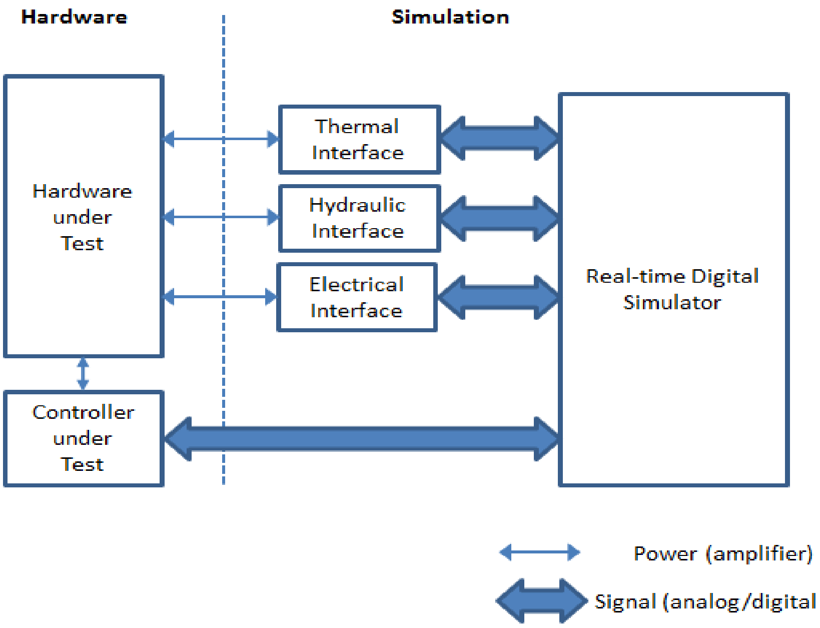

Figure 2.5 Concept of PHIL to simulate Multi-physics subsystems in power system.

In summary, in this research study, the aforementioned concepts of co-simulation and PHIL have been utilized for the validation phase where the proposed protection strategy is developed with reference to SGAM. For the proposed simulation platform, real-time simulation of the power system model in MATLAB/SIMULINK has been coupled to JADE to incorporate MAS into power system protection. The PHIL approach was extended by placing protection relays as the hardware under the test where both analogue and digital signals from the simulation platform are injected/transmitted to the terminals of the relay using power amplifier units [40].

2.3 System Protection Review

The provision of system protection in power system network is introduced to address electrical failures or damages to the power system components while service interruptions to customers are kept minimal. However, the actual protection tasks in power system networks are implemented by protective relays and CBs which detect faults and isolate the faulty section of the line within short period of the time. Generally, in power system networks, protection zones are devised to maintain the continuity of power flow from generation to consumer while certain protection schemes are developed to ensure reliable and safe transportation of electrical power within each protection zones. In Figure 2.6, protection zones for a typical power system networks have been illustrated in which CBs specify the boundaries for primary zones while the overlap between primary protection zones are defined as backup protection zones of the protection system.

In fact, the overall reliability and safety of the power system networks is dependent on proper protection function/schemes and accurate settings for each protection zone.

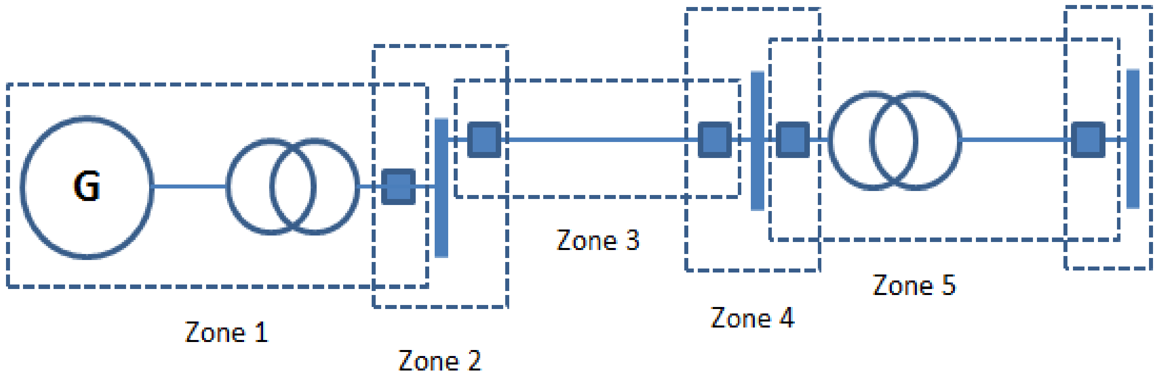

Figure 2.6 Provision of protection zones for system protection in power system networks.

Conventional power system networks are planned for a radial network topology where electric power is delivered from upstream bulk generation at power stations to downstream consumers through transmission and distribution lines. However, with the advent of new era in supplying electric power utilizing DERs in distribution networks, traditional protection arrangement based on unidirectional power flow paradigm are not valid. Moreover, complexities in interactions between DERs and distribution networks require detailed investigation on fault current analysis and variation in fault current contributions under different operating conditions. As it has been discussed through literature, application of the protection settings based on the conventional fault current calculations and protection function schemes are prone to different protection challenges such as false tripping, mal-operation, blinding, and cascaded tripping [16, 41, 42].

Despite the aforementioned challenges in system protection, utilization of modern protection technologies relying on ICT infrastructures and communication standards has envisaged promising flexibilities in establishing protection strategies to meet complexities arising from power system transitions [43, 44]. Thus, in modern protection systems, the key feature for protection strategies is the ability to exchange information among different protection functions and equipment, where advanced decision making algorithms are utilized to improve system reliability. Consequently, based on these changes for protection strategies standards such as IEC61850 and IEC61968, Common Information Model (CIM) have been adopted to expedite and promote more complex and efficient protection strategies such as SPS (System Protections Scheme), SIPS (System Integrity Protection Scheme), situational awareness, WAMP and self-healing which fall into a wider area of the system protection for future power systems [44, 45]. In the following subsections, a thorough literature review on existing protection strategies within the context of the modern power system are conducted where four prevailing approaches in system protection of interconnected distribution network are discussed.

2.3.1. Fault Current Limiter (FCL)

Primarily in power system applications, the main objective for using Fault Current Limiters (FCL) is to limit fault current at the feeders to accommodate switchgear ratings and avoid excessive currents flowing through electrical components. In fact, similar to surge protection devices, FCL is only applied to reduce the high current levels which may damage equipment rather than isolating and disconnecting the faulty section from the rest of the healthy network. Although, with the new transition in operation of power system distribution networks and interconnection of DER, the simple structure of the FCL as a passive inductor components have been improved to address protection challenges in the interconnected distribution network. Currently, with the increasing application of FCL for system protection in distribution networks, different types and technologies for FCL configuration have been adopted which are solid-state, superconducting and inductive FCL.In Figure 2.7, the two main broad types of FCLs used in power system distribution network has been illustrated. As shown in Figure 2.7(a), a serial type SSFCL with three bypass circuits can be activated in three different states for normal states with reduced loss, fault current states with reduced fault current level and over voltage condition as voltage surge protection. Although there are various types of SSFCL which have been developed with different complexities (technology) and operating applications, the structure of FCLs devices can simply be described as reactors controlled through power electronics. In the same context, the SCFCL represented in Figure 2.7 (b) is applied for the same purpose of limiting fault current in power system networks but instead of using semi-conductors and electrical components, it utilizes superconductor materials such as Yttrium-Barium-Copper-Oxcide (YBa2Cu3O2) which have highly non-linear behaviour under various ranges of the temperatures to limit the fault current in power system network [46].

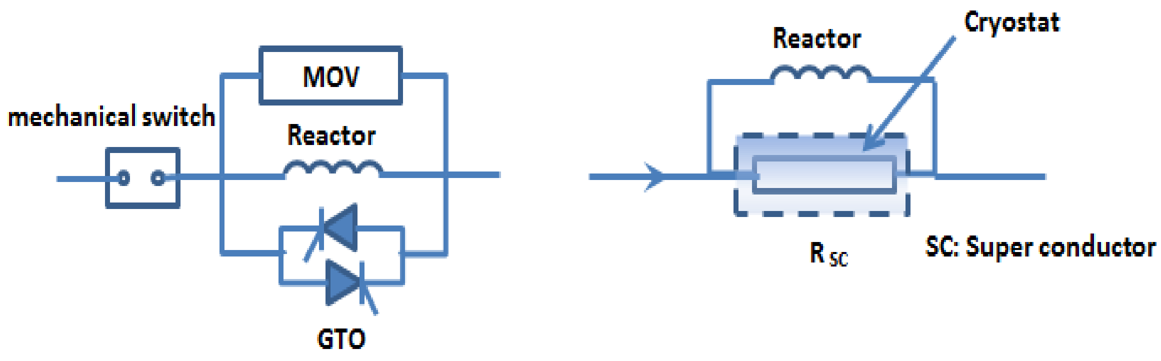

Figure 2.7 Representing two different types of FCL as SSFCL (a) and SFCL (b).

Having introduced new technologies and advancement in manufacturing and utilizing FCLs, various applications have been proposed to highlight potential solutions for system protection in radial distribution networks interconnected with DERs. In the following, some of the research studies related to FCL and their applications in interconnected distribution network are discussed. According to research papers [47-50], the main objective in using FCL approach is to avoid high fault current and protect power system components against thermal stresses and undesirable operating conditions. However, in addition to its primary purpose, restoration of protection coordination between IEDs and fuses have been highlighted as a desirable approach in utilizing FCL for system protections in distribution networks interconnected with DERs.

In [51], Shahriari et al. have suggested the application of SSFCL to address mis-coordination between the IEDs and fuses due to connection of the DER into radial distribution networks. In its proposed schemes, the SSFCL device is composed of Gate Turn-Off (GTO) thyristors paralleled with a current limiting inductor and voltage limiting components such as Metal Oxide Varistor (MOV). As explained in Figure 2.7 (a), the inductor is used to prevent high current as the turn-off signal are received by GTO thyristors and the current will pass through inductor also in the case of sudden interruption to fault current the resultant overvoltage can be prevented by the MOV during fault occurrences. Although, various factors such as simplicity in structure, control and fast response to limit fault currents have been mentioned as the advantages of the scheme, the core idea of using fixed settings for overcurrent detector (overcurrent protection) under various operating conditions of the DER is unrealistic and not matched to real-world scenario. Similarly in [52], SSFCL was used to reduce fault current contribution from the wind turbine generator units to avoid exceeding the CBs capacities for operating of the CB. Although Cakal et al. [52] has investigated the effect of FCL unit for different locations within the distribution network, but no systematic solution has been provided for a protection scheme which can detect variation of the fault current level under different operating conditions for wind turbines.

Reference [53] has introduced FCL approach to restore the coordination in the protection system for a radial power system. The advantages have been highlighted as using conventional electromechanical protective relays by making this approach less expensive. However, the complexity of the future power system has to be taken into account where different protection strategies and high penetration of the DGs are necessary to be investigated. Thus, simply in this case study contribution of the fault current during fault occurrences are limited by placing FCL at the connection points of the DG units.

In references [54, 55], further to FCL application, optimization of DG placements have also been taken into account to improve the operation time for the protection system and increasing system reliability. However, it should be noted that the proposed solution is suitable at the planning level and for a fixed topology of the power system networks this is not practical with the new paradigm in operation of the power systems. Application of super-conducting FCL investigated in [56] utilizes dynamic simulation to highlight the advantages of SCFCL due to its no losses during normal operation and its fast response to sharply limit fault current for restoration of the protection coordination systems within radial network. Accordingly, practical results for SCFCL device have been studied in [57] which further emphasis the effective performance of the SCFCL devices compared to SSFCL device however, costs corresponding to SCFCL maintenance and design are still the main drawbacks in using SCFCL.

Finally, within the context of Smart Grid and its capability for exchanging operational information utilizing ICT infrastructure, Ustun et al. [58] proposed a central control unit using communication based protection system in which fault current level is estimated through monitoring of the FCL installed at each DERs. Therefore, with any changes in operating condition of the DERs, FCL status data are sent to a central unit and accordingly the settings for the relays are updated in order to detect and isolate the fault section of the line. Further to its earlier approach for a centralized communication assisted scheme for using FCL, Ustun et al.[58] proposed an extension for IEC61850 standard to embed the FCL data model into power system automation. Technically, the advantages in introducing FCL based on IEC61850 communication standard can increase the scalability of FCL application for high penetration of DERs in distribution level for future power grids [59].

2.3.2. Adaptive Protection System (APS)

For conventional protection systems, protection settings are fixed for predetermined operating conditions, thus any changes or adjustments to the settings has to be done during the outages of the protection equipment. However, in recent years, with the advancement in ICT and utilization of state of the art IEDs the feasibility of on-line changes of the settings in protection system has envisioned possible flexibilities for protection engineers to adopt sophisticated approach to address complexities associated to the modern power system protection [60, 61]. In its early definition for adaptive protection system, Rockefeller et al.[62] expressed an on-line activity that modifies the preferred protective response to a change in system conditions or requirements which is usually automatic but can include timely human intervention. In general form, adaptive protection is devised to dynamically determine protection settings by taking into account prevailing changes in operation conditions of the power system and utilizing optimization techniques for better performance of the protection system [63]. Figure 2.8 illustrates the overall structure for adaptive protection system where interactions between different modules of the adaptive protection system have been highlighted [63]. As shown in Figure 2.8 different blocks with various functionalities are arranged (tightly-coupled) to fulfil protection tasks by updating the protection settings based on the operation parameters and measurement values received from power supply network (including CB status and information on operation mode).

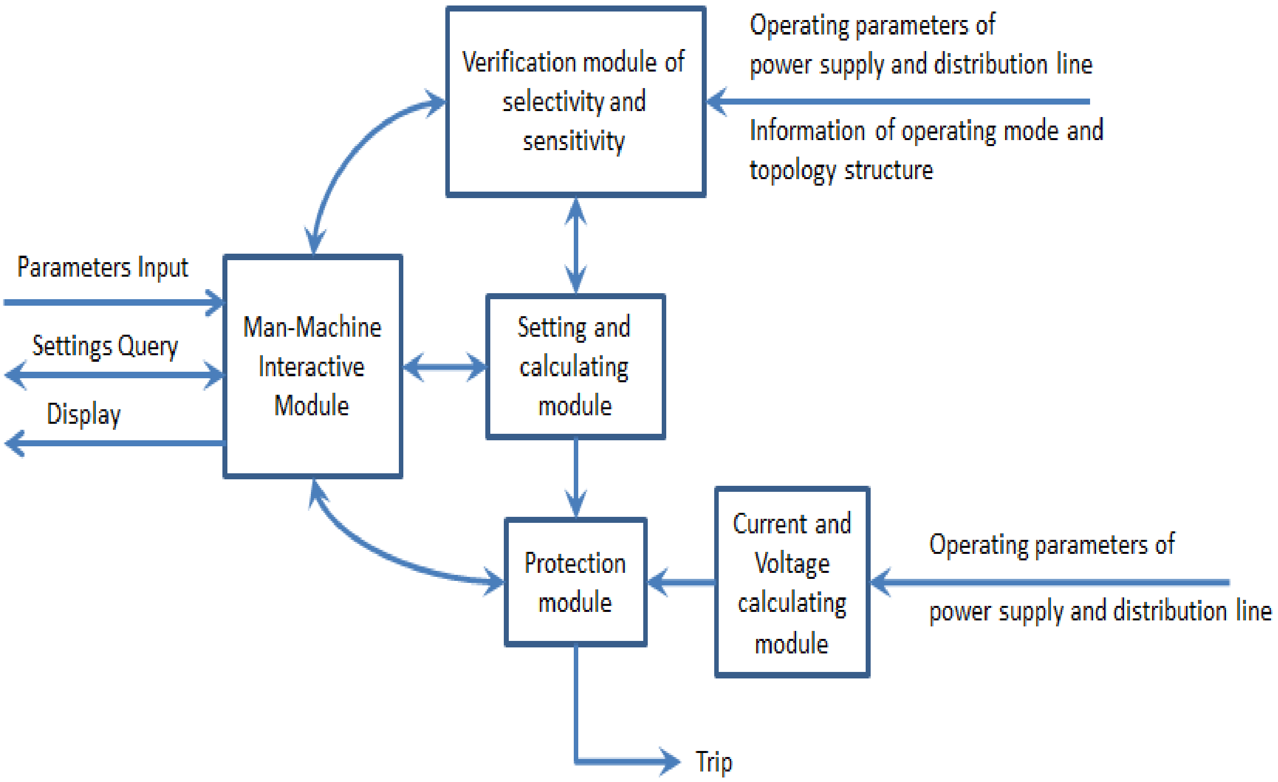

Figure 2.8 Conceptual structure for adaptive protection system in distribution network.

From technical point of view, realization of adaptive protection system relies on hardware and software elements involving hierarchical computer systems, parallel processors and remote central processors which communicate through data channels. Although the concept of adaptive protection system and adjustment to protection settings have not been new for power system protection engineers, its applications have been deferred due to wide acceptability and satisfaction with conventional protection settings in radial power system networks [61]. Moreover, the absence of advanced ICT infrastructures within conventional structure of the power system networks have been a main drawback for deployment of the adaptive protection systems within large scale power system networks. Therefore, under the new paradigm for operation of power system networks, deployment of adaptive protection systems have been identified as an acceptable solution against the challenges arising from connection of DER into distribution network [26, 64, 65]. Currently, with the advantages in utilizing power system automation standards and advanced ICT to exchange information or receiving commands between different IEDs in the power system network, application of the adaptive protection system has become a hot topic for future Smart Grid operation [16]. Through literature, various approaches have been proposed to integrate adaptive protection systems into distribution network. However, depending on update algorithm and availability of protection system infrastructure a centralized or distributed architecture have been adopted for implementation of the adaptive protection systems. In the following, two main methods for deployment of the adaptive protection systems have been investigated.

2.3.2.1 Centralized

In the context of adaptive protection system and the necessity for adjustment in protection settings of the protective devices, centralized architecture in utilizing computational and data storage devices have been underscored by many researchers [64, 66]. However, depending on complexities of the protection scheme and decision making algorithm, different approaches have been established to fulfil computational tasks and data communication for adaptive protection systems. Initially, centralized/hierarchical structure has been proposed by Rockefeller [61] where feasibility for better performance in protection system in transmission lines have been highlighted. In his research paper on adaptive relaying concepts, Rockefeller et al. [61] proposed adjustment to protection settings based on variation in operating condition and topological changes within substation level. In addition to that, to address technical aspects corresponding to realization of the adaptive protection system, several examples associated to protection functions/schemes such as adaptive distance protection, adaptive multi-terminal protection and adaptive reclosing have been discussed for improvement of the relaying performance in transmission system protection.

Further to Rockefeller, Brahma et al. [67] adopted the concept of adaptive protection system to address mis-coordination problems between the fuses and protective relays within a distribution network interconnected with DER. In his research, Brahma et al. proposed a centralized protection scheme relying on both on-line monitoring of fault current contributions from each DER and offline power flow calculation where utilization of large data storage capability is crucial. The outline of the proposed scheme is based on dividing distribution network into separated protection zones using CBs and utilizing off-line power flow data to adjust differential protection function for each protection zone. Although simulation results highlighted improvement in fault detection and restoration of the coordination between CBs and fuses within each protection zone, practical implementation of the proposed protection scheme is dependent on performing on-line and off-line tasks which is implemented in a single main protection relay. In addition to that, the ICT infrastructure and data communication challenges such as bottleneck for data communication bandwidth and disruptions in communication links have not been taken into account.

In reference [64], Oudalov et al. highlighted protection challenges within the micro-grids where transitioning from grid-connected to islanded mode lead to large variations in fault current contribution from DERs and resulting in inaccuracies for system protection settings. Further into his research studies, Oudalov et al. projected the philosophy of connect and forget for future distribution networks where DERs are supposed to be connected at distribution level while protection settings of the IEDs are adjusted through a centralized adaptive protection system relying on ICT infrastructures and computerized control centre in substations. In order to address the feasibility of centralized adaptive protection scheme in micro-grids, adjustment for Time Over Current (TOC) curves in overcurrent protection function has been proposed as an effective approach to restore protection system against the changes in operating conditions of the micro-grids. Utilization of the modern protection IEDs and state of the art capabilities of the micro-processor based IED to be configured on-line has been mentioned as an essential requirement to implement the proposed scenario. Figure 2.9 illustrates protection system architecture for a typical micro-grid developed in [64] where a centralized controller update the settings for TOC curves and send it to the IEDs in distribution network.

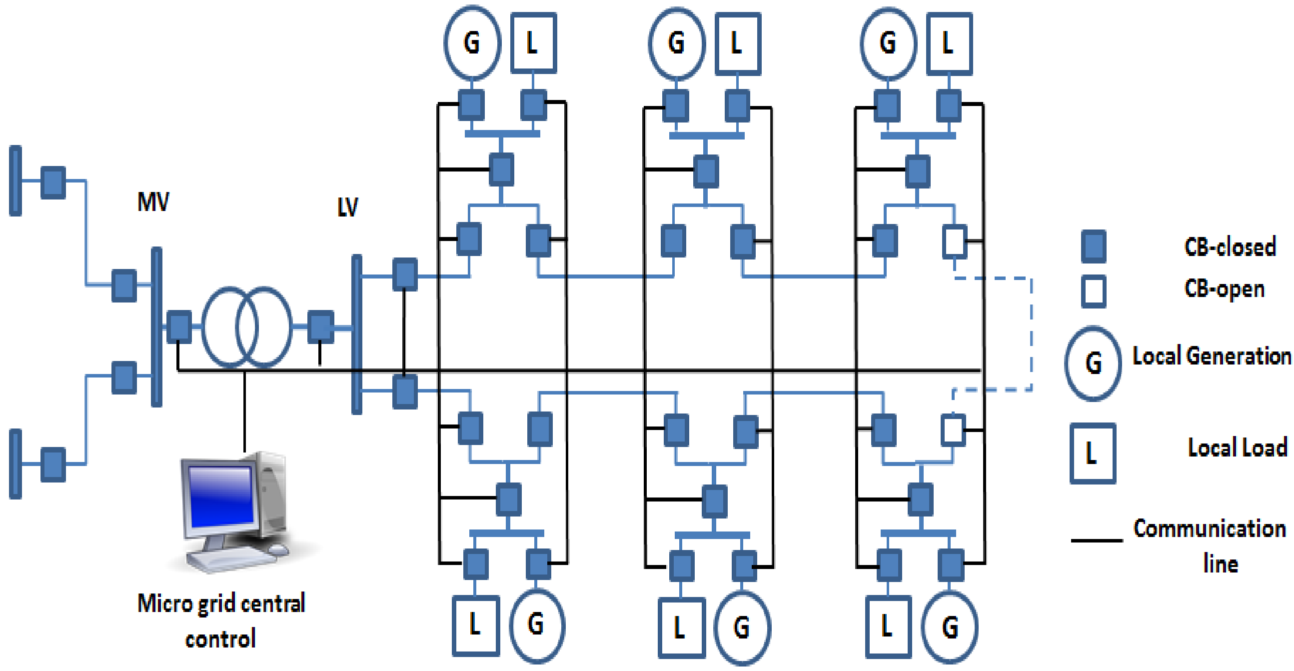

Figure 2.9 A typical architecture for centralized adaptive protection system in Micro-grids.

Similar to Oudalov, Vasileios et al. [68, 69] implemented an adaptive protection scheme in which Nonlinear Programming (NLP) method such as Particle Swarm Optimization (PSO) have been proposed to adjust TOC curves in overcurrent protection function to coordinate protection IEDs. Further to that, Vasileios et al. [70] adopted PHIL methodology to evaluate performance of the proposed adaptive algorithm by developing real-time simulation testbed including IEDs and central controller hardware to embed real-world scenario for deployment of adaptive protection strategies. In order to address both technical and practical aspects for exchanging information between the IEDs and control centre, the IEC61850 standard was introduced to guarantee implementation phase with respect to available off the shelf products. Despite its effective approach for tackling coordination problems within a typical modern grid, given the computationally intensive method using NLP algorithm and lack of scalability for expanding to different power system network, the proposed scenario can be problematic for large scale networks. Moreover, relying on centralized controller hardware, limitations in communication bandwidth and possible failure to controller hardware can affect the performance of the protection systems.

Also with the growing use of Phasor Measurement Units (PMUs) and data streaming of measurement, the scope of adaptive protection system has been expanding toward wide area monitoring and protection (WAMP) where preventive/protective actions have been introduced as specific protection schemes (SPS) to address system wide operating conditions of the modern power systems [44, 45]. Although, limitations for speed response required in primary protection cannot be met by SPS, integration of real-time data from wide area of the network into a centralized decision making system can be an effective mean to improve backup protection by analysing and updating protection settings with respect to the variable operating conditions of the power systems [43, 71].

In the same context, for wide area adaptive protection system, utilization of Artificial Intelligence (AI) and data mining algorithm has been discussed in some of the papers [71-75]. For example Bernabeu et al. [73] proposed an adaptive protection system which can optimally adjust the security/dependability balance of the protection system according to operating condition of the power system. In the proposed methodology, a classification algorithm based on Decision Tree (DTs) used to categorize the operating condition of the power system network into “safe” and “stressed” in which protection settings are adjusted accordingly to suit prevailing system condition. In his research paper, Bernabeu et al. have argued/contended that in modern power system under safe state, not isolating the fault with primary protection has greater impact than mis-operation of relays due to lack of security. Accordingly under stressed operation conditions, the bias toward security is favourable as the likelihood of manifestation of hidden failures and cascading events can be reduced. Although the proposed scheme is reliant on advanced wide area monitoring and measurement devices like PMUs, placement of the PMUs in critical points within power system networks and learning samples in DT classifications is crucial for successful realization of the proposed hypothesis. Technically, the scope of adaptive protection system is intended for non-instantaneous protection as the communication bandwidth plays limiting factor for relays to operate within 1 to 3 cycles (17 to 50ms) [73].

2.3.2.2 Decentralized

Typically in the literature, adaptive protection systems have been implicated as a centralized architecture in which central control unit consisted of data storage and processing units are devised to collect information from power system component and apply various algorithms to update the protection setting for each protection zones. In contrast to centralized approach, few papers [76-80] have studied the concept of adaptive protection system using decentralized strategies to update protection settings of the protection IEDs. Technically, for decentralized adaptive protection systems, requirements for communication bandwidth and large data storage are relaxed as the data communication is limited to local neighbourhood of the IEDs and as a result catastrophic failure in system protection due to disconnection in communication links or communication delays can be avoided. In one of the early studies on decentralized adaptive protection, Mahat et al. [80] proposed a self-reliant adaptive protection algorithm where based on local information such as CT ,VT and frequency measurements proper protection settings for TOC are selected. As a matter of fact, the analysis provided in [80] is dependent on detection of islanding and resynchronization of the DER systems with the power system network which subsequently rely on various islanding techniques [81]. In addition to embedding islanding techniques for each protection IEDs, it is necessary to adjust its protection settings of each IEDs according to fault section detection algorithm. In a nutshell, despite the advantages of decentralized approach adopted in [80] in which data communication between the IEDs have been removed to improve the reliability of the protection scheme, complexities related to the islanding detection and fault section detection algorithm can be a drawback during the implementation phase of the protection system. Moreover, there are many factors related to operating conditions of the DER such as wind turbine generators and their fault current characteristics which can have an adverse effect on both islanding detection and fault section detection algorithms.

Further studies for designing decentralized adaptive protection system has been attempted by Ciontea et al. [77] for maritime power systems in which protection IEDs can identify and adjust their settings based on communication with different relays, CBs and generators, without relying on any centralized control unit. The principle of the proposed protection strategy by [77] is composed of two standard protection functions TOC and inter-tripping where adjustments for the settings of TOC are applied simultaneously by receiving on-line information about the status of CBs and generators within the power system. Moreover, the protection scheme is reinforced against any failure for CBs tripping as the inter-tripping function is used for communication between relays to stimulate/speed up the tripping of the neighbouring relays for the backup protection zone. In spite of the efficiencies in decentralized adaptive protection presented in the paper [77], maritime power systems are not comparable to complexities of topological reconfigurations and operation status of the power system networks which are interconnected with different types of DERs. In addition to that, the use of off-line analysis of the power system cannot be a viable option for interconnected distribution networks where DERs can be connected or disconnected under various operation conditions such as islanding or grid connected. Similar to [77], Maleki et al. [76] proposed a decentralized adaptive protection system for distribution network interconnected with DERs in which relays themselves constitute a central unit for monitoring and adjustment of their settings according to variations in topology of the network and operation mode of the DGs connected to the network. Also to further improve the reliability of the protection system, a backup protection task is considered, which enables the protection scheme to restore the selectivity of the protection system as the failure of primary protection IEDs occurs. However, despite the claim of increased reliability for the protection scheme and the efficiency in removing hardware requirements for large memory storage in the protection IEDs, implementation of the proposed protection scheme relies on running off-line simulation under various scenarios where accurate modelling of the power system network under real-world scenario is inevitable.

Adopting similar approaches for adjustment of the protection settings in protection IEDs, in several papers [79, 82] a hybrid approach based on combination of localized central control unit and hierarchical communication links between the IEDs have been proposed to establish a decentralized adaptive protection system. Although it is contended in [79, 82] that combination of centralized and decentralized protection scheme can improve both flexibility and reliability of the protection system against any unpredictable fault occurrences, there are still risks for the failure at higher level communication links leading to collapse of the protection system through entire power system network. In a novel approach, Bahadornejad et al. [83] proposed an on-line estimation of Thevenin equivalent network for upstream and downstream sections of an active radial distribution network in which fault current contribution at each CB locations are calculated in the presence of DERs. In his research paper, Bahadornejad et al. [83] introduced an intrusive method where small signal external disturbances to the distribution network are injected and the voltage and current responses are used to estimate the impedance of both upstream and downstream. Despite the advantages of being on-line and decentralized for calculation of the fault current contribution and adjusting the overcurrent protection settings, the need for external hardware to generate disturbance with enough of energy not affecting the network equipment may not be a cost effective option or even not be technically possible for large scale interconnected distribution networks. Moreover, reliability of the protection scheme can be affected in case of any failure to the external hardware modules for injecting external disturbances to the system.

In conclusion, improved reliability for decentralized adaptive protection system is achieved by replacing centralized data exchange or controller units with protection IEDs where decision making process mainly rely on local measurement data and neighbouring IEDs. Although due to lack of computational and memory storage for decentralized adaptive protection schemes, these type of protection are usually relied on detailed off-line simulation and analysis to cover all possible scenarios within the operation of the power system network. Therefore, the feasibility to deploy such decentralized protection system is generally practical for small scale power system network with few interconnections of DERs or low penetration of the renewable DGs. It is worth mentioning that for this subsection literatures associated to adaptive protection system have been studied based on existing protection functions and communication infrastructures available for power system components to exchange data. However, there are other strategies in devising adaptive protection system which are defined based on different analytical domains such as MAS relying on communication standards and interoperability within the power system automation pyramids [76, 77] .

2.3.3. Graph Theory

Graph theory is a branch of mathematics used to model complex interactions within a network of objects and connecting elements which are called nodes and edges respectively. Although the foundation of graph theory has been used to model different problems in various fields of science such as computer, economics, social media and power system networks, the main advantages that have been highlighted for graph theory is the ability to decompose complex interconnected problems into sub-problems which can be less complicated for solutions. From topological point of view, a simple graph representation can be described as in Figure 2.10 (a) where circles represent nodes and lines are connecting elements. Representation of a graph are defined by set of vertices and edges which are denoted as G=(V,E) as E=[1,2,3,4,5] and V=[A,B,C,D,E].

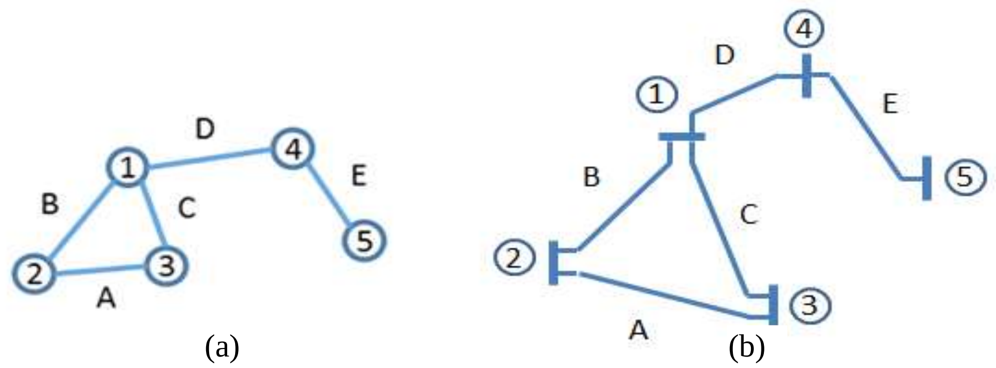

Figure 2.10 Topological representation of the power system using graph theory.

Similar to graph representation as shown in Figure 2.10 (b), power system networks can be described as collection of buses (vertices) where electrical components are interconnected by conductors as power lines (edges) coupled by electrical quantities. The main principle of the graph theory for utilizing in power system domain is the capability of capturing topological information from the power system network where graph decomposition theorems can be used for analysing protection coordination and reliability of the power system [84, 85]. Although application of graph theory in modelling and analysis of power system is dated back as early as 1879 where kirchhoff used topological nature of the power system network to develop a Z impedance matrix for graph model of the power system network, utilization of graph theory in power system protection have been introduced in early'90s in which performance of the protection systems is defined as an optimization problem in graph theoretical approaches [86].

Some of the research papers focusing on power system protection using graph theory approaches have been discussed and the advantages and disadvantages of each research studies are explained in the next subsection.

2.3.3.1 System Protection Application

In protection system application, there has been many researchers adopting graph theory to address different aspects related to coordination, fault detection and protection settings within the power system protection network. However, for almost all of the research studies, the general framework has been based on topological modelling of the power system network and further optimizing specific aspects of the protection system through decomposition techniques and computational search algorithms [87-89]. For example, Jenkins et al. [86] addressed automatic coordination for relay settings based on identification of Break Points Set (BPS) and the corresponding relative sequence matrix as relays are presented in primary-backup pairs within the power system topology to optimize minimum coordination intervals. In Jenkins et al. [86]research/proposal, the concept of functional dependency was introduced into power system protection in order to apply all the constraint information for relay settings while graph decomposition techniques were adopted to solve coordination problem for the relay settings. Although, the concept of functional dependencies between the relays have brought the advantage of computational efficiency in previous approaches using graph theoretical techniques, complexities within modern power grids and variation of operating condition of the power system have not been taken into account. In [87], Madani et al. further proposed an improvement on Jenkins et al. studies [86] by introducing minimum BPS as a key factor in reduction of the complexity and computational tasks for coordinating protection relays. According to [87] , a minimum BPS or near to minimum BPS, which can exploit the sparsity for dependencies between the relays to simplify calculation of relays settings within meshed-like network topologies were determined. As a result of the research study in [87], Madani et al. developed a fast algorithm to determine near minimum BPS where based on graph theory lemmas, the relays coordination problem can be decomposed into sub-problems with limited number of iteration for achieving the desired settings. Moreover, it has been concluded that the advantages of the minimum or near minimum BPS can be applied in any other methods in relay coordination which deals with BPS determination [87].

Although application of graph theory has been effective to model specific aspects related to protection coordination in power system networks, mathematical modelling of protection schemes in complex networks exhibiting asynchronous and concurrent interactions between flow of information and system protection requires innovative approaches to be adopted in graph theory [90]. Thus in response to aforementioned challenge, Petri-Net has gained a lot of attention as an intuitive to graph theory for better understanding of the logics in protection schemes of complex networks such as future power system network [90-92]. In fact, in Petri-Nets system, activities and structural information are defined through states-transitions where interactions of continuous power system and discrete event-driven protection schemes are taken into account within a distributed system. So far, Petri-Nets have been used in many research studies to address various aspects of system protection challenges within the context of future power networks, while interactions between continuous domain power system components and discrete event-driven protective relays are central issues to the performance of protection systems [93]. In early studies on application of Petri-Net, LO et al. [94] proposed a fault detection/diagnosis method based on modelling of the protection system with Petri-Net graph and analysis of the information available from protective devices. The method has been introduced as accurate and computationally efficient as traditional pattern recognitions methods. However, only operation of the main CBs and protective relays have been compared while status of the back-up protection relays have not been taken into account [92]. Furthermore, on application of the Petri-Nets, Jenkins et al. [95] developed a time Petri-Net graph structure to carry out performance evaluations on primary-backup coordination within protection systems of the electric power network. In his approach to model the protection scheme with Petri-Nets, the timing relationship between primary-back up relays have been introduced as constraints to transition nodes of a marked Petri-Net. As a consequence of embedding time parameters into Petri-Net model, the resulted evaluation performance for primary-backup protection schemes have been enabled to identify both the cycles of the protection schemes and compute the cycle times for each primary-back up protection relays. Although utilizing parallelism is an advantage to Petri-Net approach, a major drawback in modelling of protection schemes based on Petri-Net is the complexities of the model which becomes too large for analysis even for a modest size system [90]. With relevance to the aforementioned research studies, applications of the Petri-Net have been investigated for different purposes such as substation protection, protective relay modelling, power system reliability and analysis of distribution network topology [92].

Until recently most of the proposed graph based solutions in protection systems have been relying on mathematical modelling of the power system networks within a predefined/fixed topological structure. However, utilization of DERs at distribution levels in power system networks can alter the traditional concept for considering fixed topological structure of the power system networks as the connection, disconnection or even standalone operating of the DER can introduce adverse effects on system protection performances. In addition to that and aligned with modern concepts associated to Smart Grid operation, capabilities such as self-healing, self-diagnosis are becoming crucial factors in developing protection systems to meet system reliability and security of the future power system. Through literature, many research studies have been conducted in which computer-aided search algorithm based on topology of the power system network and coupled interaction with ICT infrastructure have been highlighted as an intuitive approach to improve protection system of the complex interconnected networks [93]. For example, Swathika et al. [96] proposed prime-aided Dijkstra's algorithm from computer science in which the topology of the power system network can be continuously identified and employed to find the shortest path from the faulted point. Moreover, protection strategy, called Centralized Protection Centre (CPC) has been devised which can adaptively change the settings of the protective relays according to selectivity levels and short path identified using Dijkstra's algorithm. Although, the proposed methodology has been tested for IEEE-21 and IEEE-40 buses network where all possible network topologies and faults have been applied, the fact that centralized approach are prone to failure and leading to disastrous outcome can be a main drawback to the proposed approach. In addition to that, despite the fact that it has been claimed by the author that minimum portion of the network has been disconnected to meet the selectivity criteria for the power system protection, the timing for the fault clearing has not been mentioned which is crucial to safe operation of the power system components and personnel. Within the same track, Ustun et al. [97] proposed network graph discovery algorithm where system protection can automatically detect the topological changes in power system network and accordingly proper protection settings are devised within distributed control modules. Although there has been some advanced concept such as plug and play integrated to automatically detect and identify changes in the topology of the network, no performance criteria for protection system have been discussed in the research work. Finally, the idea of utilizing heuristic search methods for identifying topological reconfiguration in power system networks in conjunction of graph theory has been studied in other research papers, which mainly addressed the search algorithms such as Depth First Search (DFS), Breath First Search (BFS) and some others, which can be found in the literature corresponding to graph theory within computer science [98].

2.3.4. Multi-Agent System (MAS)

The core of MAS is reliant on agent technology in computer science where new paradigm in programming has been adopted allowing agents as piece of software/hardware to interact and communicated with each other to take actions autonomously and intelligently towards a global goal [99]. Generally, Multi-Agent System (MAS) is an extension to agent-based technology [100] but its application have gained more attentions in dealing with large scale complex systems where the solution is dependent on interactions between various components. As a branch of Distributed

Artificial Intelligence (DAI), in MAS different agent types are defined to collaborate towards a main objective of the system where deriving of a closed form mathematical modelling of the system is complicated or impossible. There are many advantages associated with integrating MAS into power system which can be listed as follows [27, 101]:

- Within a complex system such as Smart Grid, various agents can be defined in order to model different interactions between heterogeneous power system components.
- In opposition to centralized approach, MAS are inherently distributed, allowing collection of operational data from a wide area of the system environment without problems with regards to communication bandwidth and limitation for computational resources.
- MAS can be scalable, which can be easily deployed to a larger system while the development cost and agent task will be unaffected.
- Robustness is another characteristic for MAS which makes it reliable for systems of largest scales where the effect of cascaded contingencies or overall failure of the system should be avoided under any circumstances.

Given the current circumstances in transitioning of the power system into Smart Grid, applications of the MAS has become a promising approach for many research studies in power system engineering [24, 102]. As a matter of fact, due to wide acceptance of MAS applications within the power system engineering, a working group on MAS has been formed by IEEE Power & Energy Society to identify and address technical challenges in applications of MAS within the power engineering domain [101]. In addition to that and in conjunction with IEEE power system standard, the standard committee in IEEE Computer Society has accepted FIPA, a de facto standard addressing specifications and interoperability issues between agent based systems, as part of its family of standards. This in fact has introduced a new momentum in promoting application of MAS with other standards in EMS and power system automation such as CIM and IEC61850. On the other hand, with the increased integration of ICT infrastructures and promotion of open interfaces between different levels of EMS, the prospect of feasibility and practicality of the MAS applications to address protection challenges in Smart Grid is increased. Therefore, while improvement and efficiency are considered as main objectives to integrate MAS for power system applications implementation and deployment of the MAS for different protection scenarios are under investigations in many research studies [24, 101, 102]. In the next subsection, a thorough literature review on application of the MAS in power system protection within the context of agent paradigm and MAS are discussed.

2.3.4.1 System Protection Application

In recent research studies for the development of protections system in interconnected distribution network, coordination and cooperation between protection IEDs constitute the main theme of many research studies where computational techniques and ICT infrastructure play a critical role to fulfil the protection tasks [103-105]. In fact, the idea of accessibility of knowledge sharing and communication between protection IEDs have been an enabling factors to extend the conventional protection philosophy from component level into system protection level where total system stability as well as avoidance of large scale cascaded blackouts are given high priority [106]. Thus, as a result of the aforementioned evolution within the modern power system protection, protection functions are devised not only taking into account local information but also using real-time global information as the dynamic changes of the power system network are communicated through embedded ICT infrastructures [107]. As an element of DAI, application of MAS in power system protection have been highlighted as an effective means/powerful technique to improve conventional protection functions as the introduction of redundant information and modularized agents design can enhance the robustness of the protection system against changes in operation of the power systems [107]. However, utilization of the MAS for protection system is dependent on detailed considerations associated with system architecture and decision making process within MAS framework [108]. In the literature, incorporation of MAS into protection system has been addressed through various protection schemes in which designing and development of the protection agents have been defined based on subtasks within the proposed protection schemes. Thus, from technical point of view the inherent flexibility in defining agent types and cooperation between different agents have led to the adoption of various protection strategies with specified architectural arrangements for deploying protection agents [107, 109]. Moreover, given the prospect of the advanced technological equipment and presumed interoperability between the agents within the domain of power system automation, development of the WAMPAC system based on MAS has been widely explored by many protection engineers who are dealing with protection challenges related to interconnection of DER into distribution network [16, 24]. Correspondingly, researches associated with the two main architectural arrangements for deployment of the MAS into power protection system are discussed.

2.3.4.1.1 Hierarchical

Basically, in designing multi-agent protection system, MAS architecture can be defined in different ways where according to the architectural arrangements various roles of agents and their relationships are allocated. One of the main architectures in developing MAPS is hierarchical approach which, has been adopted in many research studies related to system control and protection schemes for modern distribution networks [110]. In fact, the paradigm of hierarchical architecture for designing of MAPS is reliant on dividing protection schemes into subtasks with different levels of abstractions or generalizations where relevant information for decision makings at higher levels of the hierarchy is used. In Figure 2.11, a typical architecture with hierarchical approach to develop MAS has been illustrated where agents in different levels facilitate the decision making process at control centre [111]. Similarly, for MAPS local agents at process level are used to collect information and communicated by central agents at higher level of the hierarchy to fulfil decision making process and protection scheme [27].

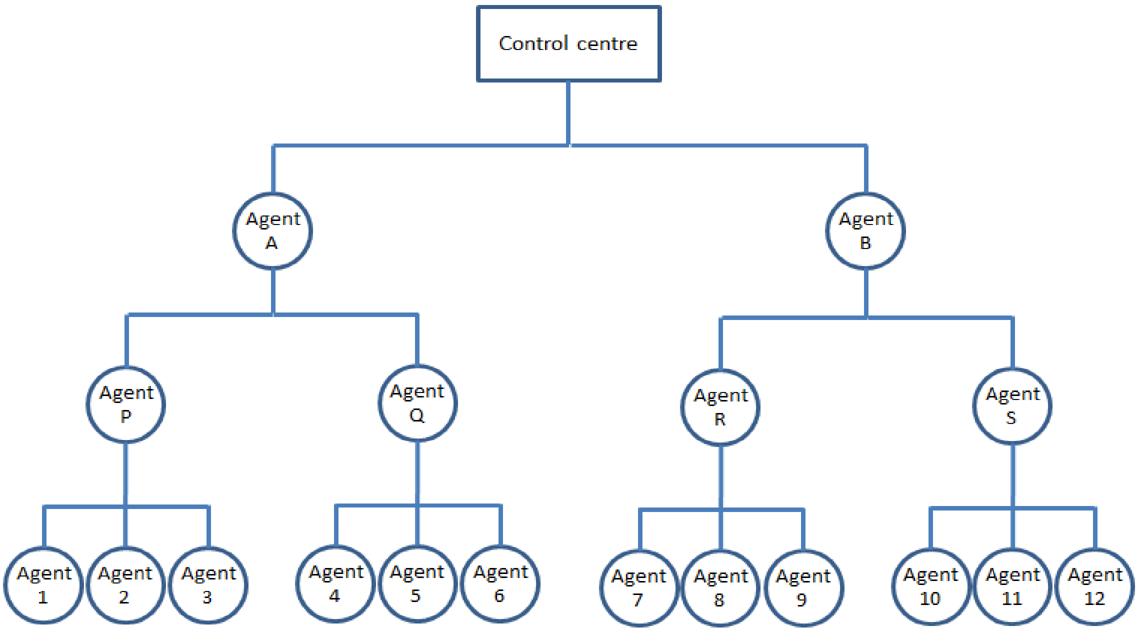

Figure 2.11 Hierarchical arrangement in developing MAS architecture.

Actually, matching with human organization management procedures, selection of hierarchical approach in protection system has become a main strategy for designing MAPS which cover a geographically wide area [110]. However, there are detailed considerations related to knowledge integration, agent behaviours and decision making process which have been the topic of many research studies for designing MAPS [108]. For example, in [104] investigations on agent technology and its advantages for system protection in a substation of a large-scale network has been conducted where an adaptive protection system based on multi-layer multi-agent system architecture was developed. As a main feature to its proposed methodology Mingyu et al.[104] defined a multi-layer architecture in which not only agents can have local view of the system, but agents in various layers can fulfil wide area protection tasks by utilizing cooperation and social abilities inherent to agent technology paradigm. In the paper Mingyu et al. [104] has proposed three layers of system, substation and equipment layer where various agent types and their tasks are defined to improve flexibility and adaptability in protection settings of the protection relays. Although it has been shown that application of MAS for power system protection is becoming an effective approach to intelligently and adaptively optimizes protection system performance, the research paper has only addressed the MAPS capabilities relying on its architectural and conceptual aspects. Moreover, the study of MAPS was merely limited to transmission and substation levels which compared to distribution network interconnected with DERs has less complexities. Similar to Yang et al., in [112] WAN and IP intranet utilized to establish real-time data exchange between the protection relay agents and dispatch control centre where based on status information received from substation update to protection settings are calculated and submitted to relay agents. In the research paper [112] aside from technical viewpoints addressing communication mechanism suitable for real-time adaptive protection system, Song et al. [112] introduced a MAS, which allows the adjustment of protection settings for backup relays according to real-time wide area information receiving from the power system network. As a result of that Song et al. adopted a hierarchical approach similar to structural and geographical features of the power system network where various agent types and tasks are assigned to fulfil adaptive coordinated protection based on agents cooperation [112]. Finally, the process of adjusting backup protection settings are conducted by assigning agent tasks and various agent types consisting of dispatching agent, decision-making agent, communication control agent and settings verification agents. Similar approaches based on MAS has been developed and tested with other research papers referenced in [102, 108, 113].

Further to the aforementioned research studies, considering more complex scenarios such as interconnection of DERs into distribution networks, Liu et al. [114] proposed a coordinative adaptive protection scheme in which settings of the protection relays are updated under different operation modes. In the approach to devise protection settings for TOC curves in over current protection relays, Liu et al. [114] adopted a hierarchical MAS consisting of control, cooperation society and distributed levels where agents not only can interact and communicate within their own layers but they can also pass information or share their knowledge with agents in the other society levels. The cooperative tasks between the 3 agent levels are defined based on collection of multiple states such as connection/disconnection of the DG units and network topology of the distribution system which are critical for adjusting the TOC curves to protect equipment in distribution network. Despite the consideration of matching real-world scenario to future prospect of power system network infrastructures, definition of multi-level agent societies and unconstrained communication links between agents within a same layer and agents in upper levels cannot be a reliable assumption for MAPS due to limited communication bandwidth. Taking into account both operational and topological changes in distribution network interconnected with DERs, Wan et al. [115] underscored the need for on-line adjustment in protection coordination between protection IEDs, as traditional calculation of pickup current settings are fit for standalone decision making based on local measurements. Moreover, determining relay coordination for various operation conditions can be a tedious and time consuming task in power system protection engineering. To address this multitude of drawbacks associated to coordination of the protection IEDs, Wan et al. [115] proposed an on-line adaptive protection coordination scheme in which communication and cooperation between different components of the protection system play critical roles. Similar to previous approaches based on agent-technology and communication protocols defined between agents, many of the research papers have adopted a hierarchical MAS architecture where agents of the same type constitute their own society and can interact with each other to exchange information or support the process of decision making to fulfil system protection tasks [27, 116].

In the aforementioned research studies, agent technology has been adopted to define solutions to improve certain aspects related to protection system although the solutions are mainly limited to a specific case or scenario in which some of the essential technical points have been condoned or ignored. With the advent of new paradigm for EMS and complex interdependencies between different levels of the power system network, research studies are directed towards more realistic and context dependant strategies for developing intelligent MA protection system which are consistent with ICT infrastructures of the future power systems and its communication standards. In [117] a multi-agent system based on organizational levels of the power system domain has been proposed to develop a protection system in a typical distribution network interconnected with DERs. Shang et al. [117] has considered different requirements necessary for protection system within future distribution network where system reliability, standardization, scalability and cost efficiency has been highlighted as important characteristics for the proposed MAPS. Similarly, considering advanced ICT infrastructure embedded into future Smart Grid architecture, Abedini et al. [118] proposed a hierarchical arrangement for developing a MAPS in which a holistic view regarding the interdependencies between different levels of the operation in power system network has been taken into account. In [118] the importance of overall economic and capability of operation under grid connected/ islanded mode have envisaged protection system task/scheme within interconnected distribution network as an interwoven/interdependent multi-criteria decision making process. Therefore, in the proposed MAPS for interconnected distribution network, agent communication is defined through levels of organizational and management layers which not only relies on advanced technological equipment such as PMU and smart meters, but also requires wide range of information from the process level to electricity market level. Consequently, for the MAPS architecture, Abedini et al. defined the whole distribution network as collection of micro-grid operator agents (MOPAs) communicating with distribution network operator (DNO) agents at higher level of the EMS. Although Abedini et al. [118] has tried to lay out a technical and conceptual arguments to identify architectural arrangements and requirements for developing

MAPS within Smart Grids operation framework, but no numerical solutions or study cases have been provided to support the technical viewpoints.

Application of power system automation and its potential to be extended for implementing MAPS has been discussed in [119]. In its approach for developing MAPS, Apostolov [119] used the very specific characteristics of the IEC61850 standard which is called logical nodes (LN) as the functional elements or protection subtasks that can operate in distributed environment while they can exchange their data through the hierarchy of power system network via communication networks. Further to that and in order to extend interoperability and configurability of the MAPS based on power system automation standard, Yang et al.[120] proposed the use of IEC61850/IEC61499 standard to implement distributed protection application for sympathetic tripping, selective backup and distribution bus protection schemes. Although all the characteristics as aforementioned are matched with the prospect of Smart Grid automation scenario, the application has only been applied on radial distribution networks where protection settings are fixed for specified operation conditions.

In summary, MAS has brought about many advantages such as distributedness and cooperation between protection system elements allowing protection engineers to develop complex algorithm and protection schemes suitable for RAS, SPS, SIPS and WAMPAC [121]. However, there are still various aspects related to knowledge sharing, interoperability and architectural arrangement for MAPS, which have the main drawbacks for real-world implementation of the protection system.

2.3.4.1.2 Distributed

As mentioned earlier characteristics and performance of MAS can be attributed to architectural arrangements of the hardware and software components enclosing agent environments, which fulfil protection task within their agent society. For MAS, distributed architecture is defined, as each individual agent can interact within their agent community to receive and share knowledge. In addition to that and opposed to hierarchical architecture for MAS, in distributed approach for designing MAS, agents are deployed according to their tasks where all the data communication and knowledge sharing corresponding to the overall system performance takes place within a single layer (or no layered architecture). As a result of that for decentralized architecture a common communication framework supports the interactions between different agents of the agent community. In Figure 2.12, a typical representation of distributed architecture for MAS has been illustrated where agents of different types and tasks can interact directly through a common facility directory [27]. As represented in Figure 2.12, the arrows illustrate two way communications between each agent as well as access to request or response to facility directory services within distributed architecture for MAS.

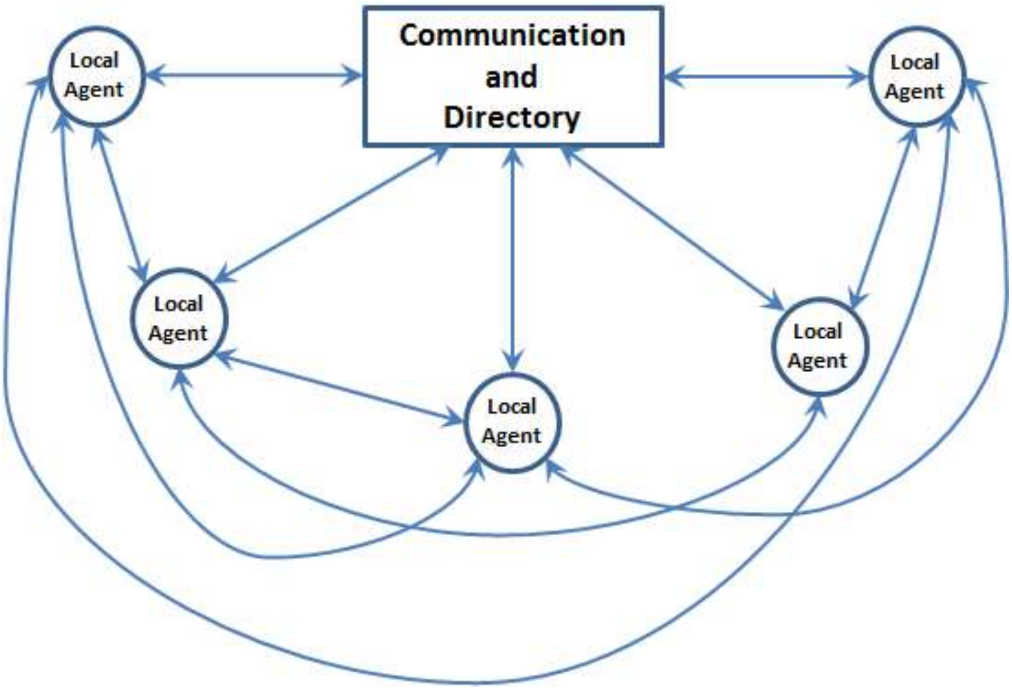

Figure 2.12 Distributed Architecture in MAS.

Having discussed the architectural aspects of the MAS, there are certain advantages corresponding to decentralized MAS which highlight a rewarding ground to develop innovative protection schemes potential to handle protection complexities, associated with modern power system distribution networks. In fact, advantages such as less restriction on communication bandwidth, higher fault tolerance and scalability in design are the prominent characteristics for distributed architecture of the MAS. In its early application related to power system protection Wong et al. [122, 123] proposed a multi-agent paradigm to address designing of protection schemes based on definition of sub-tasks and object oriented environment in which agents are designated and specialized for specific components in power system. By proposing a generic architecture for power system protection, Wong et al. [124] combined the advantages of rule-based expert systems and multi-agent paradigm to develop an Intelligent System Power Protection (ISPP), which has the potential to simplify protection schemes into subtasks and combine partial solutions to enhance system protection performance beyond the conventional protection scheme. Moreover, in regard to object-oriented design and utilization of abstraction, inheritance, reusability and extensibility concepts, Wong et al. [122]structured agents as classes that can cooperate and share knowledge based on their expertise knowledge in specific area of the domain. Although the proposed methodology has been able to remove restrictions in expert systems for maintaining complex rule-based system while they can integrate different reasoning strategies to address protection system tasks, but no implementations or verification results have been presented.

In a case study to apply adaptive system protection for improving limitations on non-pilot distance relays within a multi-terminal EHV transmission lines, Coury et al. [125] adopted the concept of agent based technology to address under-reach and over-reach problems within distance protection relays. The basic idea adopted in [125] relied on designing local agents which are employed as distributed computational units capable of carrying decision making according to the changes in operation condition of the network. Thus, for developing the interaction mechanism between the agents Coury et al. [125] defined three agent types of operation, breaker status and coordination agents where certain sub-tasks such as monitoring measurements and topological changes in network connections are fulfilled continuously during pre-fault condition. In case of any changes of the operation condition detected at the tee line terminals, proper settings for primary and backup zone protection of the distance relays are chosen from off-line calculated settings stored within coordination agents. In addition to addressing information exchange mechanism between the agents, Coury et al. [125] has also emphasized on using communication protocol which can meet the requirement imperative for reliability issues in power system protection in EHV lines. Finally, by utilizing digital simulation software tools (PSCAD/EMT), it has been shown that application of the agent technology not only has ensured correct operation of the distance protection under various conditions of the power system, it can also reduce the fault clearance time compared to conventional fixed settings.

Zeng et al.[126] proposed the use of agent relay concept and utilizing communication between the agents to cooperate for implementing adaptive protection system for improving power quality within interconnected distribution network. With further improvement to Coury's [125] study, Zeng et al. [126] proposed further improvement for system protection schemes where MAPS not only detect and locate High Impedance Faults (HIF) but it also perform load shedding in order to maintain load-generation balance for higher power quality within distribution network. For the agent based protection scheme, Zeng et al. [126] adopted a distributed and decentralized strategy where relays are defined as agents capable of performing multi-tasks such as detecting and locating fault. Consequently, the protection system consists of group of relay agents, which autonomously accomplish their task and share the information to protect the system under various conditions in a collaborative manner. The detection of HIF is determined by a subtask assigned to an agent capable of extracting fault features using wavelet ANNs. Following that fault location, task is defined by cooperation between the relay agents where upon receiving fault detection message fuzzy classification algorithm are calculated to route the faulty line and its corresponding CBs. Finally, the process of load shedding is performed using the load-generation balance for disconnection of low priority loads or stepping up generation sources ensuring power quality expected within distribution network interconnected with DERs. Despite the advantages of the proposed MAPS for using distributed architecture covering different parts of the distribution system and taking into account power quality as an important objective for the proposed MAPS, delays corresponding to communication and cooperation between agent relays may not be viable in the case of various faults such as 3 phase faults or even phase to ground faults.

Hosseini et al. [78] proposed a decentralized approach for protection system in which cooperation between agents are limited to certain number of agents at the neighbouring distance of the faulty section. Therefore, considering the efficiency in using communication bandwidth and reducing unnecessary data communication, Hosseini et al. [78] embedded a localized knowledge sharing and data exchange strategy to ensure the highest probability of correct operation to clear the fault. Aside from architectural organization of the agents and in conjunction with achieving higher reliability for system protection, Hosseini et al. [78] proposed a probabilistic decision-making algorithm where probability of correct operation of the protection devices and communication links have been taken into account to choose superior strategy among all possible options. Although there are advantages for the proposed protection schemes such as higher reliability and robustness against cascaded failures in interconnected distribution networks, issues related to fault detection and fault clearing time has not been addressed.

In summary, for decentralized or distributed architecture, decision making algorithm is a challenging part for developing MAPS as many requirements such as computational burdens, communication bandwidth and adequate information associated with operation condition of the power system networks have to be exchanged while availability of the technologies have to be verified within real-world scenario. In addition to that, emerging themes and concepts related to future EMS such as self-healing, RAS and SIPS have led to many research studies based on MAS which have utilized distributed architecture and decision making algorithms as key element to address system protection challenges within large scale interconnected distribution networks[14, 43].

2.4 Research Contribution

The scope of this PhD research project focuses on protection system in interconnected distribution network and complexities arising from variation of the operation conditions as DERs such as DFIG wind turbines are connected at distribution levels. To address this challenging issue an integrative view regarding the operation of future power system network as a Complex Interactive Network (CIN) has been adopted where protection IEDs are defined with set of protection agents capable of exchanging information and sharing knowledge with their neighbouring protection IED nodes. Additionally, in light of facilitating protection IEDs with protection agents which are loosely coupled within a MAS framework, a distributed decision making process based on human mind reasoning and social interactions are established to update the protection settings according to operation scenarios within interconnected distribution network.

Also, in the process of decision making parameters such as intermittencies in renewable energies (operation condition of the DFIG system), penetration of the DERs (number of DFIG systems connected at the distribution level) and dynamical changes in topology of the interconnected distribution network (grid-connected to islanded mode operation) have been conducted in to identify and select proper TOC curves within protection IEDs in real-time. Finally, implementation and verification of the simulation results for the proposed MAS is established using state of the art real-time simulation techniques such as HIL and co-simulation to address potential advantages and capability of the MAPS in dealing with protection challenges in distribution network interconnected with DERs. The outcomes of the proposed Multi-Agent Protection System (MAPS) can introduce multiple characteristics for the protection system which are essential to be integrated within interconnected distribution networks. These characteristics are as follow:

- **Adaptive**

Compared to conventional approach, protection settings in protection IEDs in the proposed MAPS protection settings (TOC curves) are devised to be updated with respect to operation conditions in the interconnected distribution network. Through literature the concept of changing protection settings to meet required functionality and performance for the protection system in interconnected distribution network.

- **Heuristic/Intelligent**

In conventional approach accurate and reliable protection settings are established through calculation of fault current contribution using existing standards/formula however, for interconnected distribution networks certain parameters (intermittencies in renewable energies, islanded mode, DERs penetration levels) can affect accuracy in fault current calculation method. Thus, integration of the heuristic/intelligent approach based on MAS has been proven to be an effective approach to address uncertainties for protection settings in interconnected distribution networks.

- **Distributed**

With the protection IEDs distributed across power system network and enabled for messaging communication under MAS framework (loosely coupled) application of WAMP schemes can be introduced to address stability issues associated to protection system in large-scale distribution networks with high penetration of the DERs connected to the network. However, constrain associated to conventional protection system strategies and its decision making process based on local measurements from CTs and VTs are limited for zonal protection system, where each protection IEDs monitors and protect certain power system component in the network.

- **Scalability**

Given the large-scale meshed topology and interconnection of heterogeneous power system components such as DER, protection system for future power systems have to be scalable which reduces the complexity in deployment of the protection system in interconnected distribution network and further reduces the costs for development of the protection system. Also, the use of standards such as FIPA and IEC 61850 protocols have been adopted to promote interoperability and extensibility in the proposed MAPS.

2.5 Summary

In the first step, an overview on SGAM considering interactions between different layers of the power system automation within the context of future power system is discussed. Also simulation techniques such as co-simulation and HIL have been introduced for implementation testbed in protection systems which rely on ICT infrastructure to fulfil their protection tasks. For the second part, the focus has been turned on reviewing literature on protection system in interconnected distribution network. The FCL application with three types of solid-state, superconducting and inductive FCL including their applications in power system protection of the interconnected distribution networks is explored. Traditionally, the use of FCL has been adopted to limit high fault current preventing damages to the protected elements and it provides less expensive solution compared to modern protection IEDs, but it cannot be a viable option for interconnected distribution network where high penetration of DERs with various operation conditions are assumed. While FCL are defined for certain operation condition within interconnected distribution network, adaptive protection systems have been introduced to improve the resilience in protection systems by adjusting the protection settings according to prevailing operation conditions. Two different architectures, centralized and decentralized adaptive protection systems have been explored in the literature where reliability and accuracy of the protection settings is improved compared to conventional fixed protection settings. However, for centralized architecture there are issues related to communication bandwidth and centralized processing unit affecting the reliability of the protection schemes due to disruption in the communication links. On the other hand, in decentralized architecture, protection IEDs are tightly-coupled to exchange system information for simple topological changes within interconnected distribution networks although it is not suitable for large-scale distribution network where various DERs are connected. Application of the graph theory to formulate protection coordination through topological theorems have been explained in few papers where optimization of the coordinated time interval (CTI) for protection IEDs are addressed through breath first search (BFS) and Dijkstra’s algorithm. Despites its effective approach to automatically consider the distribution network and connected DERs as a typical graph topology problem, due to computationally intensive search algorithms application of graph theorems, they are usually suitable for networks with fixed topological representations. Finally, MAS and its capability to combine both adaptive protection system and graph theory for defining a loosely-coupled power system network are highlighted for designing a protection scheme in interconnected distribution networks. Chapter 2 highlights MAS to have both adaptability and interoperability for embedding heuristic decision making algorithms where distributed information from neighbouring protection IEDs can be utilized to enhance performance of conventional protection schemes within the context of interconnected distribution network.

CHAPTER 3
INTERCONNECTED DISTRIBUTION NETWORK

The main aim in this chapter is to develop time domain simulation for a distribution network interconnected with DERs which later will be used in Chapter 4 to investigate fault current behaviour of the system. In this chapter, mathematical modelling and dynamic interactions between different elements of a typical interconnected distribution network are derived and demonstrated. In the first section, a brief explanation on technical aspects and operational challenges in control and protection systems of an interconnected distribution network is discussed. In the second section, topological connections for DERs such as DFIG and DG are demonstrated, and accordingly technical details related to the control systems embedded in both systems are explained. In addition to that other electrical components within distribution networks and their operational tasks are discussed. Further in the third section, detailed mathematical equations and control systems are devised for DFIG and DG systems. In fourth section, model development process and operational performance of the control systems for DFIG and DG systems are validated by introducing real-world operation scenarios such as variation in DFIG penetration and transitioning from grid-connected to islanded mode. Finally, in the fifth section, a summary of the chapter and the highlight of the importance in the sequence of the proposed research methodology are presented.

3.1 Developing Interconnected Distribution Network

Although one of the main objectives of expanding existing distribution network into an interconnected distribution network with DERs is to achieve higher efficiencies and operational securities expected for future power systems, there are technical complexities which have to be addressed as a step toward the realization of future power grids. In fact, power supply industry experiences a paradigm shift in many aspects corresponding to reliable and safe operation of the interconnected distribution networks which have to be taken into account and coordinated by system operators (SO) and planning engineers. Consequently, compared to conventional power system, successful modelling and development of distribution network interconnected with DERs are dependent on coordination between different levels of operation and control systems, which interact in a hierarchical multi-layer decision making processes [127]. Thus, according to this approach, not only component-oriented modelling of each element of the power system network is important but the integral operation and stability of the subnetworks of the interconnected distribution network have to be considered under various operational conditions. With this approach for real-world scenario, development of interconnected distribution network is reliant on effective cooperation between many expertise and utilization of the advanced technologies and strategies during the planning and design phases [127, 128], which is not in the scope of the current PhD research study. However, in order to manage and address the operation of the distribution network interconnected to DERs with an appropriate level of complexities for conducting research studies within system protection area, two main aspects of the system operation which are different from traditional distribution networks have been explained. The control systems and protection strategies for interconnected distribution network are explained in the next subsection. Although the main concepts and functionalities of each system has been the focus of this section, technical feasibilities and implementations related to each strategy have been waived as they have already been discussed in Chapter 2 for literature review on Smart Grid operation and SGAM.

3.1.1. Hierarchical control system

In view of the increasing volatility in operation condition of interconnected distribution networks the role of dynamic control is becoming critically important, to maintain system stability and regulatory requirement of delivering electric power. To manage power system operation under various conditions, specific control strategies and coordination between different subsystems are required. The use of hierarchical and distributed control strategies for interconnected distribution network or micro-grids have been studied in the literature as effective approach to contain both system stability and power quality. Within the framework of hierarchical control system and multifaceted character of power system operation, each individual controller is designed for different functional levels and response time characteristics are decentralized at particular levels to achieve desired operation for overall system. In Figure 3.1, functionalities and time-scales corresponding at each levels of the hierarchical control system for interconnected distribution networks have been illustrated [128, 129].

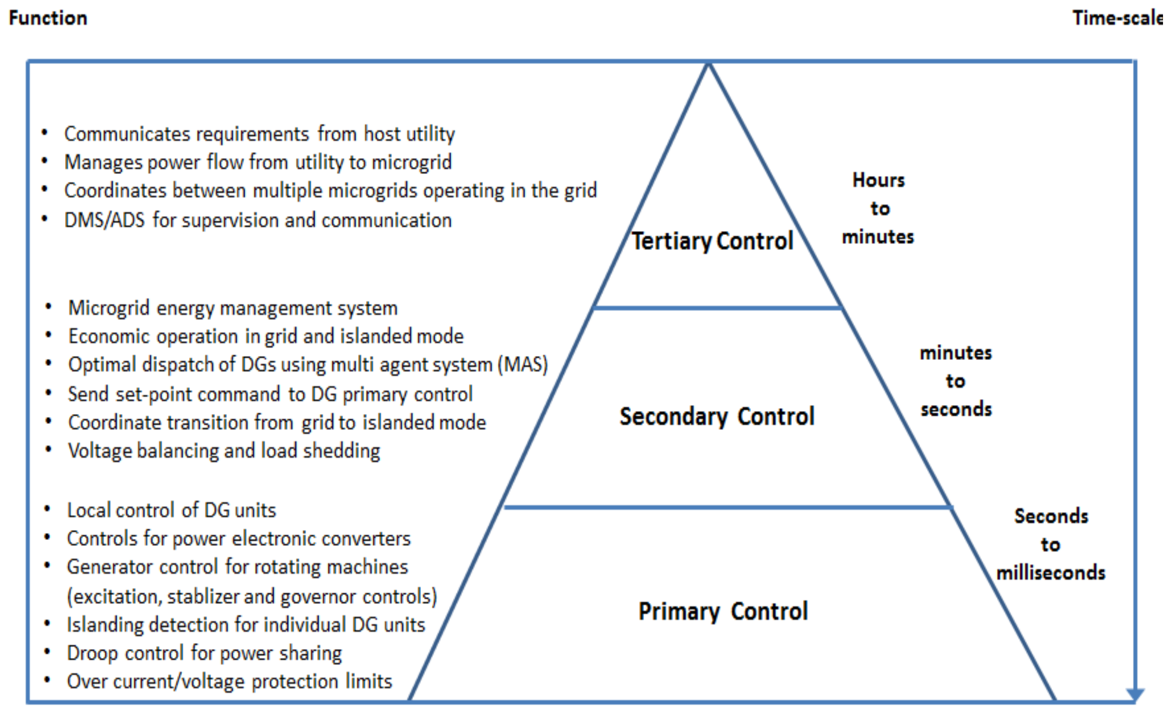

Figure 3.1 Hierarchical structure for control systems in Micro-grid [129].

In order to coordinate between control levels, modern information system and ICT infrastructure are embedded into the structure of control system, which is based on centralized and decentralized topology so that the hierarchical control system is transformed into an autonomously controlled network [128]. Thus, for interconnected distribution network, the focus of hierarchical control system is to maintain voltage and frequency stability under all combinations of load-generation scenarios where local measurements are utilized. There are other approaches based on new operational equipment such as FACTS and HVDC where coordination between subsystems are carried out through decision making process. In conclusion, the control system for interconnected distribution network relies on ICT infrastructure to coordinate the actions between different control levels according to hierarchy pyramid of the functionalities and timescale. Therefore, in this research study, in order to simulate interconnected distribution network for system protection, the control systems at the higher levels of the control system are not taken into account due to larger time-scales for reacting to system disturbances. However, in order to ensure system stability during transition from grid-connected to islanded mode, the load-generation balance and frequency stability of the system have been planned based on sizing of the DERs and choosing frequency control loops as the primary level in the hierarchy of control systems.

3.1.2. Protection System

In radial distribution network, design strategies for protection systems have been established through years of practices and experimentations which has become straightforward task for protection engineers to develop and provide applicable settings for protective relays within each protection zones. Technically, the term conventional protection schemes are mainly including protection functions such as time over current (TOC), distance and differential protection which are used in radial distribution networks as a last line of defence against any faults. However, the paradigm of unidirectional power flow in radial distribution networks have undergone drastic changes as interconnections of DERs such as wind turbine, Diesel Generator, and capability of islanded mode operation within distribution network levels have introduced technical challenges for applying previously established philosophy for conventional protection schemes. In the literature [41, 42, 130] complexities related to topological and operational changes of the DERs have been identified as the main drawbacks for adopting conventional protection systems for interconnected distribution networks as conventional protection schemes are devised for quick response to local measurements for protecting of power system components. However, in distribution network interconnected with DERs, protecting individual electric components has to be coordinated based on both local measurements and global information, which takes into account the operation condition of the power system network. Consequently, in designing protection schemes for interconnected distribution networks, suitable methods are required to maintain system stability and avoid cascaded failures which can lead to complete shutdown of the network system [127, 131]. In reference [132], potential solutions for developing protection schemes in interconnected distribution networks are proposed as novel strategies specific for connected low-fault DERs and robust transmission-grade differential protection schemes. Figure 3.2 illustrates the requirement of a novel approach for protection system in interconnected distribution network which has been identified as a solution for compromising cost-effectiveness and robustness of the protection system [132].

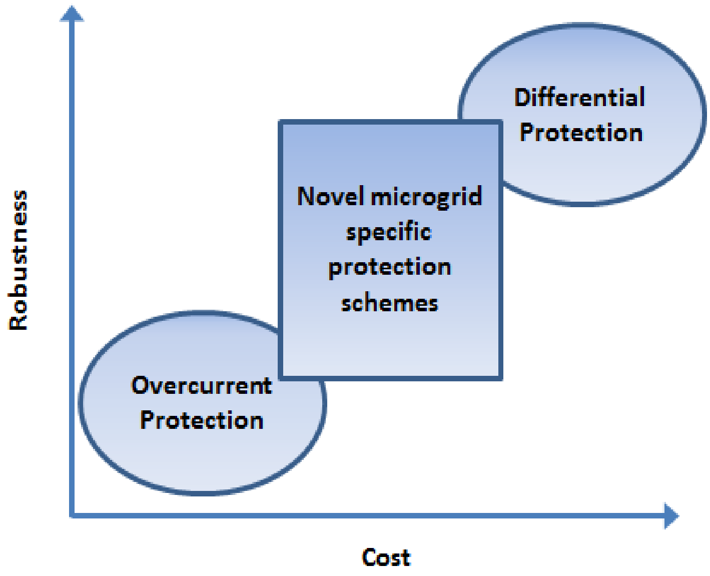

Figure 3.2 Protection gap in devising protection schemes for Micro-grid.

According to the aforementioned protection schemes, not only conventional protection schemes are inadequate to meet the required performance for system reliability but taking into account system integrity within protection schemes is an essential element for developing protection system in interconnected distribution networks. Thus, novel protection strategies relying on ICT infrastructure and communication networks are integrated into the decision-making process of the protection schemes to achieve required flexibility and enhanced stability measures within the interconnected distribution network. Some of the protection schemes proposed in the field of wide area monitoring, protection and control (WAMPAC) are System Integrity Protection Scheme (SIPS), System Protection Scheme (SPS) etc [127, 129]. In summary, for designing and the development of the protection system in distribution network interconnected with DERs, both dynamic models of individual power system components and operational scenarios underlying topological changes at the Point of Common Coupling (PCC) have to be addressed appropriately. To study the proposed research objectives on system protection based on MAS, a typical distribution network connected with DFIG and DG has been described in section 3.2.

3.2 System Description

Generally, for electrical power system studies, modelling and development of a power system network is a foundation to further investigations on performance assessments and integral operation of the power systems. Thus, to conduct research studies on protection system in distribution network interconnected with DERs, defining and development of a typical distribution network and its component is a critical step to address credibility and validity of the research outcomes in this thesis. However, for interconnected distribution network, there are various factors correspond to connection of DERs including size, type and connection points depending on the domain of study which can introduce significant impact in modelling phase. For example, in system protection for interconnected distribution network, accurate description of the DERs and technical details corresponding to structural configurations, operational characteristics and dynamic control system are important for credibility and validity of the research outcomes.

Thus, to establish the proposed methodology for system protection, a typical power system network interconnected with DFIG and DG system at distribution level has been developed which is used through different phases of the research study for analysis, investigation and demonstration of the results. In Figure 3.3, Single Line Diagram (SLD) of the proposed power system network for studying protection system in interconnected networks has been illustrated.

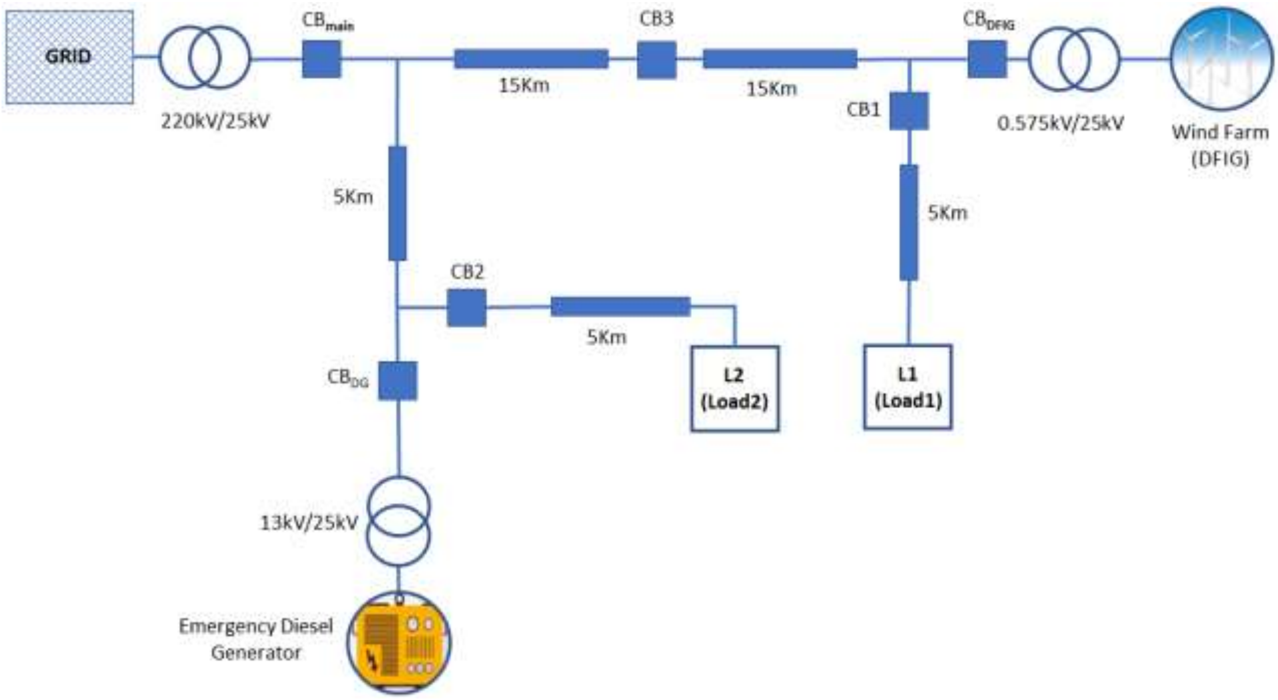

Figure 3.3 Proposed interconnected power system for studying system protection.

As it has been shown in Figure 3.3, the DFIG system is connected down-stream of the PCC (at CB_{main}) close to local load1 (L1). The control system for DFIG system is based on Maximum Power Point Tracking (MPPT) which can inject different levels of electrical power into distribution network depending on wind speeds. A DG system is connected to control the system frequency during low wind conditions and enabling islanding mode where the distribution network can operate standalone by disconnecting PCC circuit breaker due to grid contingencies and unpredicted blackouts. The local load2 (L2) close to DG is also fed by the DG which has embedded frequency control system to act as frequency controller during the islanding mode operation. The circuit breakers (CBs) are devised at each connection point for DERs and Loads to isolate the fault section of the line. Moreover, DFIG and DG have been connected to the distribution network through their voltage step-up transformers and its corresponding circuit breakers. The details of the simulation parameters and the ratings of the DFIG and DG systems have been listed in Appendix A.1.

3.2.1. Operation Modes

In developing the proposed interconnected power system network, transition between different modes of operations is essential to match the real-world scenarios of connecting DERs into power system networks. However, there are several aspects related to system stability and technical issues associated with DERs, characteristics which can introduce constrains during planning and screening phase of the project to address specific operational modes of the interconnected distribution networks. Similarly, for developing simulation model of the interconnected network as discussed earlier in this section, identification of operation modes and technical requirements to satisfy reliable operation of the system under various operation modes is presumed for any further studies within protection system for interconnected networks. From technical point of view, topological changes from grid-connected to islanded mode or vice versa in interconnected networks are reliant on specific capabilities and services provided by DERs, which have to be coordinated to ensure safe transitions between various operation modes within interconnected network. Although grid integration and system stability are interrelated topics in many research studies, in order to limit the scope of technical issues within the protection system study and avoid complexities corresponded to synchronization and control strategies in this study, only disconnection at the PCC is considered [10]. The characteristics of the two operation modes for grid-connected and islanded mode are discussed as follows.

3.2.1.1 Grid-Connected Mode

According to network configuration represented in Figure 3.3, under grid-connected mode elements such as DFIG, DG and local loads L_1, L_2 stay synchronized with the main grid via CB connection at PCC, which allows balance in power fluctuations between up-stream and down-stream of the PCC. While generation output for DFIG system can vary from high wind to low wind speed or even parking mode introducing volatilities to power flow at PCC in grid-connected topology, economical and environmental aspects are the main concerns as system impacts arising from DFIG connections are secondary. Also, DG system is mainly defined as a standby system with small contribution for power generation during grid-connected mode. For grid-connected mode there are some terms and specifications such as exporting and non-exporting which highlight some technical complexities in operation under grid-connected mode. In this study, the proposed interconnected network is devised to cover a more general aspect of grid-connected mode as exporting interconnection where some or all of the energy generation from DERs can be distributed through PCC into distribution network [133]. Finally, interconnections of DERs are currently part of a standard (IEEE 1547) [134] which involves functional technical requirements and specifications for embedded hardware/firmware in DER control systems known as Fault Ride Through (FRT) capabilities.

3.2.1.2 Islanded Mode

Transition to islanded mode occurs by disconnection of CB at PCC where DFIG, DG and local loads L_1, L_2 constitute a power network island to operate independently from the main grid. As the structural topology of the network is changed, system control plays a critical role to balance load-generation during the islanding operation mode. In comparison to grid-connected mode, there are some characteristics specific to islanded mode of operation, such as less mass inertia and intermittencies within wind energies, which make stability of the islanded power system sensitive to any disturbances. Moreover, from protection system perspectives fault current levels and fault current contribution can be altered differently compared to the grid-connected mode. Therefore, in order to meet the requirements for stable transitioning from grid-connected to islanded mode, control of voltage and frequency have been highlighted as key factors [133]. In response to that and considering technical feasibilities, connection of DG downstream to PCC has been devised as frequency and voltage controller during islanded operation of the system. For DG system operation, primary control loops embedded in genset control unit is supposed to maintain voltage and frequency at rated operation condition. However, whilst transitioning into islanded mode or intermittencies for wind energies occurs, DG control loops can also fulfil load-generation balance depending on the size of the DG selected. Also, with respect to technical and structural configuration, connection of DG system to maintain appropriate voltage level at the DFIG stator terminals is critical to parallel operation of DFIG and DG systems during islanded mode as DFIG systems are sensitive to voltage drop at their stator terminals. Having discussed technical points related to development and operation of an interconnected distribution network under real-world scenario, it is worth mentioning that transitioning from islanded to grid-connected mode has not been demonstrated due to unnecessary complexities involved for simulating synchronization controller for connection to main grid via CB at PCC. Although from the perspective of the system protection the process of connection or disconnection at PCC can be translated as topological changes, protection settings can be adjusted similar to grid-connected mode. In the next section, operational principles and modelling of DERs including DFIG and DG systems are explained.

3.3 DFIG System

Typically, a DFIG wind power system is composed of various components which have been illustrated in Figure 3.4. As shown, in the schematic configuration for DFIG system, a power generating unit consists of turbine blades, gearbox and a wound rotor induction machine (WRIM) connected directly to the grid via its stator terminal as its rotor terminal is connected to a back to back converter. The back to back converter consists of two Voltage Source Inverters (VSI) linked by a common DC-link capacitor. Technically, the back to back converter controls power flow of the DFIG in order to deliver required power to the grid. According to [135], the main advantage of the DFIG configuration is related to its ability to operate under sub-synchronous and super-synchronous condition which implies a wider operating point in comparison to fixed speed configurations. In addition, DFIG wind power system where back to back converter handles rotor power, which is a fraction of the stator output power, low ratings of VSI can further improve the cost-efficiency. Although, compared to fixed speed wind turbine, DGFIG control system relies on advanced control strategies and embedded control systems which drive PWM switching circuits [136, 137].

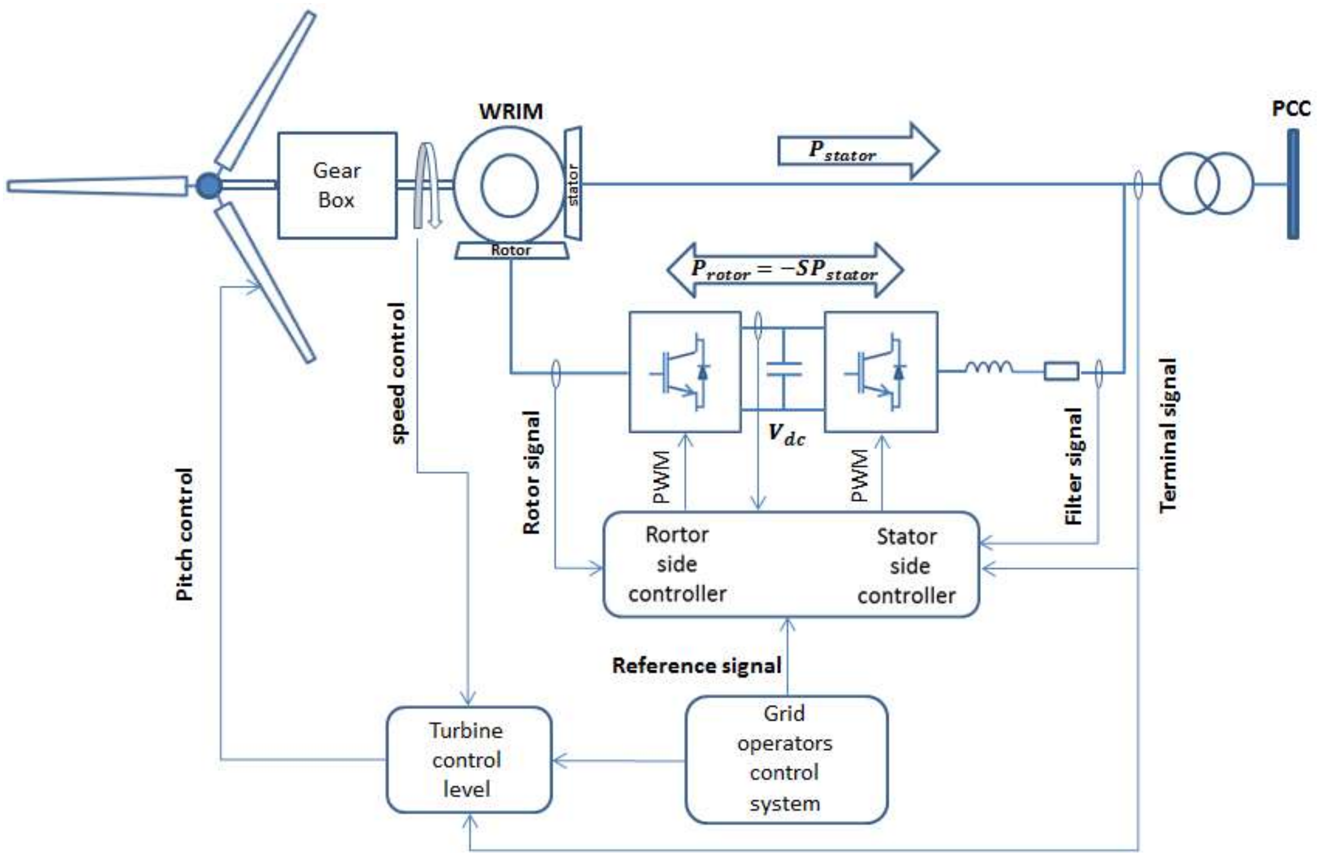

Figure 3.4 Schematic block diagram for DFIG control system.

3.3.1. Control System and Grid Codes

For DFIG system, despite its higher efficiency compared to other types of wind power generation, its sensitivity to transients and voltage sags is a main drawback which comes at the expense of complexities in control systems to incorporate grid interconnection measures. In case of any fault occurrences for small scale penetration of the wind power, DFIG system is separated from the grid. However, as the penetration of DFIG wind turbines increases, disconnection from grid for any contingencies can cause transient stability problems or even blackouts [138]. Consequently, System Operators (SO) have introduced some minimum requirements for integration of wind power systems in order to ensure reliable operation of network during fault periods. Although different countries have their own requirements for integration of wind power systems, there is a consensus for windfarms to stay connected to grid during fault occurrences [139]. Figure 3.5 illustrates grid codes in form of voltage profile adopted by different countries for interconnection of DFIG during voltage sags. Basically, the required grid codes have instigated many wind farm owners and researchers in the field, to incorporate certain strategies in DFIG control system which is referred to Fault Ride Through (FRT) capabilities. Different control systems embedded for DFIG system and strategies adopted for implementing FRT have been explained in the next subsection.

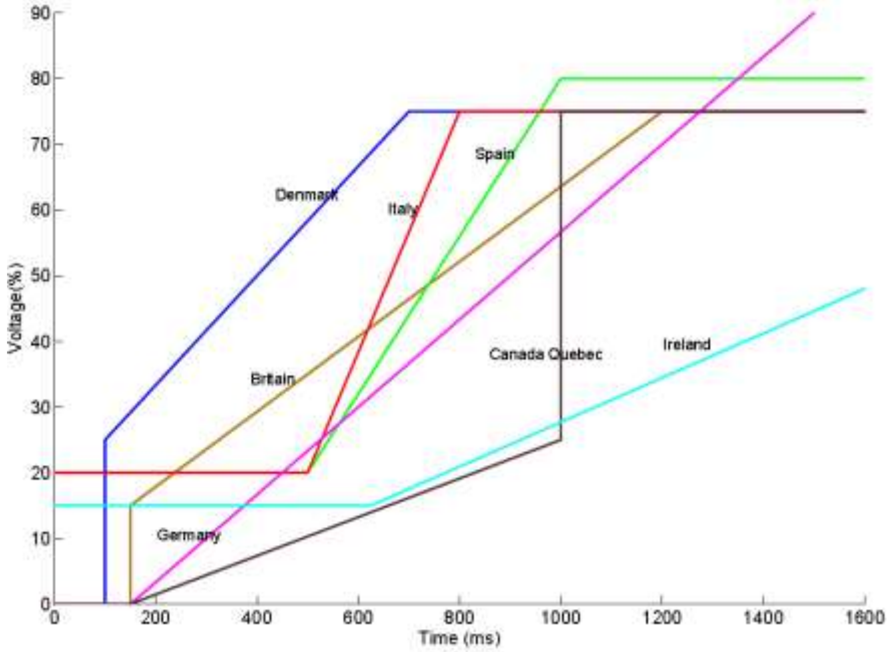

Figure 3.5 Voltage profile required for interconnecting DFIG system in different countries.

3.3.1.1 Rotor-Side Convertor (RSC) Control

For DFIG system control, Rotor-Side Converter (RSC) is used to control active and reactive power at the stator terminal where DFIG system is directly connected to the grid. As shown in Figure 3.4, the RSC is a VSI which uses stored energy in DC link capacitor to generate any voltage with arbitrary frequency and phase limited by capacitor voltage and switching frequency. Thus, in simple term the RSC can be considered as an ideal controlled voltage source regulating the rotor current to develop desired electrical torque in the WRIM which generates active power output at the stator terminals. In addition, using FOC principles and decoupling techniques the rotor current can be applied to control voltage at the stator terminals of the DFIG system. Usually, for DFIG system electrical torque is regulated to extract maximum output power according to power-speed characteristic curves which is called Maximum Power Point Tracking (MPPT) curve while the voltage control can support reactive power to the grid [136]. Although, it should be noted that the control schemes correspond to normal operation of the DFIG system, under fault scenarios with voltage drop at the stator terminal, embedded FRT measures are applied with respect to grid codes adopted by SOs. Consequently, fault current contribution and studying system protection, developing DFIG system and its embedded control loops are critical to reflect protection challenges within interconnected distribution networks. In section 3.6, detailed mathematical and dynamic models for the control loops in DFIG system are developed.

3.3.1.2 Grid-Side Convertor (GSC) Control

Similar to operation of the RSC, GSC is also a VSI which can regulate the capacitor voltage by draining stored energy in the DC link capacitor and deliver active and reactive power to the grid via a three-phase R-L filter. Although the aforementioned operation is held during super-synchronous operating of the DFIG where the rotor circuit delivers power to the capacitor, the back-to-back converter is energized by the rotor power. During the sub-synchronous operation of the DFIG system, the capacitor is energized by GSC through draining the energy from grid as rotor circuit draws energy. Therefore, aside from regulating voltage for DC link capacitor, GSC can generate or absorb active and reactive power at the grid connection point. Usually, under normal operation of the DFIG, the reactive power delivered to the grid is set for null while the active power is commensurate to the rotor active power [136]. Although, with the introduction of FRT concept for grid codes, GSC control loops can be used for voltage support during grid contingencies. Finally, in comparison to WRIM ratings, smaller size for convertors ratings can curtail the significance of fault current contribution from GSC for system protection applications. However, detailed simulation of the control loops and voltage regulators can guarantee accuracy in operation of DFIG system.

3.3.2. Turbine Control

For any Wind Energy Conversion Systems (WECS), turbine blades are the front end part of the system extracting wind power through aerodynamic interactions between turbine blades and wind speed profile within the area swept by turbine blades. Among various control subsystems in DFIG system, turbine control is applied to limit the wind power proportional to the ratings of DFIG system and it is used during high wind speed or wind gust. It has also been used to reduce tower loads and mechanical stresses for gear box in DFIG system [140], which incur the highest cost and off time for wind turbines. For turbine control system, pitch angle of the turbine blades is the main control parameter, which can alter available wind power harvest by utilizing pitching mechanism bolted to the turbine's hub to rotate turbine blade into or out of wind flow. Although, embedded turbine control guarantees reliable and safe operation of the DFIG system, the longer time constant for pitching mechanism (in seconds) compared with fault durations and fast control loops in DFIG control systems, turbine control system is identified as secondary control system [141].Therefore, dynamic of the turbine control system and pitching mechanism have not been taken into account for system protection studies where time-scales are confined to milliseconds.

3.4 Diesel Generator

Generally, a diesel generator (DG) is a compression ignition engine widely used for emergency supplies or local power generation unit of the electricity in remote areas like hospitals and farms. The principle of the DG system is based on conversion of potential chemical energy into electrical energy where a diesel engine is used as the prime mover to drive AC synchronous generator through couple shafts. In Figure 3.6, a typical diesel generator and its elements have been illustrated. The power supply continuity of an off-grid system should be backed-up by other reliable and non-fluctuant sources of primary energy, generally diesel generator sets [142].

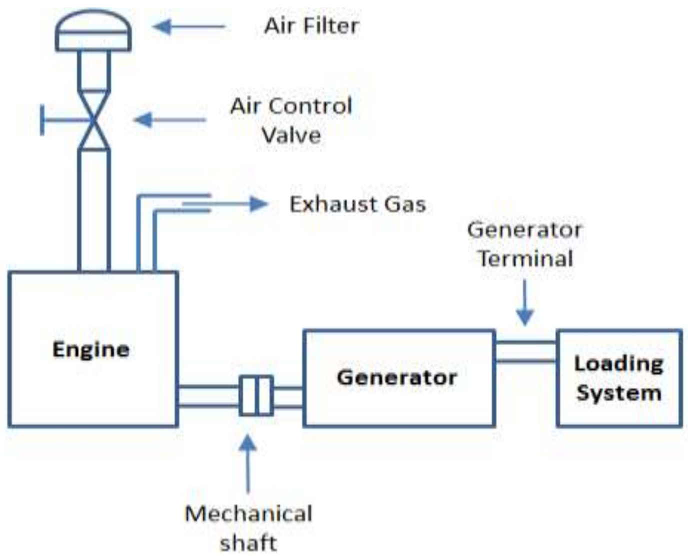

Figure 3.6 A typical structure for diesel-generator set.

Similar to vehicle engines the diesel generators comprise of fuel system, lubrication system, ventilation pipes and a rotating shaft connecting diesel engine mechanical torque to AC generators. The structure of the diesel generator is mainly divided in two main subsystem generator set and control unit in which generator set entails the mechanical parts like diesel engine and AC generator machine while the control unit is electrical equipment used to distribute electric energy output.

Although there are some advantages such as fast start up and generating of controllable electric power to improve dynamic stability, due to high cost for the diesel and carbon emissions diesel generators are mainly used in small sizes for emergencies in order to keep the continuity of the power supply. The tasks and functionalities of each part of a diesel generator are discussed as follows.

3.4.1. Generator Set

A modern generator set is a rigid structure on public chassis in which a diesel engine and generator make an integrated compact unit convenient as mobile power generator for stand-alone operation or back-up power supply. Typically, generator set entails a rotary diesel engine including the whole cycle of cooling, lubrication and fuel system for efficient ignition of the fuel, also the mechanical rotating part like engine flywheel shafts are fitted into flexible shaft of AC generator side. In general, there are various criteria such as fuel efficiency, ambient conditions and engine design which are deciding factors to select generator set. However, from the perspective of power system operation, it is the sizing of diesel engine and types of applications such as peak-shaving, or emergency power conferred to select generator set [143]. Although, reliable operation of the generator set depends on components constituting the network system, improper sized generator set can cause large voltage and frequency dips which damage sensitive loads and equipment.

3.4.2. Control Unit

For DG systems, control unit is similar to Human Machine Interface (HMI) equipment where monitoring parameters and operation conditions can be adjusted by the operators. In modern DG systems, variety of features related to fuel efficiencies and cost management have been provided which are not subject of the primary control loops. Typically, stable operation of the DG system is guaranteed through two main control system loops, ie. voltage and frequency control loops. The task of voltage control loop is to maintain the stator voltage of the AC generators within the acceptable range of nominal voltage while frequency control system is a simple feedback loop maintaining rotational speed of the flywheel shaft to rated frequency of the AC generator. As shown in Figure 3.7, voltage and frequency control loops are separately devised to interact with AC generator and diesel engine operations respectively. For voltage control loop, the Automatic Voltage Regulator (AVR) controls the exciter field to provide a constant terminal voltage. Also, for frequency control using fuel valve injection similar to conventional governor control in steam engines, diesel engine can be accelerated or decelerated to adjust angular speed of the flywheel shaft with synchronous speed of the AC generator. Later in section 3.6, mathematical model of each control system and its PI controller are represented to address the complexity of the interaction in power system network. The most important point of digital controllers is the embedded microprocessors that perform various control functions for the excitation system [142, 144].

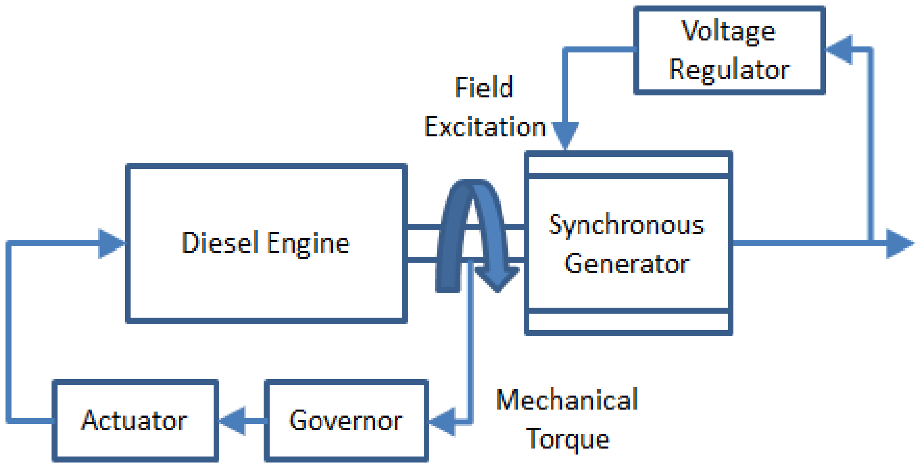

Figure 3.7 Automatic control units with embedded control circuits.

3.5 Grid Components

The grid-side connection in interconnected distribution network is modelled by a balanced three phase voltage source which represents a stiff network at the PCC with connected DERs. Therefore, mathematical modelling of the grid is simply derived as a Thevnin equivalent circuit where sinusoidal voltage source in series with resistor and inductor replacing transmission lines and transformers [145]. Technically, grid models are defined as stiff network which supply constant voltage and frequency independent of the active or reactive power flow in the network. Figure 3.8 illustrates the response for frequency-power and voltage-reactive power for infinite bus system.

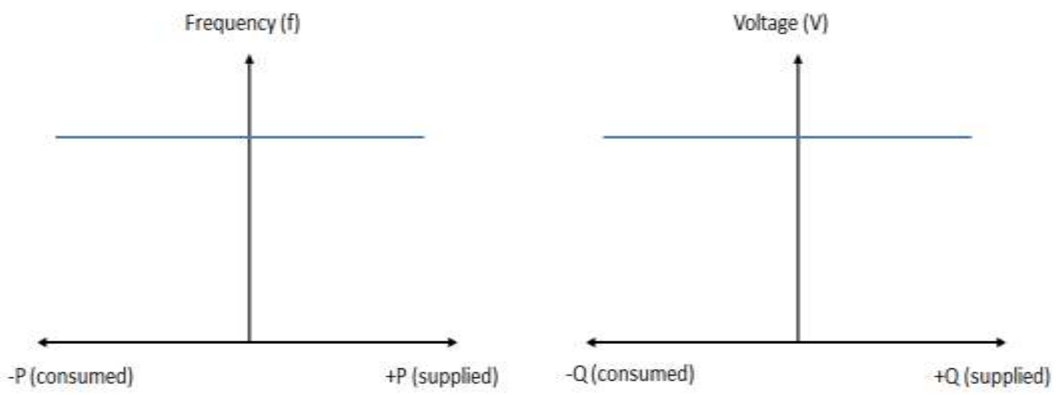

Figure 3.8 Characteristics of grid-side connection for interconnected network.

3.5.1. Transformers

In power system networks, 3-phase transformers are used for changing voltage levels in various stages of the transmission/transportation and distribution of the electric power. A 3-phase transformer is constructed by three single-phase transformers which have common magnetic core for the primary and secondary windings in each phase. In Figure 3.9, conceptual representation of a 3-phase transformer and set of windings for primary and secondary coils have been illustrated. There are various parameters such as turn ratio and windings configuration at primary and secondary sides, which can be used for different applications in power system networks. Generally, in power system network step-up and step-down transformers are used to make long-distance transmission of electric power economical and practical. Also, for 3-phase transformers there are common configurations for windings connection in primary and secondary sides which are Δ-Y , Y-Y , grounded and ungrounded [145].

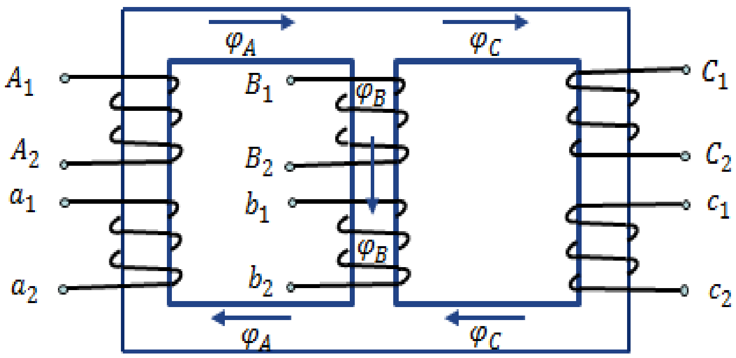

Figure 3.9 A conceptual representation for configuration of two windings 3-phase transformer.

In this research study based on the same principle of mutual induction for magnetic circuits applied in a single-phase transformer, the mathematical equations for two windings 3-phase transformer have been adopted. Although, there are various modification and corrections such as saturation, hysteresis effects, etc., these factors have not been applied as the dynamic model is approximated for ideal linear transformer. Thus, by assuming a linearized model the matrix representation for the 3-phase transformer is listed in equation (3.1):

$$[\boldsymbol{\psi}] = [\boldsymbol{\Re}]^{-1}.[\boldsymbol{\varphi}] = [\boldsymbol{P}][\boldsymbol{\varphi}] \qquad \textbf{Equation 3.1}$$

where

φ is the applied mmf

ψ the developed magnetic flux

$\Re$ reluctance matrix

P inverse reluctance matrix or permeance matrix

Further details regarding the derivation of the matrices and parameter of the 3-phase transformer model have been explained in reference [145].

3.5.2. Distribution Lines

Distribution lines are mediums which transfer electrical energies to consumers over a geographically wide area of power system network. Hence, the connections between different components of the interconnected distribution network, mathematical modelling and representation of the power lines are critical to demonstrate both steady state and transient conditions in the power system networks [146]. In the literature, there have been various models for mathematical representation of the power lines where depending on types and applications some simplifications or changes are applied [145]. In this research study, the adopted equivalent model for power distribution lines is short distance overhead line with lumped parameters for resistors, inductors and capacitors. Generally, for shorter length distribution lines comparing to transmission lines the length of the conductor should be less than 50km to be considered as short distance. In Figure 3.10, equivalent circuit for PI section model for a balanced 3-phase distribution line has been illustrated.

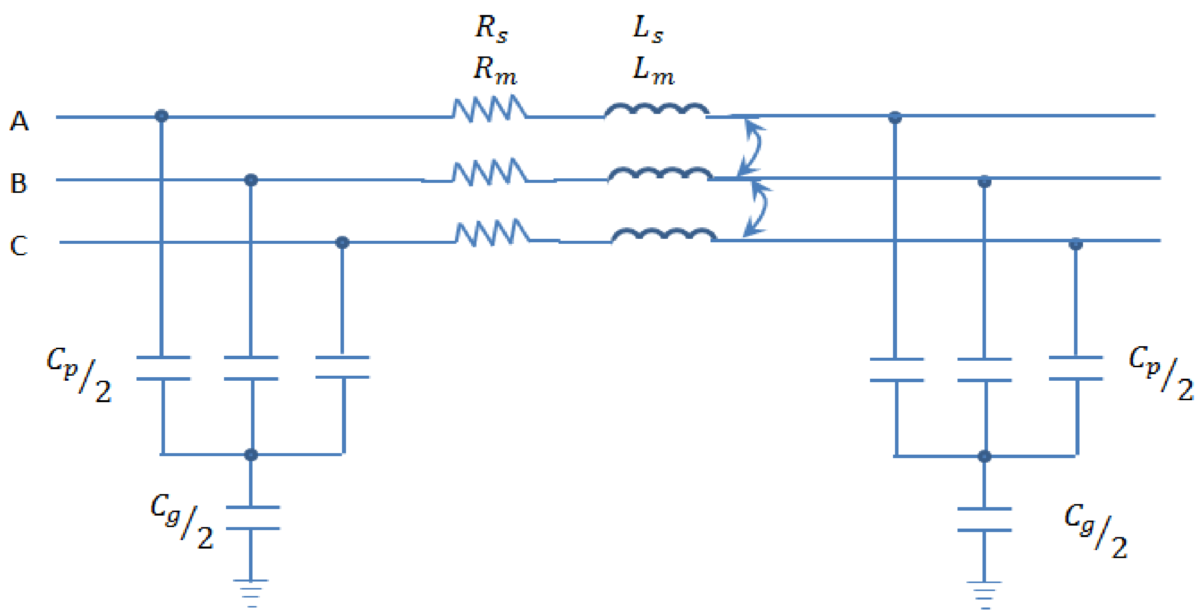

Figure 3.10 Lumped equivalent PI model for 3-phase balanced distribution lines.

Although, it should be noted that in Figure 3.10, the resistors, inductors and capacitors are line parameters which take into account both mutual effects from the other two conductors and the ground capacitor. Thus, subscripts ‘s’ and ‘m’ for resistors and inductors represent lumped values for self and mutual couplings in a balanced 3-phase PI section model of a distribution line. Similarly, the subscripts ‘p’ and ‘g’ for capacitors are representing mutual phase and ground capacitor for a balanced 3-phase short distance distribution lines. For the sake of brevity and simplicity mathematical modelling of the distribution line is not represented however, in reference [145], detailed calculations and assumptions for deriving matrix form equivalent mathematical model has been explained.

3.5.3. Load

Depending on the operation scenario and the research scope, both dynamic and static load models can be used within the distribution networks. However, for this research study, a balanced 3-phase load model composed of passive elements resistors, inductors and capacitors which are connected in series for star (Y or wye) or Δ configuration. Although there are other different loads such as constant power load, constant current load which can be modelled, constant impedance model is generally adopted because the characteristics of the load is not critical with respect to network frequency [147]. In Figure 3.11, a typical representation for grounded 3-phase balanced load with constant impedance has been illustrated. The Z impedance for each leg of the 3-phase load represents constant and equal impedances. Details of modelling and representations of the 3-phase loads are given in reference [145]. As it is obvious there are no mutual effects within balanced 3-phase load model.

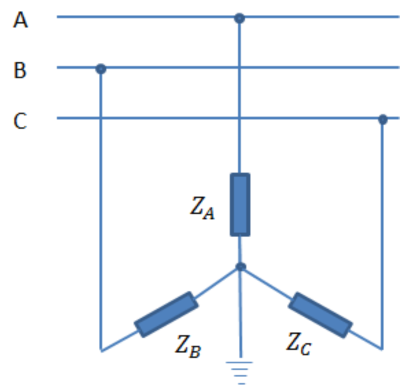

Figure 3.11 Representation of a 3-phase balanced load grounded in star connected.

3.6 Mathematical Modelling

Generally, analysis of the power system behaviour is studied through transformation of physical phenomena into mathematical representation of voltages and currents in differential equations. Thus far, technical aspects related to operational and functional tasks of each individual element for interconnected distribution network have been discussed. However, depending on the type of study being performed, mathematical modelling and dynamic stability of the power system components are critical to accurately and reliably simulate power system behaviour for particular studies in power system domain. In interconnected networks, DERs with dynamic models and control systems constitute a heterogeneous system where interactions between subsystems of different time-scales rely on time-domain modelling of the transient phenomena in power systems.

Consequently, a holistic approach taking into account effective parameters in operation of the interconnected distribution networks under real-world scenario has been adopted where time-domain simulation of the DERs (DFIG and DG) and their components are simulated to investigate fault current behaviour and protection system analysis. A suitable basis to tackle complexities in modelling subsystems is to follow systematic description of the relevant physical phenomena and accordingly develop the mathematical representation of the subsystems with differential equations. Finally, the overall representation of the interconnected distribution network is implemented by combining individual models and their control loops to simulate the behaviour of entire interconnections [127]. In the subsections 3.6.1 and 3.6.2, mathematical representations of the DERs including DFIG system, DG and their control loops will be derived.

3.6.1. DFIG Dynamic Model

Basically, the theory of operation of the WRIM is based on rotating magnetic field around the air-gap of the machine where the stator windings of the machine are fed by a 3-phase voltage lines. As the lines of the flux cut the rotor conductors due to the Lenz's law, the induced voltage creates a current flow whose polarity opposes the excitation field polarity. As illustrated in Figure 3.12, a typical 3-phase WRIM is comprised of six inductors which are aligned with their corresponding phase axes. Moreover, phase axes are divided into stator phase coordinate and rotor phase coordinate which are the bases for the analysis of the magnetic coupled circuits in 3-phase coordinate system. As seen in Figure 3.12, the stator phase coordinate $(a_s - b_s - c_s)$ is the stationary one which is assumed to be attached in stator housing frame while the rotor phase coordinate $(a_r - b_r - c_r)$ rotates with the rotor shaft and have relative angular position with respect to the stator phase axes.

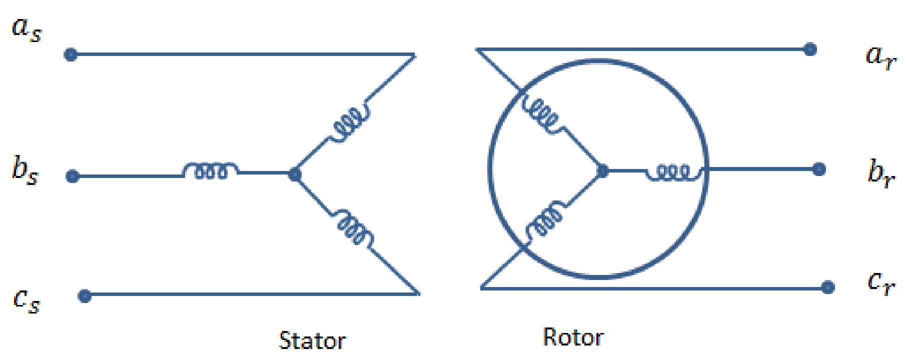

Figure 3.12 a-b-c Windings arrangement in a 3-phase WRIM.

Following the description of the 3-phase coordinates in WRIM, one can derive the 3-phase quantities by expressing them with respect to the 3-phase coordinates illustrated in Figure 3.12. In the next subsection, the voltage equation for each individual phase axes will be derived.

3.6.1.1 Voltage Equations

Essentially the stator side of a 3-phase WRIM can be represented as three individual windings with similar voltage equations for each phase given in equation (3.2) to (3.4):

$$\boldsymbol{V_{as} = R_s I_{as} + \frac{d\psi_{as}}{dt}} \qquad \textbf{Equation 3.2}$$

$$\boldsymbol{V_{bs} = R_s I_{bs} + \frac{d\psi_{bs}}{dt}} \qquad \textbf{Equation 3.3}$$

$$\boldsymbol{V_{cs} = R_s I_{cs} + \frac{d\psi_{cs}}{dt}} \qquad \textbf{Equation 3.4}$$

For the voltage equations **V** and **I** represent voltage and current phasors at the WRIM terminals where subscript s and r stand for stator and rotor sides. The operator $\frac{\mathrm{d}}{\mathrm{dt}}$ is time differentiation for the operand ψ which represents magnetic flux linkages. By following similar approach for the rotor windings, the voltage equations are derived as in equation (3.5) to (3.7):

$$\boldsymbol{V_{ar} = R_r I_{ar} + \frac{d\psi_{ar}}{dt}} \qquad \textbf{Equation 3.5}$$

$$\boldsymbol{V_{br} = R_r I_{br} + \frac{d\psi_{br}}{dt}} \qquad \textbf{Equation 3.6}$$

$$\boldsymbol{V_{cr} = R_r I_{cr} + \frac{d\psi_{cr}}{dt}} \qquad \textbf{Equation 3.7}$$

3.6.1.2 Flux Linkage Equations

Due to the rotating rotor of the WRIM and the principle of the magnetic coupled circuits, the flux linkages of the WRIM can be written in matrix form as shown in equation (3.8)[145].

$$\boldsymbol{\begin{bmatrix} \psi_s^{abc} \\ \psi_r^{abc} \end{bmatrix} = \begin{bmatrix} L_{ss}^{abc} & L_{sr}^{abc} \\ L_{rs}^{abc} & L_{rr}^{abc} \end{bmatrix} \begin{bmatrix} I_s^{abc} \\ I_r^{abc} \end{bmatrix}} \qquad \textbf{Equation 3.8}$$

$$\boldsymbol{\psi_s^{abc} = [\psi_{as} \quad \psi_{bs} \quad \psi_{cs}]^T} \qquad \textbf{Equation 3.9}$$

$$\boldsymbol{\psi_r^{abc} = [\psi_{ar} \quad \psi_{br} \quad \psi_{cr}]^T} \qquad \textbf{Equation 3.10}$$

$$\boldsymbol{I_s^{abc} = [I_{as} \quad I_{bs} \quad I_{cs}]^T} \qquad \textbf{Equation 3.11}$$

$$\boldsymbol{I_r^{abc} = [I_{ar} \quad I_{br} \quad I_{cr}]^T} \qquad \textbf{Equation 3.12}$$

Where

L_{ss}^{abc} is 3 × 3 matrix for mutual inductance of each individual stator self-inductance matrix

$$\boldsymbol{L_{ss}^{abc} = \begin{bmatrix} L_{aa}^s & L_{ab}^s & L_{ac}^s \\ L_{ba}^s & L_{bb}^s & L_{bc}^s \\ L_{ca}^s & L_{cb}^s & L_{cc}^s \end{bmatrix}} \qquad \textbf{Equation 3.13}$$

L_{rr}^{abc} a 3 × 3 matrix representing mutual inductance of each individual rotor self-inductance matrix

$$L_{rr}^{abc} = \begin{bmatrix} L_{aa}^{r} & L_{ab}^{r} & L_{ac}^{r} \\ L_{ba}^{r} & L_{bb}^{r} & L_{bc}^{r} \\ L_{ca}^{r} & L_{cb}^{r} & L_{cc}^{r} \end{bmatrix} \qquad \textbf{Equation 3.14}$$

L_{rs}^{abc} and L_{sr}^{abc} are the mutual inductances of stator and rotor which are functions of the rotor position (θ_r) which in turn is a time dependent variable. It should be also noted that in equations (3.8) to (3.11), the subscripts 's' and 'r' stand for the stator and rotor coordinates while the 'ψ' and 'I' represent the magnetic flux linkage and the current respectively.

3.6.2. DFIG Control Loops

The principle of the DFIG control is based on the Field-Oriented Control (FOC) of the WRIM where 3-phase AC magnetic field is transformed into two orthogonal magnetic fields synchronously rotating with separately excited DC current components on an imaginary d-q frame. Basically, one of the advantages of transforming 3-phase voltage equations of the WRIM into equivalent d-q frame is decoupling of the active and reactive power injected to the grid by DFIG system. Therefore, in this section designing of the control systems for WRIM are determined based on d-q voltage equations however, details corresponded to transformation and derivations of d-q voltage equations from 3-phase voltage equations of the WRIM have been addressed in [136]. In general, the Stator Flux-Oriented (SFO) approach is the common technique which has been applied for the DFIG control. Figure 3.13 illustrates applying SFO principle where the d-axis of the synchronously rotating d-q frame is aligned with the synchronously rotating stator flux ($\boldsymbol{\psi_s}$) in a 3-phase abc coordinate.

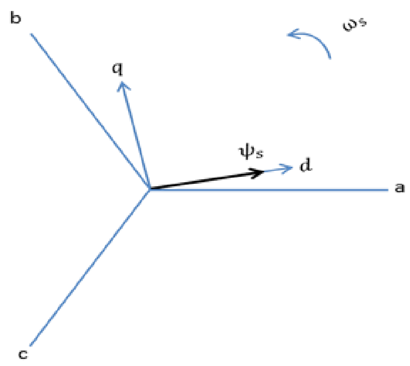

Figure 3.13 Alignment of d-q axis based on SFO approach.

According to the SFO the following assumptions can be deduced which is expressed by equations (3.15).

$$\boldsymbol{\psi_{qs} = 0} \quad \& \quad \boldsymbol{\psi_{ds} = \psi_s} \qquad \textbf{Equation 3.15}$$

Thus, with regard to the above condition and the dynamic model of the WRIM in d-q frame [136], the d-q voltage equations for the stator side can be rearranged into equations (3.16) and (3.17).

$$\boldsymbol{V_{ds} = R_s I_{ds} + \frac{d\psi_{ds}}{dt}}$$ **Equation 3.16**

$$\boldsymbol{V_{qs} = R_s I_{qs} + \omega_s \psi_{ds} + \frac{d\psi_{qs}}{dt}}$$ **Equation 3.17**

By considering the stator flux as constant due to fast dynamic of the stator side (grid connected) and at the same time neglecting stator resistance equations (3.18) and (3.19) are hold.

$$\boldsymbol{V_{ds} \cong 0}$$ **Equation 3.18**

$$\boldsymbol{V_{qs} \cong \omega_s \psi_{ds}}$$ **Equation 3.19**

On the other hand, from equations (3.16) to (3.17) and applying SFO condition flux linkages are derived in equations (3.20) and (3.21):

$$\boldsymbol{\psi_{qs} = L_s I_{qs} + L_m I_{qr} \xrightarrow{\psi_{qs}=0} I_{qs} = -\frac{L_m}{L_s} I_{qr}}$$ **Equation 3.20**

$$\boldsymbol{\psi_{qr} = L_m I_{qs} + L_r I_{qr} \xrightarrow{I_{qs}=-\frac{L_m}{L_s}I_{qr}} \psi_{qr} = \sigma I_{qr}}$$ **Equation 3.21**

Where

$$\boldsymbol{\sigma = \left(\frac{L_r L_s - L_m^2}{L_s}\right)}$$ **Equation 3.22**

Finally, by applying SFO, the d-component of the stator current is expressed in equation (3.23).

$$\boldsymbol{\psi_{ds} = L_s I_{ds} + L_m I_{dr} \xrightarrow{SFO} I_{ds} = \frac{\psi_s - L_m I_{dr}}{L_s}}$$ **Equation 3.23**

Following the aforementioned characteristics deduced from applying SFO, one can proceed for devising controller for the power control in the DFIG system.

3.6.2.1.1 Active Power Control

One of the outcomes of applying SFO for the DFIG power generating system is the decoupling of the active power and reactive power of the system. In a 3-phase WRIM the active and reactive power at the stator side terminal are derived from equations (3.24) and (3.25).

$$\boldsymbol{P_s = \frac{3}{2}\left(V_{ds} I_{ds} + V_{qs} I_{qs}\right)}$$ **Equation 3.24**

$$\boldsymbol{Q_s = \frac{3}{2}\left(V_{qs} I_{ds} - V_{ds} I_{qs}\right)}$$ **Equation 3.25**

In similar approach, with applying SFO conditions from equations (3.18), (3.19) and (3.23) the active and reactive powers at stator of the DFIG system can be derived in equations (3.26) and (3.27).

$$\boldsymbol{\xrightarrow{SFO} P_s = \frac{3}{2}\left(V_{qs} I_{qs}\right) = -\frac{3}{2}\frac{L_m}{L_s} V_{qs} I_{qr}}$$ **Equation 3.26**

$$\xrightarrow{SFO} Q_s = \frac{3}{2}\left(V_{qs}I_{ds}\right) = \frac{3}{2}V_{qs}\left(\frac{\psi_s - L_m I_{dr}}{L_s}\right) \quad \textbf{Equation 3.27}$$

Therefore, the active power and reactive power of the DFIG are decoupled and can be controlled by I_{qr} and I_{dr} respectively. As derived in equations (3.26) and (3.27) the rotor current of the WRIM are the control variables for the active and reactive power of the DFIG which in turn are controlled by the V_{qr} and V_{dr} respectively. In fact, the objective of the MSC is to regulate the injected active and reactive power into the grid through a cascaded control loop. In Figure 3.14 the schematic block diagram representing the control loop for regulating active power in DFIG system has been illustrated. There are two PI control loops which are cascaded as current control loop (inner loop) with regulator G_{c2} and active power control loop (outer loop) with G_{c1}.

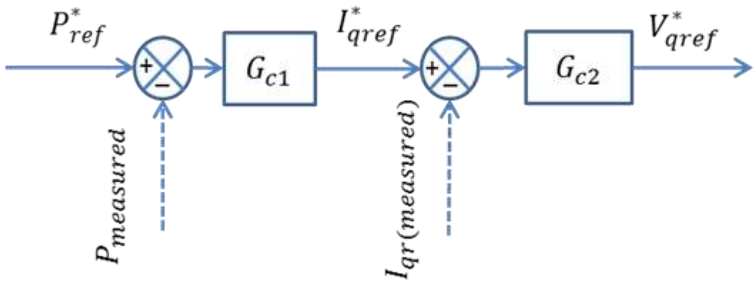

Figure 3.14 Schematic block diagram for control loop of the active power.

In Figure 3.15, the schematic block diagram for reactive power control of the DFIG system has been illustrated, where current control loop (inner loop) is identified by a PI controller with G_{c4} transfer functions and reactive power controllers (outer loop) represented by G_{c3}.

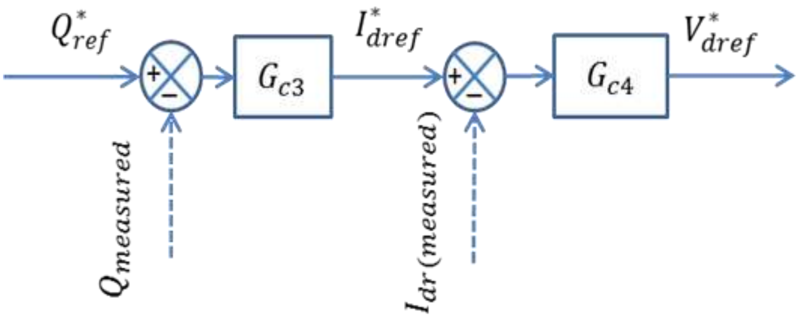

Figure 3.15 Schematic block diagram for control loop of the reactive power.

Similar to d-q voltage for stator sided by applying SFO condition and taking into account the d-q voltage equations at rotor side, the rotor voltage equation in d-q frame can be rearranged into equations (3.29) and (3.30).

$$\xrightarrow{\psi_{ds}=constan} \frac{d\psi_{ds}}{dt} = 0 \xrightarrow{arrive} \frac{dI_{ds}}{dt} = \sigma\frac{dI_{dr}}{dt} \quad \textbf{Equation 3.28}$$

$$\boldsymbol{V_{dr} = R_r I_{dr} - (\omega_s - \omega_r)\sigma I_{qr} + \sigma \frac{dI_{dr}}{dt}}$$ **Equation 3.29**

$$\boldsymbol{V_{qr} = R_r I_{qr} + \frac{L_m}{L_s}\psi_s + \sigma I_{dr} + \sigma \frac{dI_{qr}}{dt}}$$ **Equation 3.30**

As it is obvious from equations (3.29) and (3.30) the rotor voltages (V_{dr}, V_{qr}) are cross-coupled by the rotor currents (I_{dr}, I_{qr}) which introduce complexities for designing the controller. In order to overcome this problem, the rotor voltage can be rewritten in two separated terms the reference voltage (V^*_{ref}) and the decoupling-term which can be rewritten by equations (3.31) and (3.32).

$$\boldsymbol{V_{dr} = V^*_{dref} - \overbrace{(\omega_s - \omega_r)\sigma I_{qr}}^{decoupling\ Term}}$$ **Equation 3.31**

$$\boldsymbol{V_{qr} = V^*_{qref} + \overbrace{\left(\frac{L_m}{L_s}\psi_s + \sigma I_{dr}\right)}^{decoupling\ Term}}$$ **Equation 3.32**

Thus, the decoupling terms in equations (3.31) and (3.32) are the first order plants which can be represented in a control loop illustrated in Figure 3.16 and Figure 3.17.

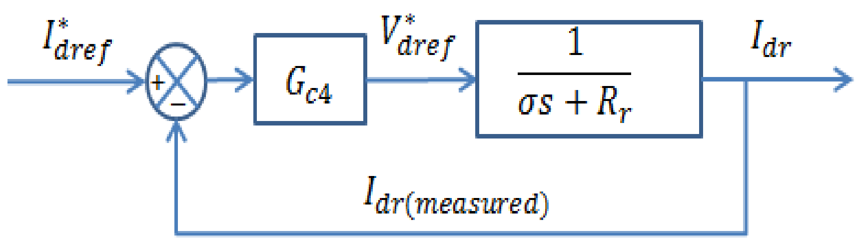

Figure 3.16 Schematic block diagram representing inner control loop for active current.

For both G_{c4} and G_{c2} the PI controllers are designed to regulate reference currents of I^*_{dref} and I^*_{qref} which by applying the Internal Model Control (IMC), proportional and integration constants (k_p 's and k_i 's of the controllers are determined.

$$k_{pc4} = 0.3 \quad , k_{ic4} = 8 \qquad k_{pc2} = 0.3 \quad , k_{ic2} = 8$$

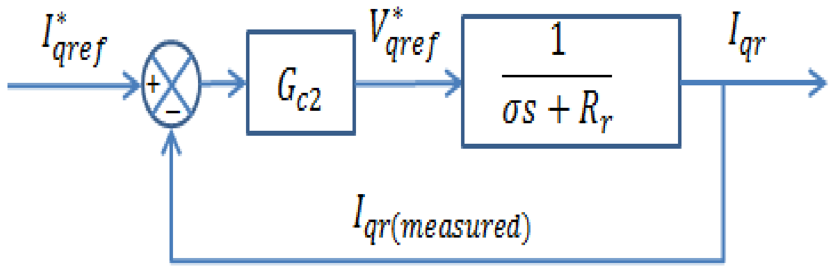

Figure 3.17 Schematic block diagram representing inner control loop for reactive current.

Finally, in order to generate the rotor voltage in equations (3.29) and (3.30) the decoupling terms are feed-forwarded to the controller output.

3.6.2.1.2 Grid-Side Control

The control loops for GSC is similar to the RSC, where two cascaded control loops regulate GSC system under variable operating slip of the DFIG system (variable speed). However, in the GSC the DC-link voltage and the reactive power of the grid-side filter are control variables. In the following, design of the controller for the aforementioned variables is developed.

3.6.2.1.3 DC Link Control

The DC-link voltage of the back to back converter is aimed to provide constant voltage for the converter capacitor where the stored energy in the capacitor is utilized to regulate the power flow between the GSC and RSC. Thus, considering the power flow in the DC-link capacitor, the power equation is expressed by equation (3.33).

$$\frac{1}{2}C\frac{d(V_{dc}^2)}{dt} = P_r + P_f \qquad \textbf{Equation 3.33}$$

Where P_f is the harmonic filter devised at the grid-side to reduce power quality issues related to the converters and P_r represents power flow for DFIG rotor side. Calculation of P_f can be expressed with equation 3.34. In equation (3.34) subscript f and g refer to filter-side and grid-side variables.

$$P_f = \frac{3}{2}\left(V_{df}I_{df} + V_{qf}I_{qf}\right) = \frac{3}{2}\left(V_{dg}I_{df} + V_{qg}I_{qf}\right) \qquad \textbf{Equation 3.34}$$

By applying SFO condition for the stator voltage (grid voltage) from equation 3.18, equation (3.35) is obtained from equation (3.34) for power flow in GSC filter.

$$P_f = \frac{3}{2}V_{qg}I_{qf} \qquad \textbf{Equation 3.35}$$

Consequently, the dynamic equation for the DC-link capacitor can be rewritten in equation (3.36).

$$\frac{d(V_{dc}^2)}{dt} = \frac{3V_{qg}I_{qf}}{C_{dc}} + P_r \qquad \textbf{Equation 3.36}$$

Whereby considering the rotor power (P_r) as a disturbance, the transfer function for DC-link voltage squared is expressed by equation (3.37).

$$V_{dc}^2 = \frac{3V_{qg}I_{qf}}{C_{dc}S} \qquad \textbf{Equation 3.37}$$

On the other hand, with expressing voltage equations for grid-side filter in d-q frame, similar to d-q voltage equations for stator, equation (3.38) can be used for current loop (inner loop) to regulate voltage for DC capacitor.

$$V_{qf} = V_{qs} + R_f I_{qf} + \omega_s L_f I_{df} + L_f \frac{dI_{qf}}{dt}$$ **Equation 3.38**

By rewriting equation (3.8) in compensating term and decoupling term, equation (3.39) is obtained.

$$V_{qf} = R_f I_{qf} + L_f \frac{dI_{qf}}{dt} + \overbrace{\omega_s L_f I_{df} + V_{qs}}^{decoupling\ term}$$ **Equation 3.39**

Taking equation (3.37) and (3.39) as the transfer functions for the outer and inner loop, the cascaded control loop for the DC-Link voltage control is illustrated in Figure 3.18.

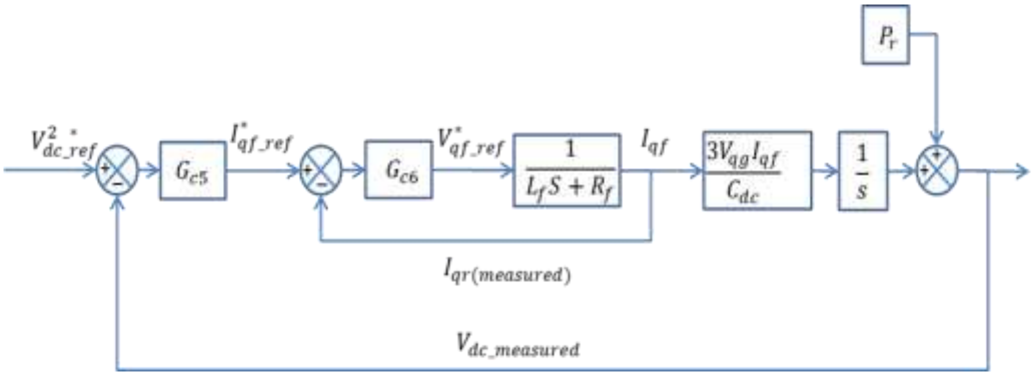

Figure 3.18 Schematic block diagram representing DC-Link voltage control loops.

Finally, based on the IMC and bandwidth condition for the cascaded control loops the PI controller parameters are (subscripts c5 and c6 refer to regulator blocks G_{c5} and G_{c6} respectively).

$$k_{pc5} = 0.002 \quad , k_{ic5} = 0.05 \qquad k_{pc6} = 1 \quad , k_{ic6} = 100$$

3.6.2.1.4 Reactive Power Control

Generally, during the normal operation of DFIG system control the reactive power for the GSC is set for null ($Q_f = 0$). However, in the light of the recent grid codes for integration of the DFIG system and the fault ride through (FRT) capabilities one requires to address the reactive power control for the grid-side filter. The steps that are taken to control the reactive power of the grid filter are the same as mentioned for the DC-Link voltage control with differences in transfer functions in the loop for the designed controller. As it has been illustrated in Figure 3.19, the control loops are consistent of current loop (inner loop) and reactive power loop (outer loop).

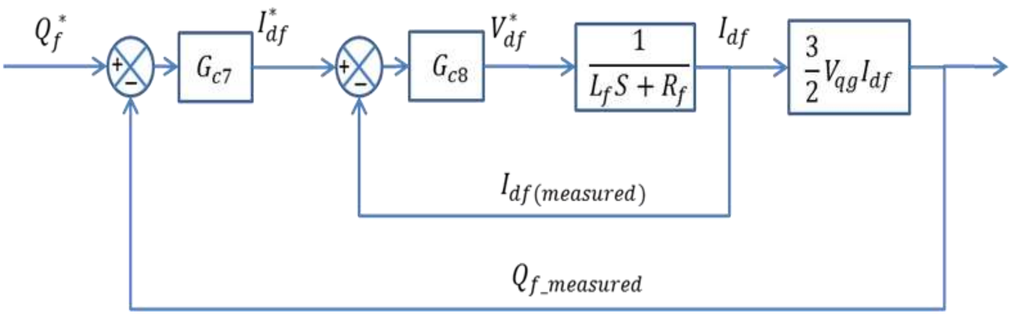

Figure 3.19 Schematic block diagram representing GSC control loops for reactive power.

The reactive power of the grid-side filter injected into grid can be expressed as:

$$\boldsymbol{Q_{filter}} = \frac{3}{2}\left(\boldsymbol{V_{qf}I_{df}} - \boldsymbol{V_{df}I_{qf}}\right) = \frac{3}{2}\left(\boldsymbol{V_{qg}I_{df}} - \boldsymbol{V_{dg}I_{qf}}\right) \qquad \textbf{Equation 3.40}$$

Whereby applying the SFO conditions in equation (3.40), reactive power for grid-side filter is expressed in equation (3.41).

$$\boldsymbol{Q_f} = \frac{3}{2}\boldsymbol{V_{qg}I_{df}} \qquad \textbf{Equation 3.41}$$

And also, the d-axis voltage of the grid-side filter can be written as:

$$\boldsymbol{V_{df}} = \boldsymbol{R_f I_{df}} + \boldsymbol{L_f}\frac{\boldsymbol{dI_{df}}}{\boldsymbol{dt}} - \overbrace{\boldsymbol{\omega_s L_f I_{qf}}}^{\textit{decoupling term}} + \overbrace{\boldsymbol{V_{ds}}}^{\mathbf{0}} \qquad \textbf{Equation 3.42}$$

Thus, according to the IMC and the bandwidth characteristics for the cascaded loop control, the control parameters for the PI controllers are determined with proportional and integration constants (subscripts c7 and c8 refer to regulator blocks G_{c7} and G_{c8} respectively)[148].

$$k_{pc7} = 3 \quad , k_{ic7} = 5 \qquad k_{pc8} = 1 \quad , k_{ic8} = 100$$

3.6.2.2 Drive Train Dynamic Model

The drive train is inserted between the turbine shaft and the DFIG rotor shaft in order to attain suitable speed range for the rotor shaft of the generator [149]. However, the importance of modelling the drive train is associated with the oscillations introduced by wind gusts and voltage sags [150-152] which can affect the transient stability of the system and the failure in drive train. Moreover, due to mass inertial and angular velocity dynamic of the drive train, it can further improve the accuracy in simulation of DFIG system under different grid disturbances [153-155]. According to the literature [156-158], the dynamics of the drive train can be represented by two-mass model connecting the turbine shaft (low speed shaft) to generator side (high speed shaft). In Figure 3.20, two inertia of the turbine and generator linked through a set of springs and dampers have been represented the flexibility of the connecting shafts.

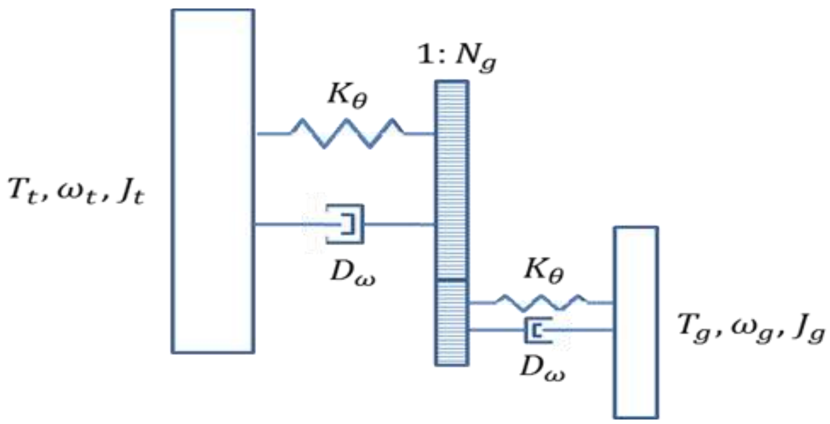

Figure 3.20 A simple two-mass model representation of the drive train for DFIG system.

In general, the dynamic model of a simple two-mass model drive train can be expressed through set of differential equation (3.43) to (3.45)[156].

$$\boldsymbol{J_t \dot{\omega}_t = T_t - D_\omega \left(\omega_t - \frac{\omega_g}{N_g}\right) - K_\theta \overbrace{\left(\theta_t - \frac{\theta_g}{N_g}\right)}^{\theta}} \quad \textbf{Equation 3.43}$$

$$\boldsymbol{J_g \dot{\omega}_g = T_g + \frac{D_\omega}{N_g}\left(\omega_t - \frac{\omega_g}{N_g}\right) + \frac{K_\theta}{N_g} \overbrace{\left(\theta_t - \frac{\theta_g}{N_g}\right)}^{\theta}} \quad \textbf{Equation 3.44}$$

$$\boldsymbol{\dot{\theta} = \omega_t - \frac{\omega_g}{N_g}} \quad \textbf{Equation 3.45}$$

Where

ω_t and ω_g are the turbine and generator angular speed

T_t and T_g are the turbine and generator torques

D_ω and K_θ are the shaft damping constant and shaft spring constant

And N_g is the gear ratio.

3.6.3. DG Dynamic Model

As shown in Figure 3.21 from system modelling point of view, a typical configuration of the DG can be represented with two mechanical and electrical subsystems of diesel engine and Synchronous Generator (SG) which are directly coupled through a common rotating shaft. Basically, the importance of mathematical modelling and simulation of DG system is mainly concerned with its performance during the period of islanded mode operation. In fact, for interconnected distribution network, requirement for maintaining dynamic stability and fast responses to any load disturbances or transitional conditions is crucial for investigation on fault current behaviour and protection system performance. Thus, simulation model for DG system should be precise enough to represent detailed interactions between different elements and subsystems of the DG system with respect to their suitable timescales. In Figure 3.21, two separate control systems are governor and exciter which regulate frequency and voltage of the DG output. The control loops are devised to interact with both mathematical models for SG and diesel engine in time domain simulation to adjust voltage and frequency at the stator terminal of DG.

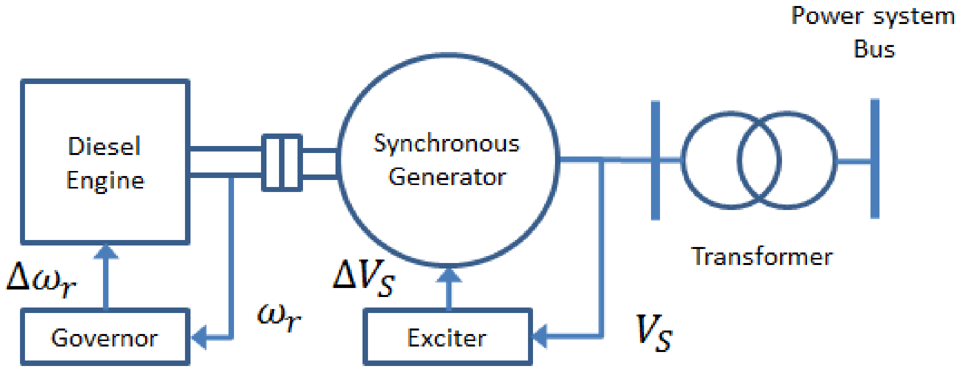

Figure 3.21 Structural configuration and subsystems in a typical Diesel Generator.

3.6.3.1 Synchronous Machine (SM) Model-Salient Pole

There are different models and types of SM which can be used to represent dynamic model of the SG for power generation applications. However, depending on the analysis and focus of the research study elaborate models of the SM can be obtained considering magnetic circuit of the machine and accurate parameters that serves the purpose of the study. In this subsection, the mathematical modelling and conventions are based on the IEEE standard in modelling synchronous machine [159] where coupled-magnetic circuit approach has been adopted for mathematical representation of the synchronous generator. Although, there are some similarities in the physical structure of the SM and IM which is mainly related to the existence of stator and rotor parts but (the rotor is excited by DC voltage) the rotor side windings in SG have different arrangements with damper windings which are necessary for stable operation of the SG during any oscillation in power generation systems. In Figure 3.22(a) and 3.22(b), sectional views and arrangement of the rotor side windings have been illustrated respectively. As seen in Figure 3.22 the stator axes are represented by *abc* axes line with 120° angle between each other. For the rotor part the d-q axis are defined based on the rotor structure in the salient type SM where d-axis is along the salient pole (normal to the stator winding plane) while the q-axis is perpendicular to d-axis (aligned to the damper windings) on the salient pole. The rotor field is excited by a dc voltage represented by v_{fd} and the rotor current is i_{fd}. Hence the SM model considers damper windings on d-axis and q-axis (depending on the required accuracy of the model) one damper winding is used along the d-axis and two damper windings are devised in the slots of the pole face of the rotor (shown in Figure 3.22(b), to act as closed path during non-synchronous operation –avoiding unstable mechanical oscillation of the rotor-hunting). In Figure 3.22 (b) the damper windings are represented as 1d, 1q and 2q with voltages of v_{1d}, v_{1q}, v_{2q} and currents of i_{1d}, i_{1q}, i_{2q} respectively.

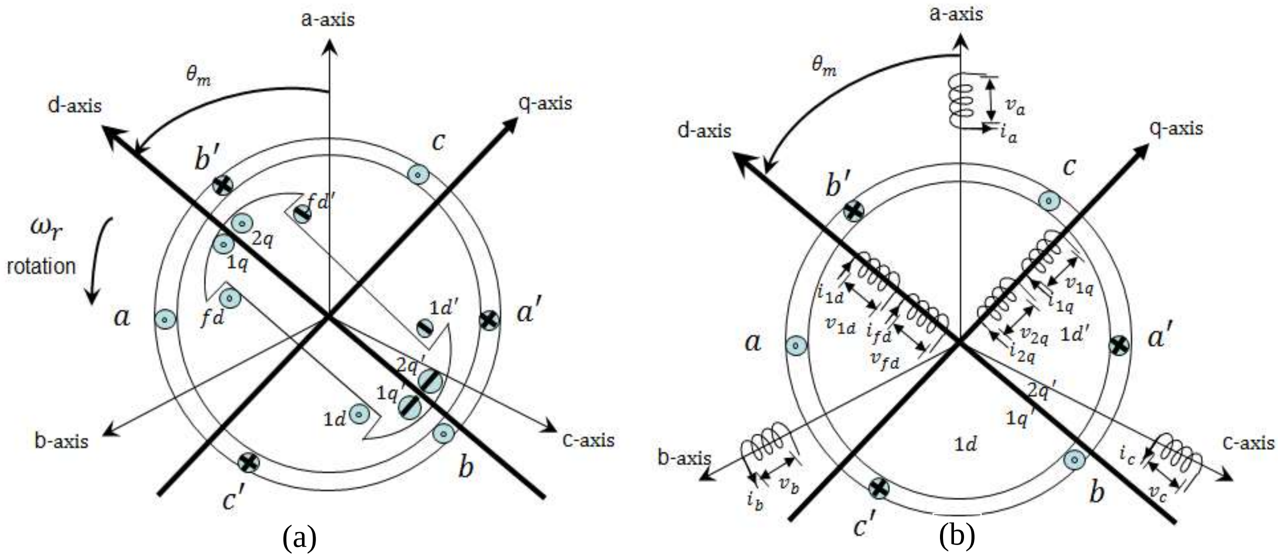

Figure 3.22 Typical arrangements for stator and rotor windings in 3-phase synchronous machine.

Finally, mathematical equations related to principles of the electromagnetic circuits are derived for both voltage equations and flux linkages within SM.

3.6.3.2 Voltage Equations

Similar to WRIM derivation of the voltage equations for a typical SM represented in Figure 3.22 can be achieved by applying Kirchhof Voltage Law (KVL) for each phase in the stator and rotor frame axis. Equations (3.46) to (3.48) represent terminal phase voltages at the stator terminal and also equations (3.49) to (3.52) express voltage equations for rotor windings in d-q axis (frame).

$$V_{as} = -R_s I_{as} + \frac{d\psi_{as}}{dt} \qquad \textbf{Equation 3.46}$$

$$V_{bs} = -R_s I_{bs} + \frac{d\psi_{bs}}{dt} \qquad \textbf{Equation 3.47}$$

$$V_{cs} = -R_s I_{cs} + \frac{d\psi_{cs}}{dt} \qquad \textbf{Equation 3.48}$$

$$V_{fd} = R_{fd} i_{fd} + \frac{d\psi_{fd}}{dt} \qquad \textbf{Equation 3.49}$$

$$V_{1d} = R_{1d} i_{1d} + \frac{d\psi_{1d}}{dt} \qquad \textbf{Equation 3.50}$$

$$V_{1q} = R_{1q} i_{1q} + \frac{d\psi_{1q}}{dt} \qquad \textbf{Equation 3.51}$$

$$V_{2q} = R_{2q} i_{2q} + \frac{d\psi_{2q}}{dt} \qquad \textbf{Equation 3.52}$$

where $R_{fd}, R_{1d}, R_{1q}, R_{2q}$ and ψ_{fd} , $\psi_{1d}, \psi_{1q}, \psi_{2q}$ represent resistance and flux linkages for the rotor field , damper windings 1d, 1q, and 2q respectively.

As the rotor side of the SM is excited by DC voltage, for the rotor side the rate of the change for flux linkages are (mainly develop) the terms which consider the electro-motive force (EMF) due to non-synchronous operation of SM. All resistors in the voltage equations are considered constant during the operation of the SM.

3.6.3.3 Flux Linkage Equations

The equations for flux linkages in SM are defined in a matrix form and it relates currents in different windings with their inductance which can be expressed as self-inductance and mutual inductance between the stator, rotor and damper windings within the structure of the SM. In equations (3.53) and (3.54) matrix representations of the flux linkages for stator, rotor and damper windings for SM have been expressed [159].

$$\begin{bmatrix} \psi_a \\ \psi_b \\ \psi_c \end{bmatrix} = \begin{bmatrix} L_{aa} & L_{ab} & L_{ac} \\ L_{ba} & L_{bb} & L_{bc} \\ L_{ca} & L_{cb} & L_{cc} \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} + \begin{bmatrix} L_{afd} & L_{a1d} & L_{a1q} & L_{a2q} \\ L_{bfd} & L_{b1d} & L_{b1q} & L_{b2q} \\ L_{cfd} & L_{c1d} & L_{c1q} & L_{c2q} \end{bmatrix} \begin{bmatrix} i_{fd} \\ i_{1d} \\ i_{1q} \\ i_{2q} \end{bmatrix} \qquad \textbf{Equation 3.53}$$

$$\begin{bmatrix}\psi_{fd}\\ \psi_{1d}\\ \psi_{1q}\\ \psi_{2q}\end{bmatrix} = \begin{bmatrix}L_{fda} & L_{fdb} & L_{fdc}\\ L_{1da} & L_{1db} & L_{1dc}\\ L_{1qa} & L_{1qb} & L_{1qc}\\ L_{2qa} & L_{2qb} & L_{2qc}\end{bmatrix}\begin{bmatrix}I_a\\ I_b\\ I_c\end{bmatrix} + \begin{bmatrix}L_{fdfd} & L_{f1d} & 0 & 0\\ L_{1dfd} & L_{1d1d} & 0 & 0\\ 0 & 0 & L_{1q1q} & L_{1q2q}\\ 0 & 0 & L_{2q1q} & L_{2q2q}\end{bmatrix}\begin{bmatrix}i_{fd}\\ i_{1d}\\ i_{1q}\\ i_{2q}\end{bmatrix} \qquad \textbf{Equation 3.54}$$

The terms L_{aa}, L_{bb}, L_{cc} in equation (3.53) indicate the self-inductance for a, b, and c windings while $L_{ab}, L_{ac}, L_{bc}, L_{ba}$ and etc. represent mutual inductance between a, b, c winding in the stator frame. In similar approach the effect of mutual inductances between stator windings and the rotor windings (field winding and damper windings) are represented by $L_{xfd}, L_{x1d}, L_{x1q}$and $L_{x2q}$where x can be replaced with a,b and c phase of the stator side. In equation (3.54) the mutual inductances between the d-axis and q-axis ($L_{1d1q}, L_{fd1q}, L_{1d2q}$ and L_{fd2q}) are zero as these windings are in quadrature. Derivation of matrix equations (3.53) and (3.54) are further complicated as the dependencies between the stator and rotor inductances are related to mechanical rotor position (θ_m) in SM. The details for state space matrix representation of the SG has been derived in [160].

3.6.3.4 Diesel Engine Model

The structure of diesel engine has different subsystems such as turbocharge and throttle actuator which have to be considered for modelling the generated mechanical torque from the engine combustion system. Although some detailed models have been provided to represent complete dynamic of the diesel engine, including thermodynamic aspects of the air-fuel flow, given the focus of the study is confined to electricity production, lower order models with constant thermodynamic variables will suffice. As shown in Figure 3.23, a simple diesel engine model can be represented with a cascaded function of fast throttle actuator and combustion engine delays where the output torque is controlled by properly regulating air-fuel flow into the combustion chamber. In this model, throttle actuator operates similar to a governor in steam engines while the combustion dead-time is a non-linear function which is determined through curve fitting techniques and empirical data representing dead-time variations with flywheel speeds [142]. In order to avoid further complexities in determining and identification of the diesel engine model, the proposed model provided by [161] has been adopted as the reference model for design speed control for the DG system.

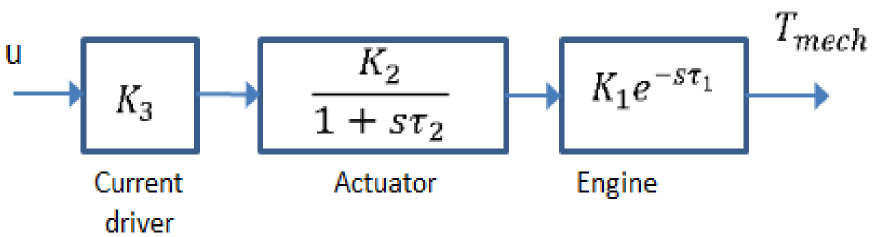

Figure 3.23 Block diagram of the diesel engine and its sub-models.

The parameters illustrated in Figure 3.23 to model diesel engine and its sub-model have been identified as follows[142]:

K_1, K_2 are the engine torque and actuator constants

K_3 a constant dependent on the operation point of the engine

T_{mech} mechanical torque produced by engine crankshaft

$\tau_1 = 0.024 \quad \tau_2 = 0.0384$

3.6.4. DG Control Systems

For modern DG system, different control systems with various objectives such as fuel efficiency or emission controls have been devised specifically for energy management and economical purposes during DG operation. However, there are two main control systems associated with power system operation and dynamic stability of the DG system which can have a comparatively fast response time to deal with the requirements for power generation and voltage regulation during disturbances. Thus, for the aforementioned reason, discussions corresponding to power system stability for voltage and frequency of the rated system are limited to governor and AVR system in diesel engine control units.

3.6.4.1 Frequency Control

In order to interconnect DERs into distribution network, the capability of Emergency Diesel Generator for controlling frequency and load generation balance is crucial for maintaining stability of the islanded system. Thus, under islanded mode operation, a fast response time speed controller is designed to regulate angular velocity of the flywheel at the nominal electrical frequency of the distribution network. There are different methods which have been suggested to deal with dead times and large disturbances at the flywheel shaft for diesel engine. The use of a governor or actuator to control the output torque for the diesel engines and consequently regulating flywheel speed through a feedback control loop is adopted for DG systems. As shown in Figure 3.24, a PID controller loop is configured for monitoring feedback from the angular velocity of the coupling shaft between diesel engine and SG. Since mathematical model and dynamic characteristics of subsystems including governor/actuator (fuel injector) and the engine delay (combustion process) are complicated processes which rely on curve fitting and experimental test, these subsystems are replaced by transfer functions derived from the reference paper [162]. Finally, the speed/frequency control loop is completed by considering the flywheel inertia and SG electrical torque within the electromechanical swing equation for DG system. Considering the dynamic model and transfer functions with their time constants for the control loop in Figure 3.24, K_D is the damping constant and the PID controller parameters have been derived as follows:

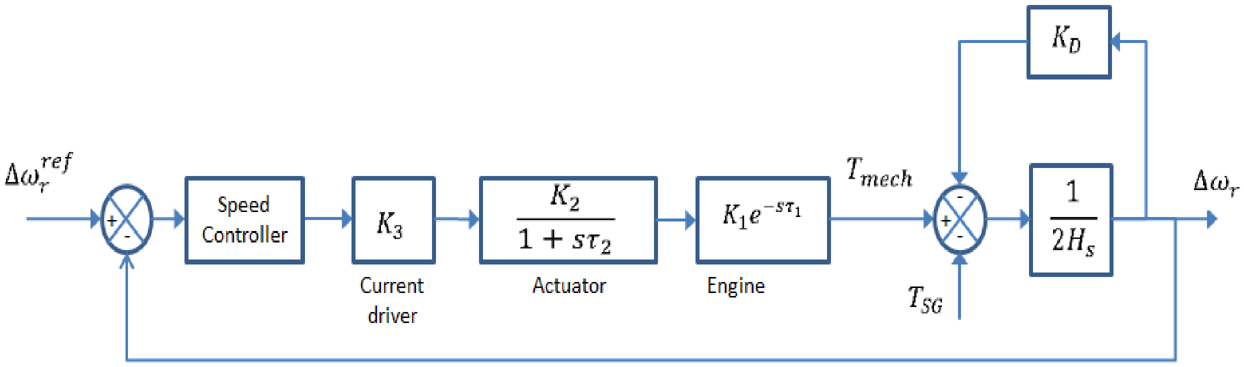

Figure 3.24 Block diagram representing frequency control loop for a diesel engine system.

$K_p = 0.01 \;\; K_i = 0.2 \; K_d = 0.02$

3.6.4.2 Automatic Voltage Regulator

For DG system, the AVR is implemented through standardized excitation system which is adopted to provide constant voltage at the stator terminal of the SG. Basically, voltage control at the connection point of the DG system is an essential requirement for satisfactory performance in transient stability and disturbances arising from load-generation balance. However, the general structure for excitation system model entails multiple control loops and one to one correspondences between different equipment retaining detailed physical parameters. In order to reduce the complexities for developing AVR models for power system stability analysis and at the same time maintain the accuracy of the power system study, IEEE standard has introduced a number of reduced and simplified AVR models which can be used to study transient stability analysis. Having explained the relevancy of the IEEE standard and necessity of the AVR embedded into DG system, the IEEE type AC1 has been adopted as appropriate model to control stator voltage in SG by adjusting the exciter field voltage at the rotor side. In Figure 3.25, the standardized IEEE type AC1 excitation system has been represented as different components and their correspondences are shown by transfer functions. Details related to coefficients of transfer functions are explained in Appendix A.2 for IEEE type AC1 excitation system for DG system [163].

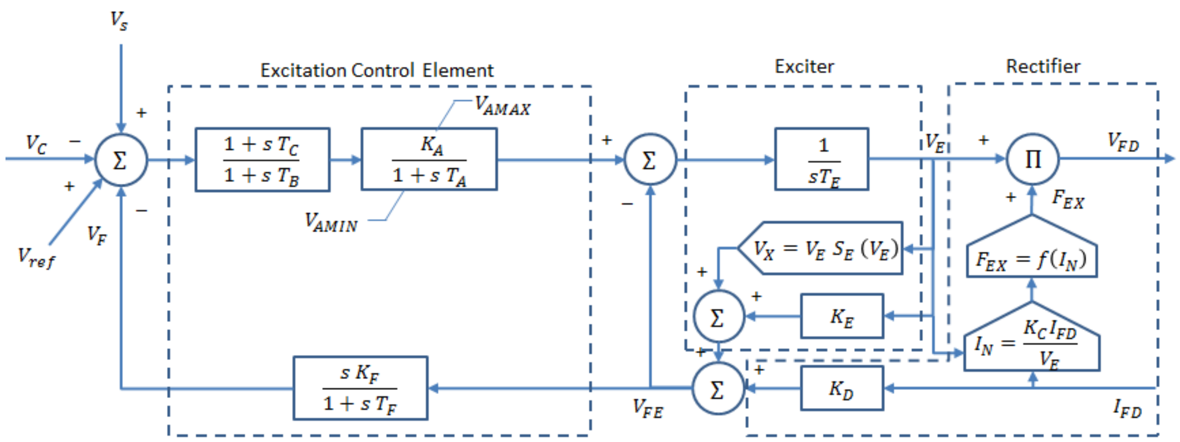

Figure 3.25 IEEE excitation system control for AVR in diesel generators.

As shown in Figure (3.25) the excitation system (IEEE Type AC1) for SG is composed of excitation control system, exciter and uncontrolled rectifier which are essential to accurately represent behaviour of the DG system during grid contingencies or perturbation in power system stabilities. Based on IEEE type AC1, the exciter circuit is an AC machine (Alternator) which provides AC current for rectifier to feed direct current for the generator field. As seen in Figure (3.25) dashed line border representing AC exciter takes into account saturation function ($V_X = V_E S_E(V_E)$) for the exciter model. Also with the regulated model of the rectifier, different operation modes are expressed with$F_{EX} = f(I_N)$. Finally, excitation control loop is devised to ensure voltage at stator terminals is stabilized as disturbances may occur in power system networks. The parameters and values illustrated for IEEE type AC1 excitation system are represented in Appendix A.2.

3.7 Model Validation

As a basis for conducting reliable and effective research studies in power systems, modelling and validation of the power system components are important tasks which have to be addressed during various stages of the research [164]. Thus, in the case of interconnected distribution network and complexities associated with interactions between different control system models, validation of the system is of grave significance for accurate simulation outcomes. In this section the focus is to validate simulation model developed according to dynamic equations derived earlier in section 3.6, which can be utilized to represent overall characteristics of the system. There are two main aspects related to operation of the proposed interconnected distribution network which have to be addressed according to technical requirements for power system supply. The first, aspect is related to the performance of control systems and its autonomous functioning to maintain overall stability of the system under various operation conditions of the DFIG system. For the second aspect transient stability of the model is evaluated for topological changes in interconnected distribution networks when load-generation balance is affected during transition to islanding operation mode. The process of model validation is a time-domain simulation based on mathematical models of each individual power system components which have been developed to preserve the dynamic characteristics of the power system over a wide spanning range of the time-scales [164].

3.7.1. Wind Speed Variation

According to the system description in Section 3.2, interconnection of the DFIG system into distribution network has been introduced as a DER which can generate and deliver electric power from the wind as a renewable source of the energy. However, in real-world scenario the operating condition of the DFIG system is dependent on availability of the wind speed and embedded control strategies devised for DFIG system which has to meet certain technical requirements. Generally, for renewable DERs such as DFIG system, power generation loop is based on maximum extraction of the wind power from wind speed profile where any fluctuation in wind speed leads to variation in operating conditions of the DFIG and changes in power generation. Thus, in order to verify the performance of the DFIG model and effective functionality of its control system, variation of the operation condition and the output power from DFIG system is compared for different wind speeds. The methodology adopted to validate the DFIG model is based on introducing wind speed as the input to the DFIG system where detailed mathematical equations and control loop parameter have been developed earlier in subsection 3.6.1. As determination of wind speed profile is a complicated process entailing highly non-linear three dimensional vectors with random fluctuations in space and time [141], for applications studying system protection and network stability, wind speed data is estimated by an average value over a period of time for an area swept by turbine blades. Thus, to simulate/demonstrate the effects of intermittencies in wind speed and resulting variations in active power output from the DFIG system, a step change in average wind speed from 9m/s to 15m/s is considered as input to validate the performance of control system and identify stable transition of DFIG system under different operating conditions (slips). As seen in Figure 3.26, operation slip of the DFIG system is changing as a result of wind speed variation and in response to maximum wind power extraction control loop in which the operation slip of the DFIG is determined to deliver active power proportional to cube of the average wind speed.

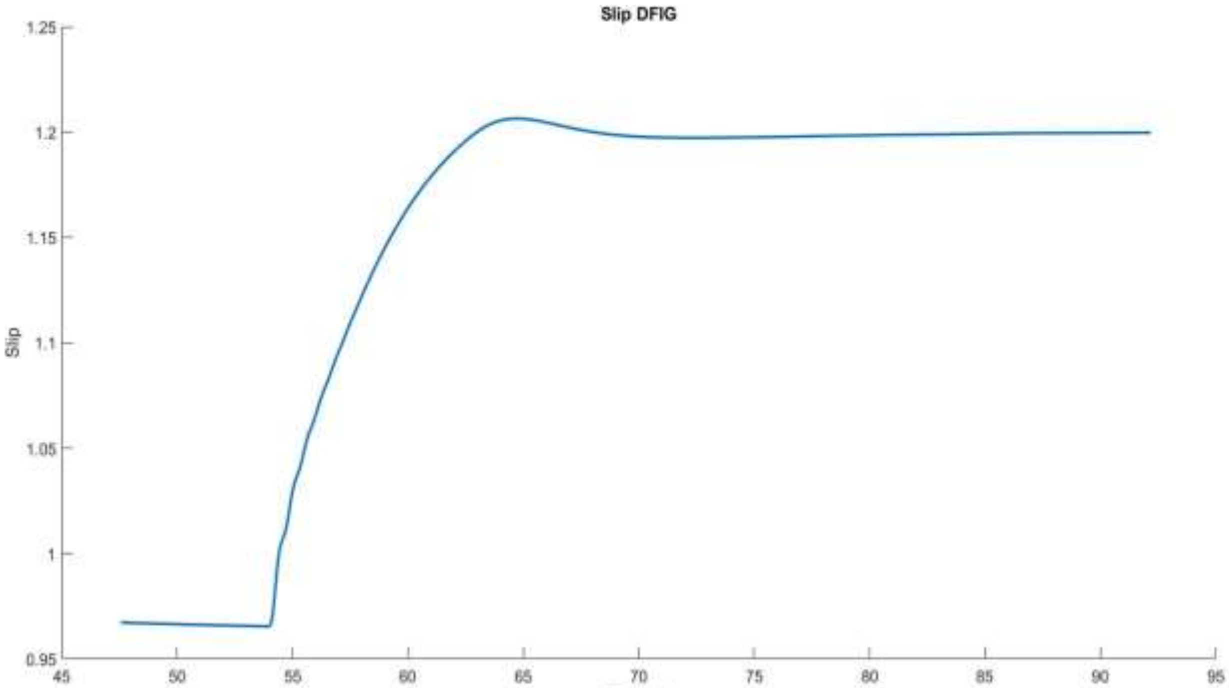

Figure 3.26 Variation of the operation slip with changes in wind speed from 9m/s to 12.5 m/s.

Furthermore, the active power output for DFIG system represented in Figure 3.27 verifies that dynamic stability of the control loop is maintained as it can effectively respond to wind speed variation by reaching to new steady state operation condition, which specifies new load-generation balanced within the interconnected distribution network.

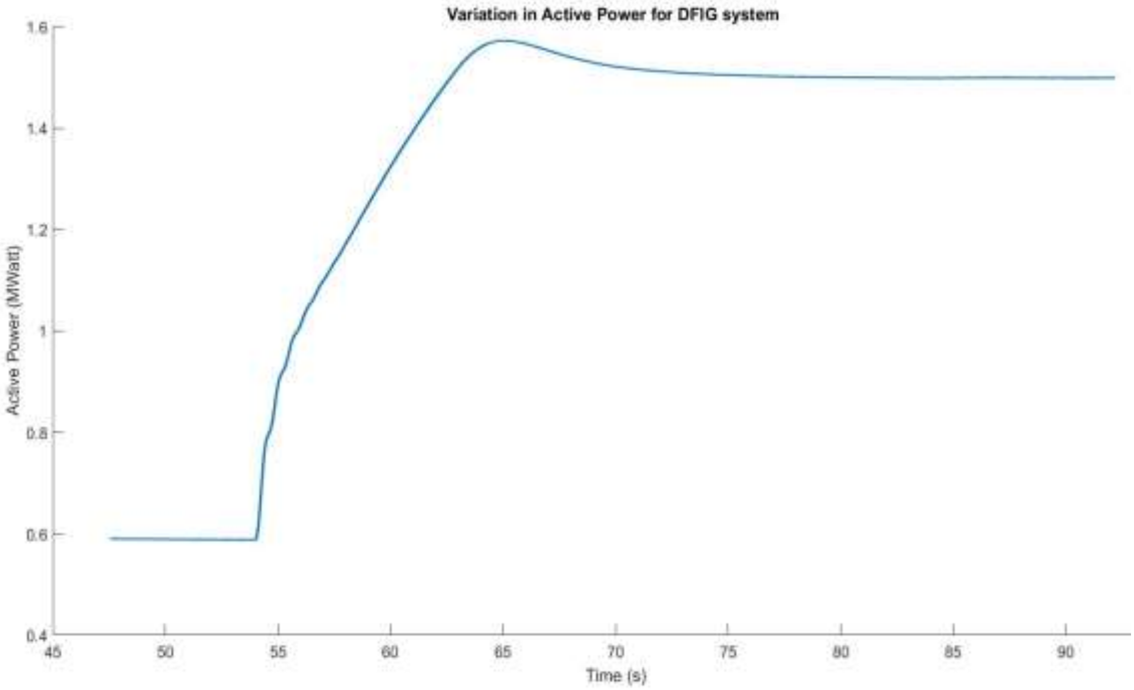

Figure 3.27 Variation in active power generation for DFIG system.

Similarly, to investigate other scenarios corresponding to different penetration of the DERs connected at distribution level, collection of DFIG systems consisting of 3 and 6 DFIG systems connected together have been used to simulate wind farm operation within the distribution network. From simulation point of view, both dynamic response and control loop performance are expected to have similar characteristics within time-domain simulation. However, the output for active power generated by windfarm will be dependent on the number of DFIG systems connected to the distribution network. Finally, validation of the windfarm is realized in time-domain as it is the case for investigation of the fault current behaviour in interconnected distribution networks.

3.7.2. Transition from Grid-Connected to Islanded Mode

For interconnected distribution network, possibility of operation under islanding mode is one of the main advantages of connecting DERs such as DFIG and DG which can improve power quality and reliability of the power supply for consumers at distribution level. However, there are technical issues related to stability of the interconnected distribution network which have to be addressed for successful transition from grid-connected to islanded mode. Therefore, in order to validate the stability for the proposed interconnected distribution model, voltage and frequency stability are two essential requirements which have to be verified for transitioning from grid-connected to islanded mode. According to the topology of the developed distribution network and in order to be consistent for real-world scenario, simulation of the islanded mode is fulfilled by disconnection/opening of the CB of the main grid while DFIG and DG systems are connected to the distribution network. Therefore, the operational characteristics of the islanded section are changed, based on the load-generation balance and the capability of the control systems for maintaining system stability, which is assessed with respect to frequency and voltage stability. In Figure 3.28, frequency stability for transitioning from grid-connected to islanded mode has been illustrated.

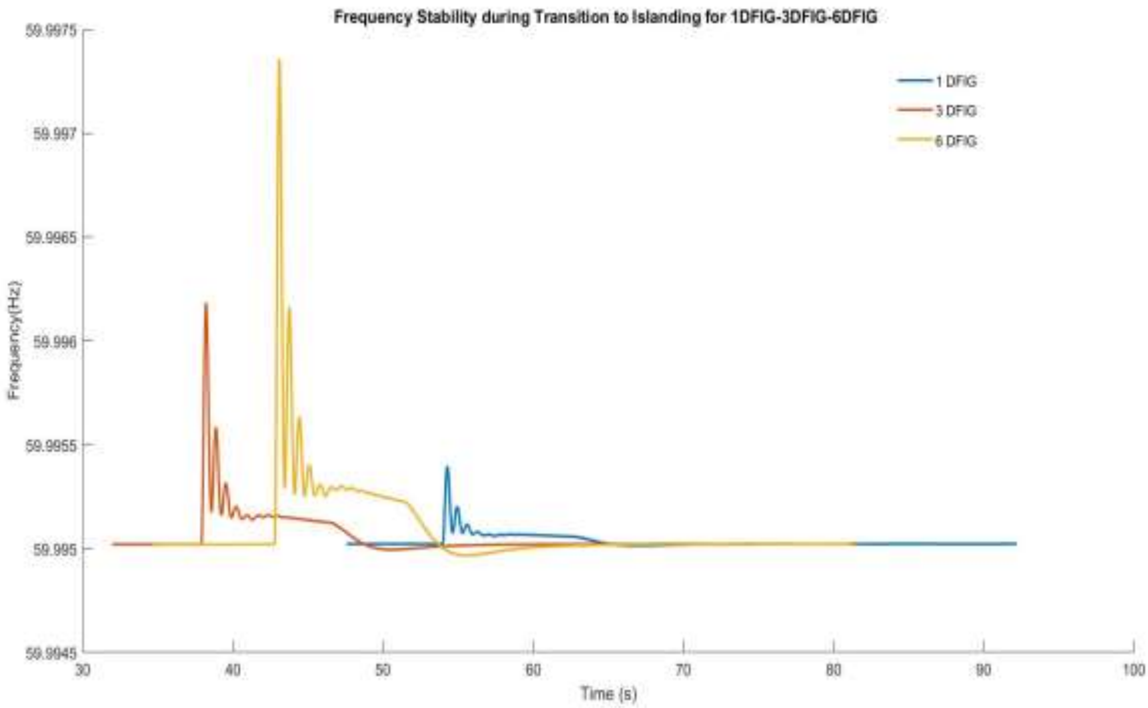

Figure 3.28 Frequency stability during transition from grid-connection to islanded mode.

The three plotted curves in Figure 3.28 are related to three scenarios for different penetration of DERs where the number of DFIG connected at the distribution level varies for the cases of 1, 3 and 6 DFIG systems. As seen in Figure 3.28, the effective functioning of the control system for compensating load-generation balance and the resulted frequency stability can be verified as system frequency is contained within acceptable range under islanded mode operation.

Having shown the frequency stability during transition to islanded mode, maintaining voltage stability is another important criterion for minimizing power quality issues in power system networks with significant penetration of the DERs. As a result of that, flexible operation of the control system integrated into DERs have to be designed to respond quickly and autonomously for any disturbance or changes in operational condition of the interconnected distribution network. In Figure 3.29, variations in voltage during the transition from grid-connected to islanded mode have been illustrated.

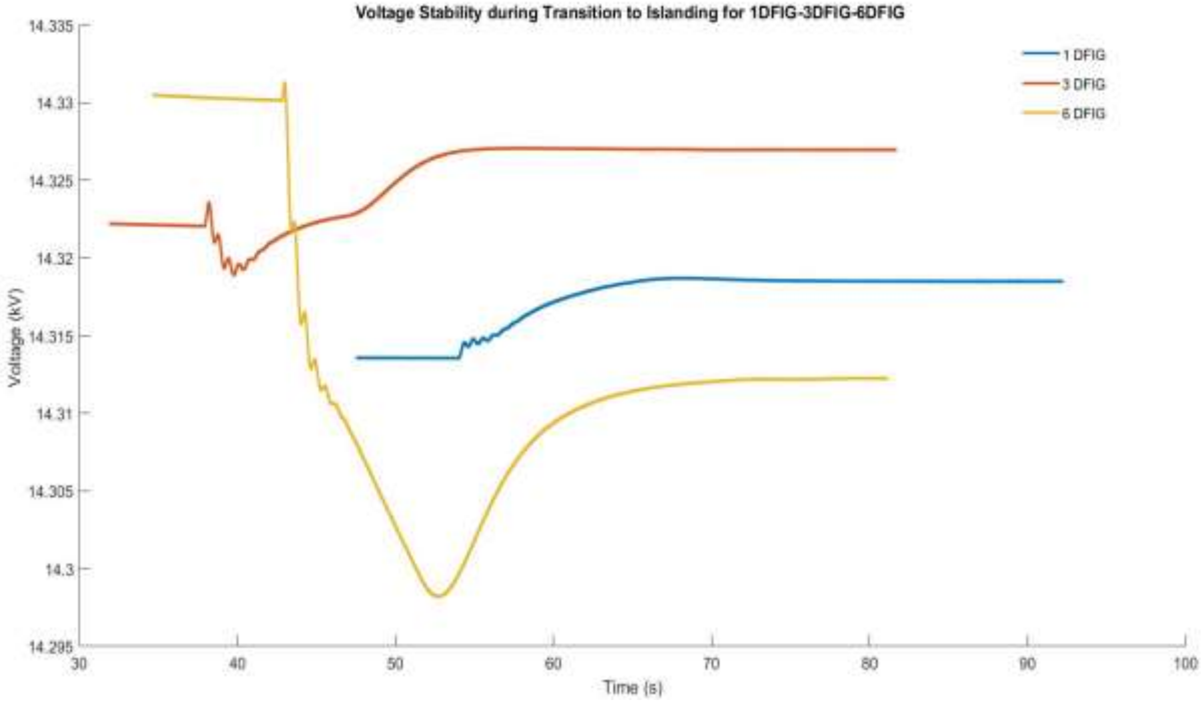

Figure 3.29 Voltage stability for islanding mode operation with different penetration levels.

As show in Figure 3.29, the ability of the control loops for both DFIG and DG system have been proven to smoothly levelled out disturbances in voltage magnitude during islanding transition. Similar to the frequency stability, three curves for different penetration of the DFIG systems have been plotted to compare and illustrate the ability of the control system to meet the desired flexibility for operation of the future power system. In summary, for analysis and study of the interconnected distribution network realizing control systems, which can address power quality issues such as frequency, voltage and harmonics under various operation conditions are essential for verification and validation of the simulation results [165].

3.8 Summary

In this chapter, a detailed time-domain simulation for an interconnected distribution network including DERs such as DFIG and DG systems has been developed in MATLAB/SIMULINK environment. Also, further to mathematical modelling of different elements, technical aspects associated with dynamic stability and configurations for connecting DERs into distribution network have been considered to ensure stability requirement in the power system network under different operation conditions. Topological changes and intermittencies for wind speed in DFIG system were introduced as external inputs to replicate state transitions for operation conditions in the interconnected distribution network under real-world scenarios. Transition from grid-connected and islanded mode is enabled by opening CBs allocated to isolate the distribution network from the main grid while changes in wind speed identified as step inputs to DFIG system dynamic model. Finally, the outcome of this chapter is considered as an essential step towards further investigation on fault current analysis within interconnected distribution network as explained in Chapter 4. Moreover, having developed and established time-domain simulation of distribution network interconnected with DERs, it is critical during the verification and evaluation phase to address system protection performance regarding the proposed protections scheme.

CHAPTER 4

FAULT CURRENT ANALYSIS

In this chapter the main focus is on fault current analysis and investigation on parameters, which affect short circuit current in the interconnected distribution networks. Basically, Chapter 4 has been developed based on journal publication from current research project titled as “fault current characteristics in distribution network interconnected with DFIG”. For distribution networks interconnected with DERs such as DFIG, complexities in fault current calculation and volatility corresponded to intermittent wind speeds are critical to determine reliable and accurate protection settings within the protection system. In fact, given the altering effect of fast response control system and embedded grid code within the DFIG system calculation of fault current is central to overcome the protection challenges within interconnected distribution networks. Therefore, the key aspect of the study in this chapter is reliant on time domain behaviour of the fault current under various operation conditions of DFIG system. Also the interconnected distribution network and dynamic models for DFIG and DG systems developed in Chapter 3 are utilized to conduct the time domain simulation. Initially, conventional approach for designing protection system based on calculation of short circuit current and TOC curve settings within the radial power system network is presented. Furthermore in section 4.2, drawbacks and disadvantages corresponding to conventional methods for calculation of the fault current levels within modern interconnected power systems are discussed. In section 4.3, the proposed methodology for investigation of fault current contribution from DERs is developed where time-domain simulation of a typical distribution network and its interconnection with DFIG systems are simulated. In order to highlight the multifaceted complexities and inaccuracies for determining fault current contribution arising from interconnection of DFIG wind farms, various aspects including penetration level (number of connected DFIG system), varying operating condition of the DFIG systems and fault locations are taken into account. Finally, protection challenges arising from inaccurate protection settings based on conventional methods are explored to highlight resultant false tripping and mis-coordination between the protection IEDs in interconnected distribution network.

4.1 Conventional Protection System Approach

In view of any fault occurrences or disturbances in power system networks, calculation of fault currents at different locations within distribution lines is imperative to select proper equipment and devices. Moreover, taking into account safety aspects both in terms of human personnel and power system equipment, calculation of the fault current is crucial for developing a reliable and effective protection system. In conventional protection system design, there are usually two values for fault current which are calculated as maximum and minimum fault currents. Generally, maximum fault current is used for sizing of the equipment and devices to prevent any damages for a short time while the minimum fault current is determined for coordination between circuit breakers and fuses in the distribution network. The minimum short circuit current usually occurs when faults are at the end of the feeder and line to ground fault and in HV transmission the minimum fault occurs for phase to phase fault. Although, it should be noted that, irrespective of the fault occurred are minimum or maximum, protection systems are devised to isolate the faulty line or section in order to maintain reliability and security of the power system network. As mentioned in Chapter 2, conventional approach has been successful for designing protection system in radial networks, where electrical power flows unidirectional from bulk generation power source to downstream consumer and loads at distribution levels.

In Figure 4.1, utilization of minimum and maximum short circuit currents have been used to devise protection settings for time over current (TOC) characteristic curves in which time-domain transient overload current is compared for detection of any fault in distribution lines. Also, as seen in Figure 4.1, using time-graded response based on maximum and minimum fault currents in TOC protection function allow proper settings to avoid thermal stress in the cable by disconnecting the CBs before the time duration reaches the cable characteristics curve.

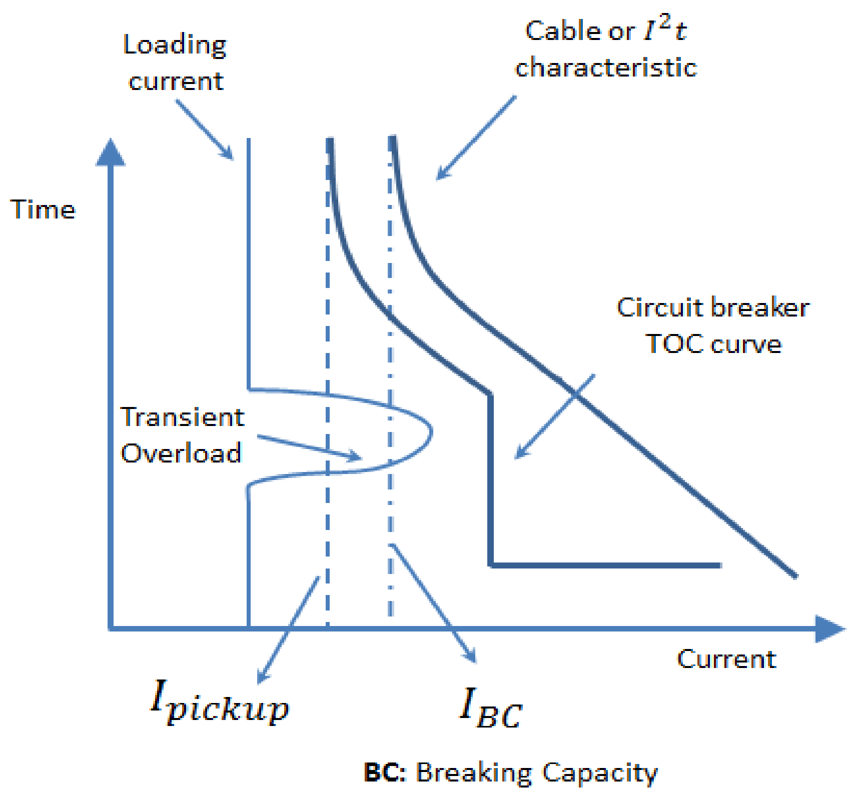

Figure 4.1 Selecting of TOC curves settings considering thermal characteristic curves of the cable.

Thus, considering the importance of accurate calculation of the short circuit current and its direct effect in dependability and security of the system protection, conventional (existing) methods in fault current calculations are discussed in the next section.

4.2 Fault Current Calculation

As discussed, earlier in section 4.1 protection settings and selections of the protection curves are determined based on fault current calculation and sizing of installation for electrical devices at each level of the power system network. Although, accuracy and consistency in calculating the fault current is a crucial factor to establish an effective and reliable protection system, there are certain behaviour which shows more complexities for analysis of the short circuit current due to faster sub-transient and DC component in comparison to transient stability analysis [166]. Hence, aside from fault current calculation, transient behaviour of the fault current is important for fault detection stage. Actually, understanding the standardized approach for calculating the fault current can provide a better insight for the extent and the requirements for fault current studies according to power system modelling. In the literature, three main methods proposed for calculation of the short circuit current for LV and HV networks have been identified as the standardised methods. The methods that are discussed in this section are impedance method, symmetrical components and IEC60909 standard, which basically define certain procedures to determine short circuit current within radial and meshed networks.

4.2.1.1 Impendence Method

Simple Ohm's law equation constitutes the principle of impedance method for calculation of the fault current where all the impedances in the fault loop, the impedance between the fault assumed to be occurred and the source, both resistance and reactance are separately added. Although, for impedance approach, all the characteristics of the distribution lines and components have to be known, it is usually used as accurate and simple solution for calculation of the short circuit currents at any point in the power system network. However, there are a number of assumptions such as constant voltage at the generation source for the entire duration of the fault and also line capacitance and load currents are neglected which can impose limits on the validity of the results. In Figure 4.2, graphical representation for a simple circuit associated with each fault type within the impedance method has been illustrated. As shown in Figure 4.2 calculation of the short circuit current for different fault type which is equivalent to current passes through impedance identified as short circuit impedance (Z_{SC}) and the voltage series with the impedance represented $\frac{U}{\sqrt{3}}$ known as line voltage. From the formula using equivalent circuits in impedance method, the maximum short circuit current is associated to 3-phas fault which is critical for selection of the equipment in the protection system.

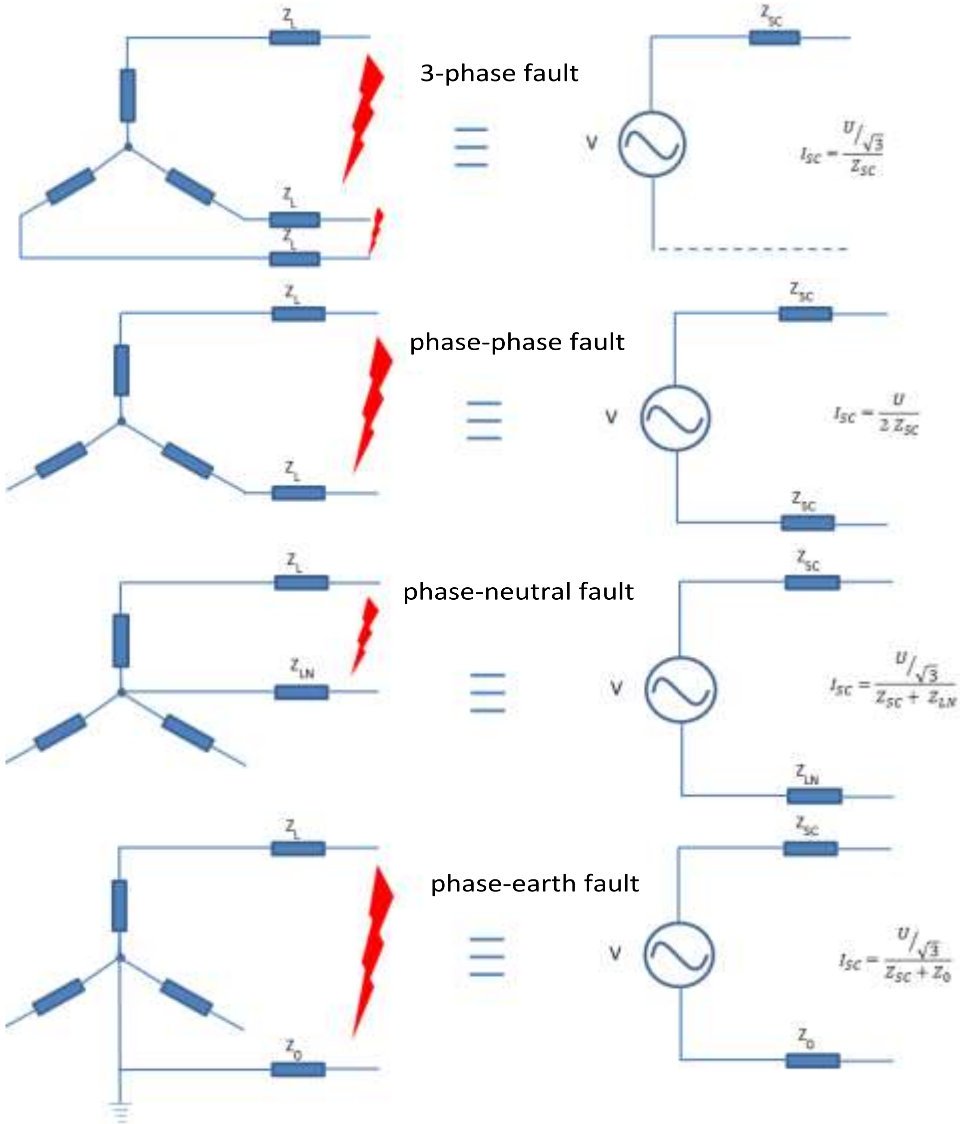

Figure 4.2 Representation of equivalent circuit for different fault types in impedance method.

Although there are other methods such as composition method and conventional method which adopt the same concept as impedance method in which to avoid unknown characteristics for power supply, power lines upstream impedance is estimated on the basis of short circuit at its origin. Despite its effectiveness in calculating fault current within radial and meshed topologies in LV and HV networks, impedance method does not take into account the fast response of the DER controllers as the voltages and currents at the terminals of the DER can vary during the fault period of the line. In addition, the impedance method does not take into account any changes due to variation in the fault conditions or prevailing changes in operation condition of the power system networks.

4.2.1.2 Symmetrical Component

The principle of symmetrical component analysis is based on resolving unbalanced phasor system into sets of three independent balanced phasors which can simplify the analysis of power system under unbalanced fault conditions. According to Fortescue's methodology, there are 3 sets of independent phasor systems called positive, negative and zero sequence components where any unbalanced 3-phase voltage or current phasors can be expressed as linear combination of the symmetrical components. Thus, calculation of fault current for unsymmetrical faults such as single phase to ground, two phases to ground or even open conductors are obtained by transformation into symmetrical component domain and once the system is solved in symmetrical component domain, the results can be transformed to the original phase domain. In Figure 4.3, three independent positive, negative and zero sequence phasor systems have been illustrated.

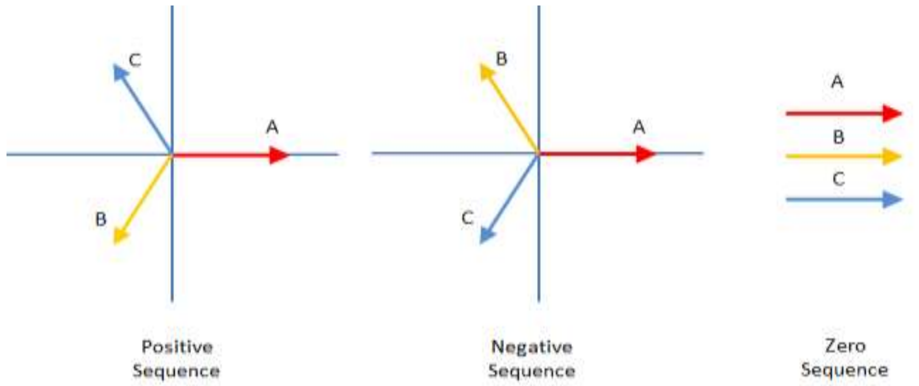

Figure 4.3 Positive, Negative and Zero sequence phasors in symmetrical component analysis.

Hence, utilizing the transformation of 3-phase system into symmetrical components domain, the analysis of power system under unbalanced fault conditions can be simplified into three independent sequence networks interconnected at the fault location. However, the key to apply and calculate the sequence networks has to be formulated and interconnected based on fault types and configuration of the 3-phase components as Y grounded or not grounded. To avoid unnecessary details for connection of the sequence networks for each fault types, various fault types and their corresponding sequence networks have been illustrated in reference [160].

4.2.1.3 IEC60909 Standard

The IEC60909 standard is a European standard which was intended to reduce the complexities in calculation of the fault current for both radial and meshed networks of 50kV. In the conventional method where short circuit current is mainly calculated based on the assumption of dead short circuit, the effects of various factors such as contact resistances, conductor temperature and the like can compromise the accuracy for the short circuit current. Thus, due to complexities and computational inaccuracies, by taking into account all the influences in calculation of the short circuit current, the IEC60909 standard has introduced special factor C which puts together both calculation methods and practical consideration to determine the fault current within the power system network [167]. In fact, according to fault calculation procedure in IEC60909 standard, there are different factors and conditions such as voltage level, distance from generator etc. which have to be taken into account using tabulated data provided in the standard. Factors and tabulated data for different parameters in IEC60909 standard have been attached in the Appendix B.1and B.2. Although the conventional approach for fault current analysis is not accurate or sometime not possible to apply within the new paradigm of the bidirectional power flow at the distribution level, there are some basic understanding and terms that need to be adopted, which can be used as an essential requirement for protection of the power system components.

4.3 Fault Current Analysis

From technical point of view, calculation of the fault current level and its contribution at fault locations is central for devising an optimal and reliable protection system. However, according to literature, interconnection of DERs can introduce complexities in determining fault current levels and altering fault current contributions depending on different operation parameters [168-171]. Moreover, introduction of different technical factors such as grid codes [172] and sizing [173] of the DERs can further complicate the calculation of fault current level using conventional methods as explained earlier. Thus, in order to highlight some of the aspects related to fault current characteristics and variation of fault current contributions in the interconnected distribution network as developed in Chapter 3, time-domain simulation results for different operating scenarios have been investigated. The main approach for taking into account contribution of the short circuit current during any grid contingencies is through simulation and integration of the fast responses control loops in DERs which can affect fault current contribution from the DER systems. Moreover, in the case of DFIG systems, embedding control loops can further accurately capture the operation condition of the DER system in real-world operation scenario. In the following, various parameters such as penetration of the DFIGs, operating condition and fault locations, which are expected to have impacts on the fault current behaviour are compared and investigated by using bar graph data and time domain simulation plots.

4.3.1. Penetration Level

Interconnection of DERs into distribution networks are encouraged by many System Operators (SO) and energy market players as an efficient and clean electricity power in a competitive power supply industry. However, challenges associated with hosting capacity and system protection issues are becoming the main drawbacks for interconnection of higher penetration of DERs into distribution networks. For interconnected distribution network during the planning and design phase, the main parameters such as type, size and ratings are considered for connecting DERs into distribution networks [173]. However, from protection system perspectives, analysis for variation in fault current capacity and selecting proper protection settings are significant for reliability and security of the system operation. In fact, wind turbines such as DFIG systems are installed collectively in wind farms and connected to the grid through the PCC, where generated power from wind turbines is delivered to the grid. Thus, taking into account real-world scenario for interconnecting DFIG systems, analysis and investigation of the fault current contribution during fault occurrences is imperative for developing a reliable and secure protection system within interconnected distribution network. In this section, interconnection of different numbers of DFIG system into distribution network as discussed in Chapter 3 is studied to highlight potential challenges to protection system arising from higher penetration of the DFIG systems. To compare devised scenarios, 3 different penetration levels for connecting DFIG system into distribution system have been considered where loading currents at certain locations (CBs) are plotted in bar graph against available DFIG system connected to the network. In Figure 4.4, comparison between different scenarios for connecting DFIG system into distribution network developed in Chapter 3 has been illustrated. As shown in Figure 4.4, the horizontal axis represents number of DFIG system connected into distribution network while the vertical axis shows loading current at certain CB locations. It is obvious from the bar graph plot that by increasing the number of DFIG wind turbines connected to the distribution network (horizontal axis) to 3 and 6 which are contributing to power generation through their connection points (CB_{DFIG}), variation in loading current represented at vertical axis can be prevailed to other CB locations such as CB_3 and CB_{main}. As a consequence of that, it is important in protection system to take into account the availability of the DFIG wind turbines or number of DFIG system which are connected to the grid, so the protection settings can be adjusted accordingly to avoid false-tripping or blinding issues arising from inaccurate pickup current level settings.

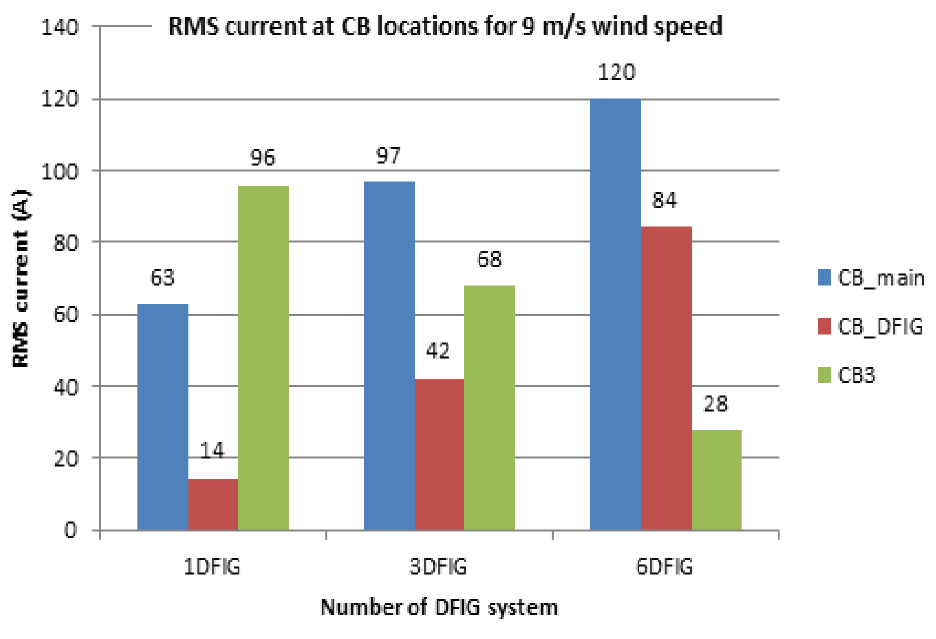

Figure 4.4 Loading current compared at CB locations for different number of DFIG.

Aside from variation in loading current level, which is mainly concerned with steady state operating condition of the DFIG systems interconnected to distribution network, the effects of higher penetration of DFIG system can increase the maximum fault current contributions within the distribution network. In order to investigate the impact of DFIG connections on fault current behaviour, time domain responses of DFIG fault currents for a down-stream 3-phase to ground fault have been plotted in Figure 4.5. As shown in Figure 4.5, the blue dashed curve represents fault current contribution for 1 DFIG connected through CB_{DFIG} , also the yellow curve corresponds to for 3 DFIGs connection. Therefore, according to Figure 4.5, with higher penetration of the DFIG system not only fault current level will increase, more conservative design approach for ratings of the CBs and protection equipment are necessary due to increase in the maximum fault current peak seen by each CBs in the distribution network.

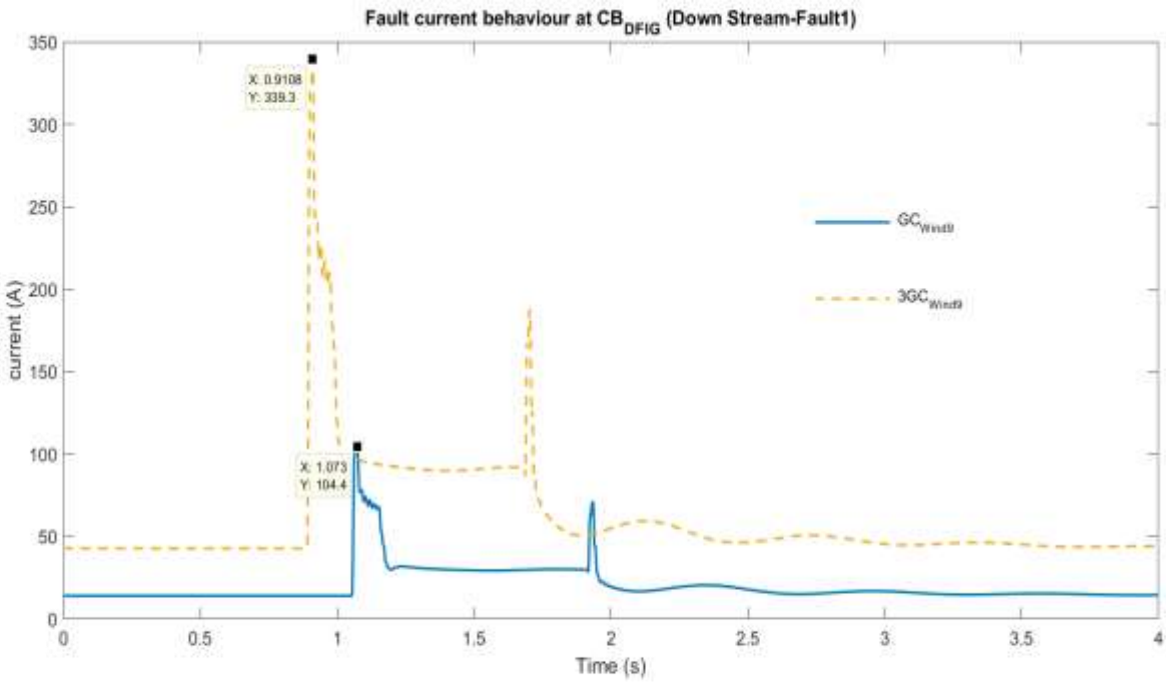

Figure 4.5 Variation of 3-phase fault current for different numbers of DFIG system.

Finally, it is worth mentioning that the aforementioned conditions are all valid for the minimum wind speed of the DFIG system which is 9 m/s. However, in the case of variation of the wind speed to the maximum allowable/safe operation, further investigation on effective parameters on fault current contribution has to be conducted. In the next section, the impact of the operation conditions and potential challenges are discussed.

4.3.2. Operation Conditions

For designing and development of protection system in interconnected distribution networks, there are technical and operational aspects related to DERs which have to be taken into account to ensure reliable and safe integration of the DERs. In the case of connecting DFIG system into distribution network, certain parameters corresponding to operation condition of the DFIG and its control system can introduce technical complexities in devising accurate protection settings within the interconnected distribution network. One of the important characteristics for operation of DFIG system is related to intermittency of wind energy and the embedded control system adjusting DFIG output power according to the presumed control strategies. This in turn can introduce volatilities into operating condition of the distribution network where protection settings are typically determined for specific steady-state loading condition. In fact, protection challenges arise in interconnected distribution network due to operational characteristics of the DFIG system and dynamical interactions piloted through embedded control systems for DFIG system. Therefore, in order to address potential challenges arising from interconnection of DERs, adopting a proper methodology to study and investigate interaction between DERs and distribution network is imperative. In the following, various scenarios for different operating conditions of the DFIG system have been investigated and compared to highlight potential challenges in protection settings within the interconnected distribution networks.

4.3.2.1 Embedded Control System

Generally, the control strategy adopted for DFIG system is based on extraction of maximum power from the wind stream as the electrical torque developed in rotor air-gap is adjusted to track aerodynamic torque produced through interaction between turbine blades and wind speed profile. In equation (4.1), extraction of wind power corresponding to specific wind speed has been expressed as a function of aerodynamic characteristics of the turbine blades.

$$\mathbf{P_{Wind\ Extracted}=0.5\ \rho_{air}\ A_{Turbine}\ V^{3}_{wind\ speed}\ C_{p}} \qquad \textbf{Equation 4.1}$$

As it is obvious from equation 4.1, wind speed is the main input variable driving the intermittencies in power generation from DFIG system. Also, the power coefficient (C_P) is a function of the blades pitch angle and tip-speed ratio which represents the operating condition of DFIG system adjusted by DFIG control loops. Thus according to equation 4.1, a PI controller embedded in DFIG system is devised to regulate the electrical torque to extract the maximum power from the wind speed [136]. The aforementioned control strategy is called Maximum Power Point Tracking (MPPT) and is implemented for normal operating condition of the DFIG system. However, the maximum extracted power varies proportional to wind speed cube leading to power flow fluctuation at the PCC prevailed into distribution network. In Figure 4.6, MPPT curve is highlighted with blue solid line connecting the maximum points for each power curves in different wind speed conditions. The horizontal axis in Figure 4.6 is the tip-speed ratio which represents the aerodynamic operation condition for DFIG turbine blades and the vertical axis specifies aerodynamic power extracted from the wind stream depending on the aerodynamic operation condition.

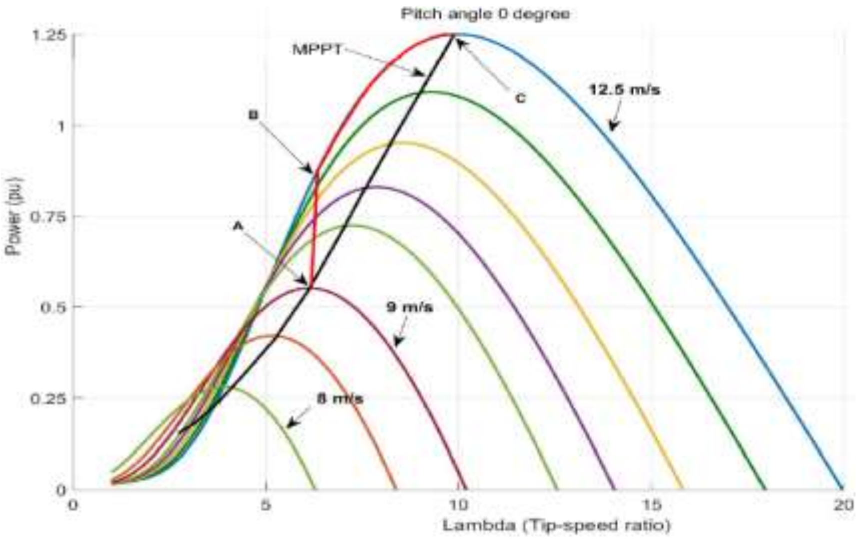

Figure 4.6 MPPT curve embedded into DFIG system control loops.

As shown in Figure 4.6, under MPPT control strategy with any variation in wind speed DFIG control system select a new aerodynamic power curve transitioning from point A to point B and adjust the electrical torque in DFIG to arrive at point C with tip-speed ratio of the maximum power extractions. Consequently, applying MPPT approach for DFIG systems interconnected into distribution network can have an impact in power generation capacity delivered by DFIG wind turbines. With the maximum power extracted by DFIG system being proportional to the cube of wind speed, the effect of variation in wind speed can impact power flow balances and accordingly introduce complexities in devising protection system settings. In Figure 4.7, the effect of variation in power generation capacity of the DFIG system have been plotted in terms of RMS values of the current injected into distribution network through PCC connection.

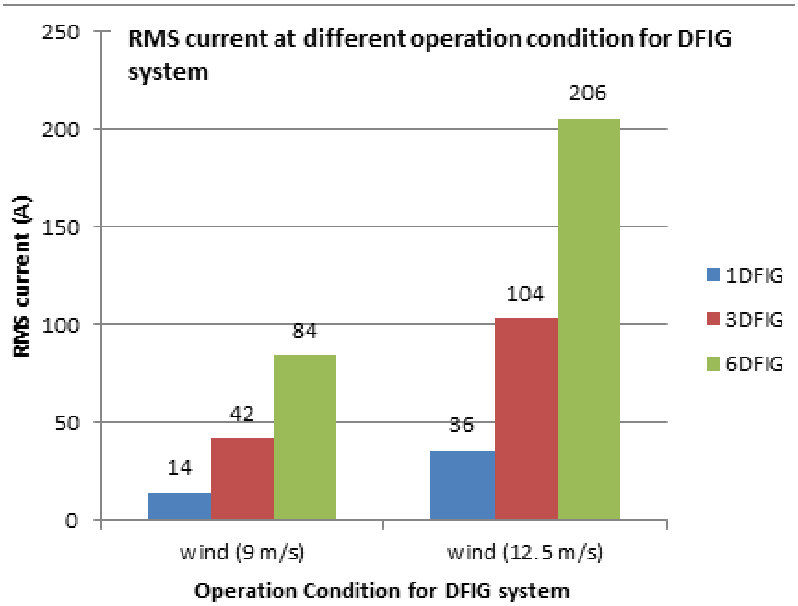

Figure 4.7 Variation in loading current for DFIG system under different operation condition.

The horizontal axis in Figure 4.7 represents the minimum and maximum limits in wind speed variations at the location of wind farm, which also has a number of DFIG systems connected into the network. Also, in vertical axis the RMS values for the current injected into distribution network under various operation scenarios has been shown. It is obvious from Figure 4.7 that in devising protection settings under different operating condition for DFIG wind farm, calculations of the minimum and maximum fault current have to be updated according to available capacity of the wind power extracted through DFIG control systems. Nevertheless, in addition to MPPT control strategy, there are certain control measures enforced by SOs, as grid codes for embedding into DFIG control systems to ensure reliability and security of interconnecting DERs into distribution networks. In the case of DFIG system, Fault Ride Through (FRT) capability has been incorporated through modification in WRIM structure with crowbar circuit and control mechanism which enable DFIG system to stay connected for certain period of suppressed voltage or grid contingencies. Thus, simultaneously taking into account the effect of wind speed and quick response of FRT control mechanism during any fault occurrences, calculation of the fault current contribution from DFIG system using conventional approach cannot be viable. As a matter of fact, the need for time domain simulation to address the complexities corresponding to fault current behaviour in DFIG system arises due to unpredictable reaction of the FRT mechanism during grid contingencies. Figure 4.8 presents time domain response of the DFIG fault current for downstream 3-phase fault with various wind speed. As shown in Figure 4.8, devising reliable protection settings to accommodate all the scenarios for fault current contribution from DFIG system interconnected into distribution network is reliant on adaptive protection settings.

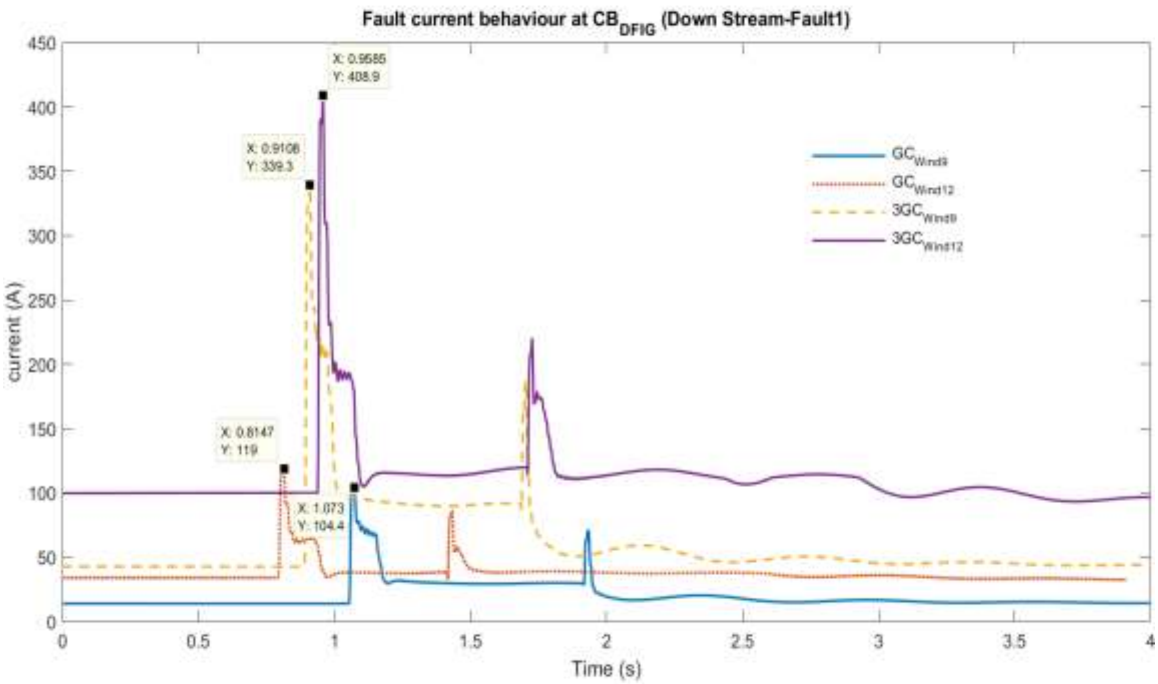

Figure 4.8 Fault current contribution in DFIG system for different slips at downstream fault.

The legends GC_{wind9}, GC_{wind12} , $3GC_{wind9}$ and 3 GC_{wind12} in Figure 4.8 stands for Grid-Connected (GC) and the number represent number of DFIG system connected into distribution network. Also the subscript 'wind9' or 'wind12' specifies wind speed as DFIG system operation condition. Finally, it is obvious from Figure 4.8 that protection settings have to be adjusted with respect to the operation condition of the DFIG system in order to detect fault and isolate the fault.

4.3.3. Grid-Connected Versus Islanded Mode

For interconnected distribution network, the main source for supplying electric power is the grid side, where the voltage and frequency of DERs stay synchronized during grid-connected operation mode. However, the advantage of having DERs such as DFIG and DG connected into distribution network is utilized to independently supply local loads during the loss of grid-connection scenarios. Generally, there are technical aspects related to local control systems for stable transition to islanded mode, which has to be considered during planning stage in connecting DER into distribution network. In the proposed scenario for interconnected distribution network, the issue of voltage and frequency stability during transitions for different operating conditions have been already validated in Chapter 3. Hence, the focus in this section is mainly concerned with fault current behaviour and adopting reliable protection settings for both grid-connected and Islanded mode of the operations.

Compared to previous scenarios, investigating fault current contribution for higher penetration and wind speed intermittencies in DFIG system, topological changes in interconnected distribution network can introduce significant impacts on system characteristics depending on different factors such as size of DERs, types of DERs and how power flow between the grid side and local DERs are managed. In order to understand the nature of transition occurring from grid-connected to islanded mode and taking into account its effect on loading currents at specific CB locations within islanded part of the network, Figure 4.9 compares variations in loading current for grid-connected and islanded mode operation. In Figure 4.9, the horizontal axis represents the number of the DFIG system connected during the transition from grid-connected to islanded mode; also the vertical axis is the RMS values correspond to the loading current at CB3 location. Although RMS values at CB3 location for different number of DFIG connected to the grid are varied according to load-generation balance, compared to the islanded mode the differences between the loading currents are negligible in the case of devising protection settings for TOC protection function at CB3. This reflects specific characteristics of the system planned for load-generation balance within islanded side, which can be affected with the changes in the size and type of DERs. Thus, it is worth mentioning that despite the negligible changes in loading currents between grid-connected and islanded mode of operation, topological changes for the interconnected distribution network can affect loading current which in turn prompt inaccurate setting from conventional protection approach. Therefore, there are some constraints for islanded mode operation applied during the planning phase to maintain certain load-generation balance within local islanded system.

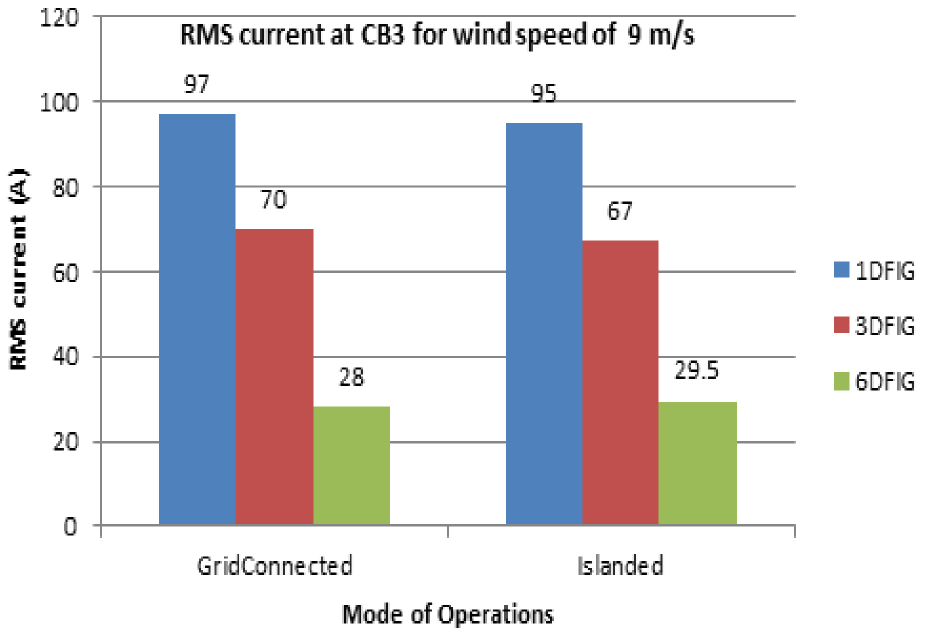

Figure 4.9 Loading current compared at CB3 under grid-connected and islanded mode.

Despite the changes in load-generation balance, which can affect loading current at tie-connections such as CB3, transitioning to islanded mode can introduce major drawback in protection system reliability by altering fault current behaviour (unsustained fault current contribution) from local generation sources such as DFIG system. Technically, compared to grid-connected mode, islanding operation characterizes low inertia with faster (frequency) dynamic response to any disturbances in the distribution network (unsustained fault current contribution). Compared to grid-connected mode where large synchronous generators with high mass inertia can slow down the natural reaction of the system in the case of contingencies and provide some respite to allow the controllers or ancillary schemes to take action, avoiding instability in the system. Thus, devising a fast and reliable protection system is inevitable to utilize the aforementioned advantages of the islanding mode operation as discussed in the literature. In order to highlight the effect of the islanded mode of operation, Figure 4.10 shows the time domain response of the fault current for two modes of operation Grid-Connected/Islanded, which has been listed for a 3-phase to ground fault applied downstream of the DFIG system (F1). From Figure 4.10, fault current behaviours under grid-connected mode can supply higher fault current level and that is independent of the operation condition of the DFIG systems as the fault is applied downstream to DFIG system. In addition to that and under similar 3-phase to ground fault scenario, fault current behaviour in islanded mode of operation is clearly differs from the grid-connected mode, which are highlighted in different colours for time domain plot curves.

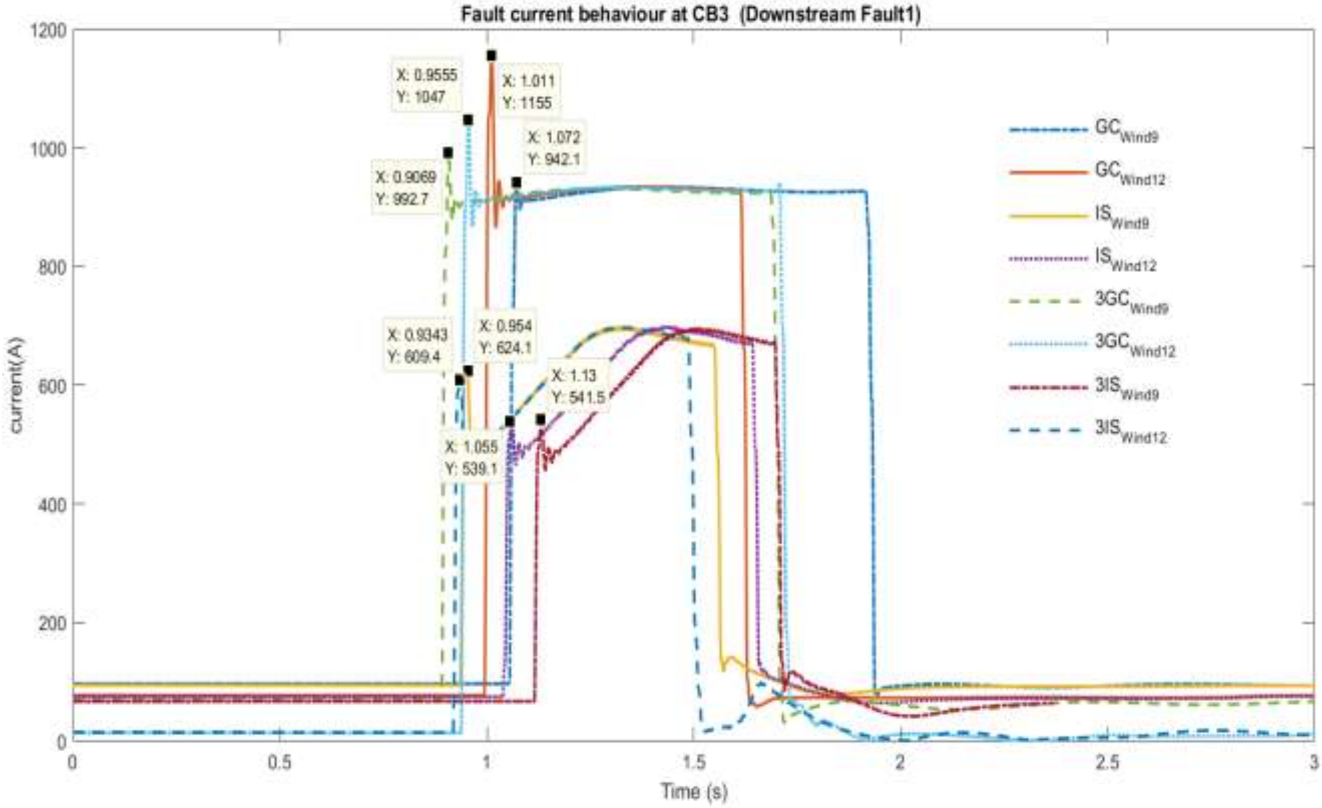

Figure 4.10 Comparing fault current contribution at CB3 for grid-connected and islanded mode.

One important aspect that can be highlighted for fault current behaviour during islanded mode operation is the effect of fast response control system which has been embedded in DERs control system to meet grid codes. As it is seen in Figure 4.10, for islanded mode operation the maximum fault current during the period of fault occurs after multiple cycles from the time that fault is initiated. But under Grid-Connected mode the maximum fault current occurs at the early stage (within 2 cycles) of the fault duration. In fact, this can be interpreted due to changes in characteristics of the islanded system and its control strategies from system stability perspectives. In the aforementioned scenario the RMS value for fault current at CB3 location does not show any impact on the DFIG operating conditions such as availability of the wind speed because of the location of the fault which is applied downstream to DFIG system. Although in the case of fault in upstream at CB2 location or the main grid, the fault current seen at CB3 under islanded mode operation can be affected, depending on different parameters such as operating condition of the DFIG system, which can further complicate calculation of the protection settings.

Consequently, given the above discussion on complexities and volatilities for fault current behaviour and measured values at different CB locations, it is obvious that consequences of using fixed settings for protection system within distribution network interconnected with DERs such as

DFIG and DG can lead to mis-coordination and blinding of the protection IEDs in detection and isolating faulty section of the distribution line.

4.3.4. Fault Location

In interconnected distribution networks, due to availability of multiple generation sources, fault current behaviour is highly directional, which adds more complexities to establish a reliable and dependable protection settings for each protection CB. Traditionally, conventional radial distribution networks are developed for single power generation source delivering electrical power upstream from bulk power generation plants to downstream loads via transmission and distribution networks. However, by interconnecting DERs the aforementioned unidirectional power flow paradigm does not hold, as local generation sources upstream and downstream of the fault location can feed the faulty section of the line. Thus, in order to investigate fault current behaviour for different fault scenarios, Figure 4.11 illustrates the locations of 3-phase to ground faults representing possible fault locations upstream (Fault1), downstream (Fault2), direct path (Fault3) and grid side fault (Fault4) referenced to tie-line CBs (CB3). As shown in Figure 4.11, with the presence of any fault at the highlighted locations, there are always three power sources that can feed the fault location through distribution lines, which in turn cause fault currents measured at CB3 vary depending on the fault at different locations. Therefore, having several paths toward the fault location with protective equipment which are supposed to respond to the fault within possible minimum shut down of the power sources, selectivity of the protection system can be affected.

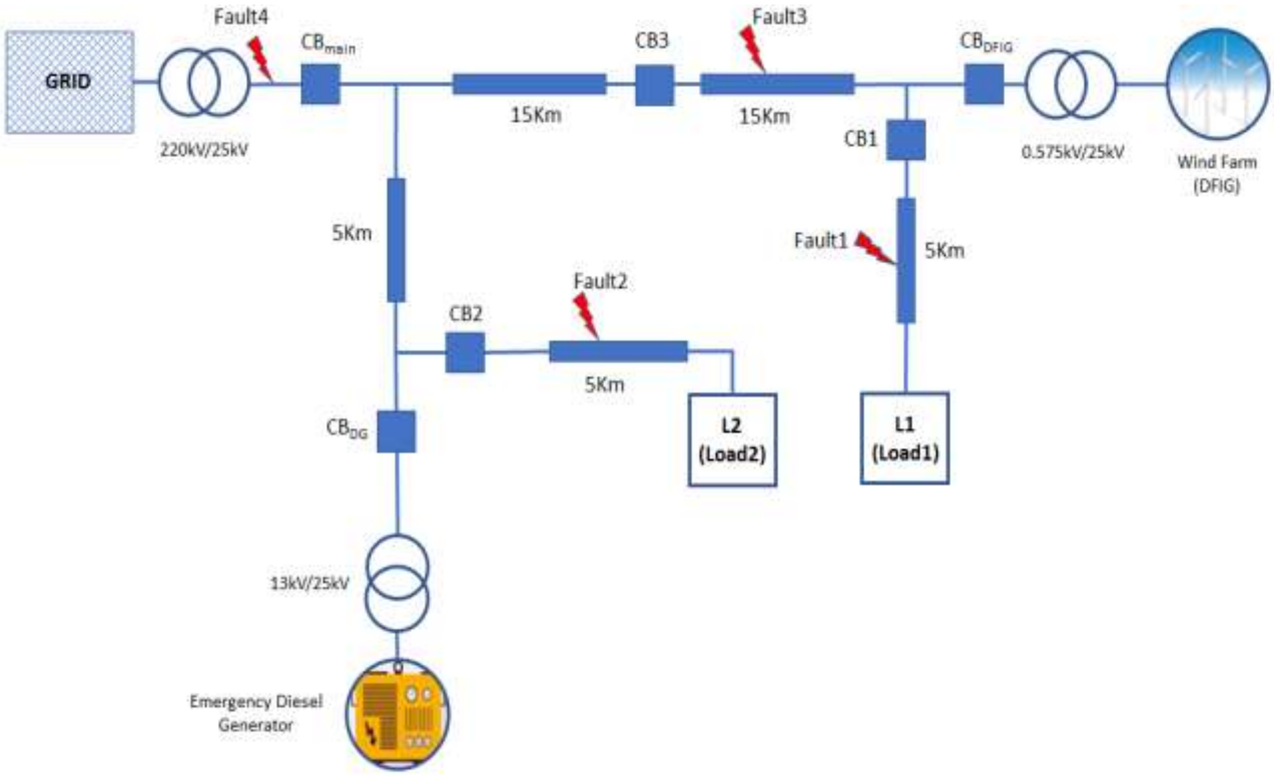

Figure 4.11 Fault scenarios for the proposed interconnected distribution network.

In the presence of the fault current of varying magnitude and to achieve proper investigation for protection system settings, time domain simulation plays a critical role to capture time varying characteristics of the fault currents. In Figure 4.12, time domain representation of the fault current at CB3 location have been illustrated for 3-phase to ground fault scenarios as discussed earlier in this section. As shown in Figure 4.12, fault current at CB3 varies depending on the fault locations, where the maximum fault current level is corresponds to downstream fault at Fault1 as grid side of the distribution network feed the fault through tie-line protected by CB3. Furthermore, the minimum fault current is related to fault at upstream of CB3 as the fault current from DFIG system is fed through CB3.

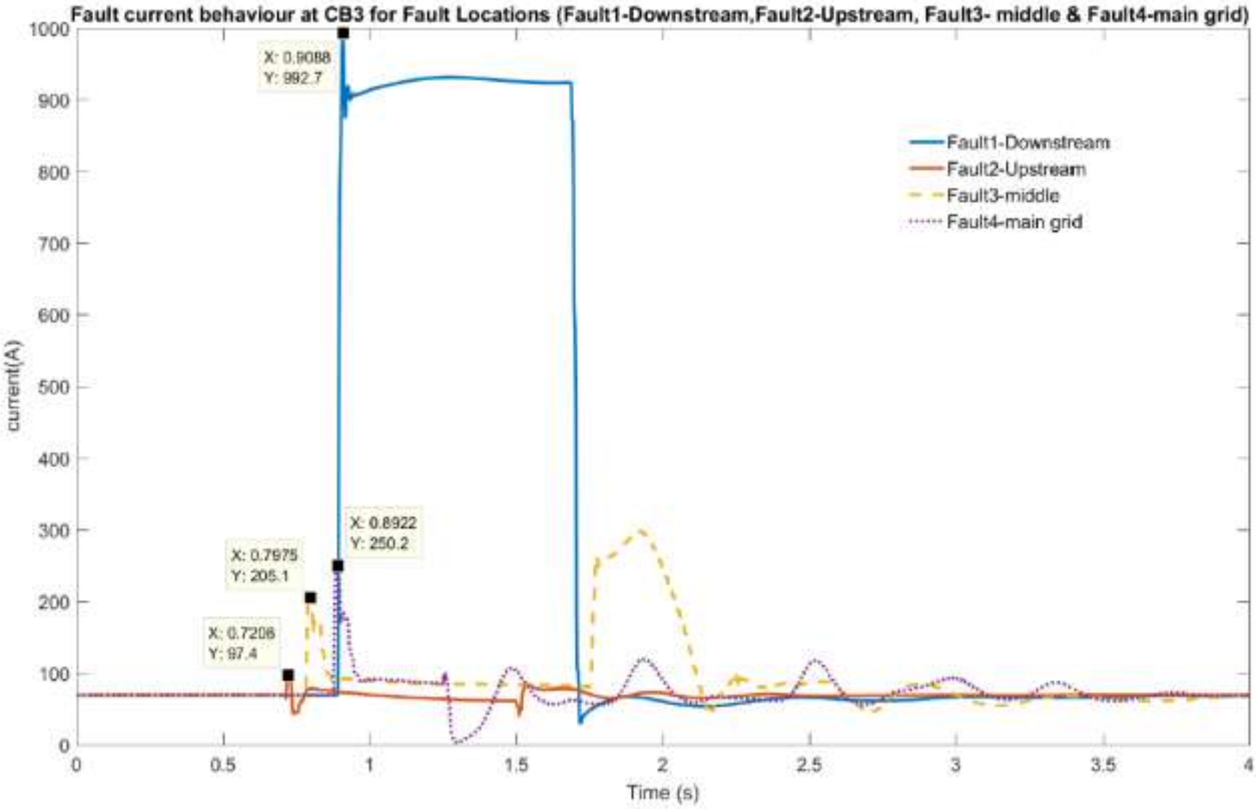

Figure 4.12 Variation in fault current level at CB3 considering to fault locations.

So far time domain simulation plots have been used to investigate fault current behaviour and parameters which can alter fault current contribution under different operation conditions within interconnected network. However, compared to conventional methods for fault current calculation representation of detailed time domain behaviour of the fault current is critical to highlight and identify drawbacks for conventional protection schemes in dealing with reliable protection settings within distribution networks interconnected with DERs such as DFIG. Thus, by considering Over Current (OC) protection scheme (mainly used due to simplicity for configuring protection settings and cost effectiveness) for protection system in distribution network, time-domain plots for the IEC TOC curve and fault current at CB3 location are compared for different fault scenarios. Figure 4.13 and Figure 4.14 compare TOC curves [17] and time domain response of the fault currents for different fault locations in the interconnected distribution network. In Figure 4.13 two different IEC very inverse TOC curves represent OC protection scheme at CB3 which are designed for Grid-Connected operation mode and 3 DFIG wind turbine are connected to the grid. The pickup values for the IEC curves are associated to two different wind speeds (9 m/s and 12 m/s) which specify by labels $3DFIG_{wind9}$ IEC_{curve} and $3DFIG_{wind12}$ IEC_{curve} respectively. Also time domain curves for the fault currents at CB3 are associated with fault locations and operation condition of the DFIG system with different wind speeds. In Figure 3.14 fault current curves $3GC_{wind9}$ Fault3 and $3GC_{wind12}$ Fault3 identify fault current curve for Fault3 under Grid-Connected operation with 3DFIG system and wind speeds of 9m/s and 12 m/s. In similar way the curve labels can be interpreted for fault scenario at Fault4.It is obvious from Figure 4.13, the IEC curve devised for operation condition where wind speed is high (12 m/s) can quickly detect and isolate the faults for both Fault3 and Fault4 while operation condition (different wind speeds) of the DFIG system is not critical however for the IEC curve where the wind speed is low (9m/s) none of the faults (Fault3 and Fault4) are detected. The aforementioned operational logic for OC protection scheme can be embedded as the system knowledge to facilitate reliable selection of the protection settings with respect to operation condition of the interconnected distribution network.

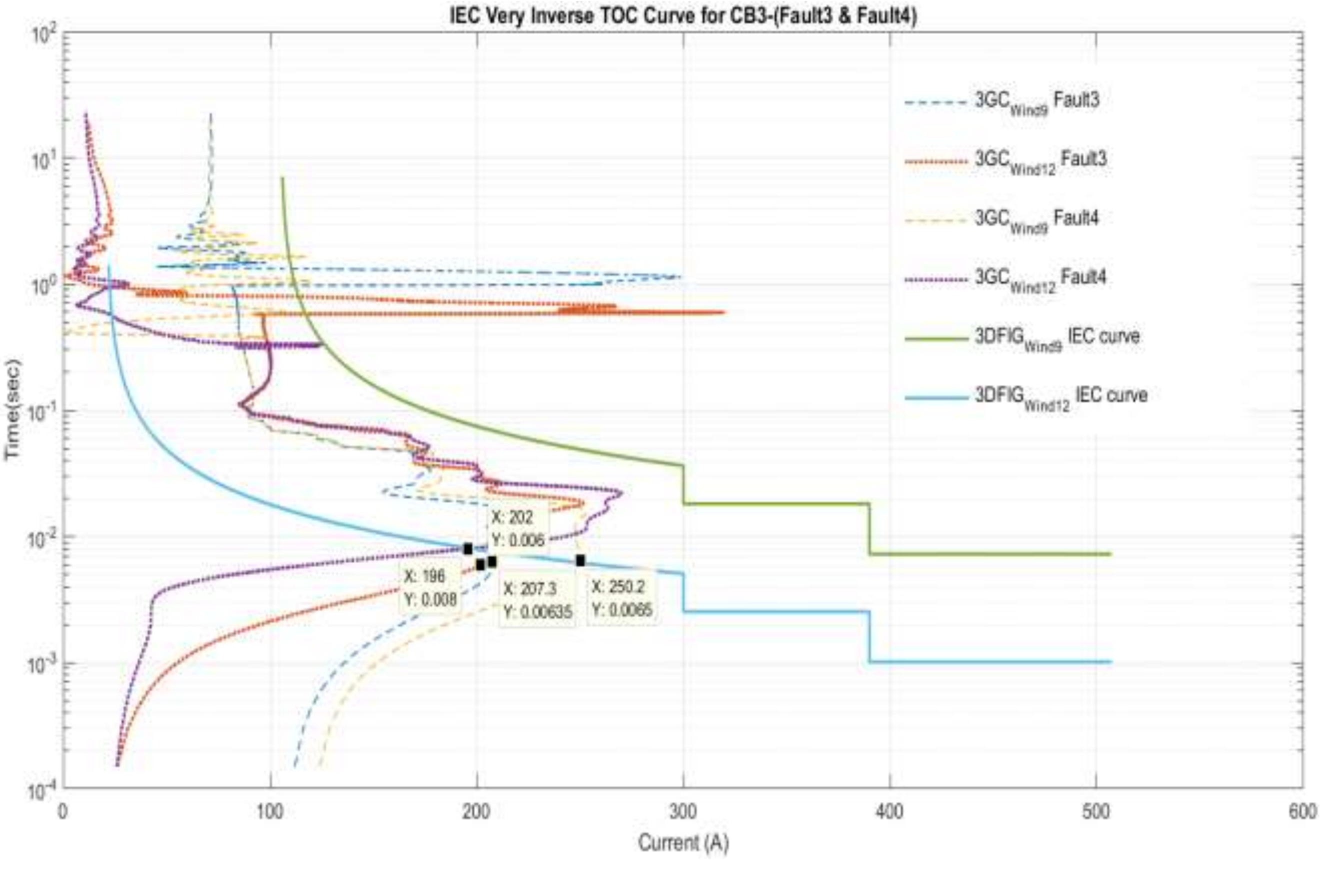

Figure 4.13 Comparison of the operation time for TOC curves at CB3 for Fault3 and Fault4.

Similar to fault scenarios described in Figure 4.13, in Figure 4.14, the two TOC curves represent OC protection schemes at CB3 where the pickup values for the IEC curves devised based on loading current at the CB3 during Grid-Connected operation mode. The operation conditions are defined for 3DFIG system connected to the grid with low wind speed of 9 m/s and high wind speed of 12 m/s. While distribution network is in Grid-Connected mode and the conditions for DFIG system are the same as discussed for Figure 4.13, the fault locations are defined as downstream (Fault1) and upstream (Fault2) fault with respect to the CB3 location. It is seen from Figure 4.14 that with different fault locations (Fault1 and Fault2) fault current at CB3 vary differently within the duration of the fault period. As shown in Figure 4.14 the fault current at CB3 for reaches 7 to 8 times of the loading current (normal operation) as Fault1 occurs downstream to CB3 farther from main grid. Also due to large fault current both IEC curves can detect the fault in downstream of the CB3 and isolate the fault very quickly. However, for any fault downstream to CB3 (Fault2) only fault current fed by DFIG system contributes to fault current at CB3 location which is low current compared to upstream fault (Fault1) scenario. The labels specified for Figure (4.14) represents similar scenarios for number of the DFIG connected to the distribution network and the wind speed which represents different operation condition for DFIG systems.

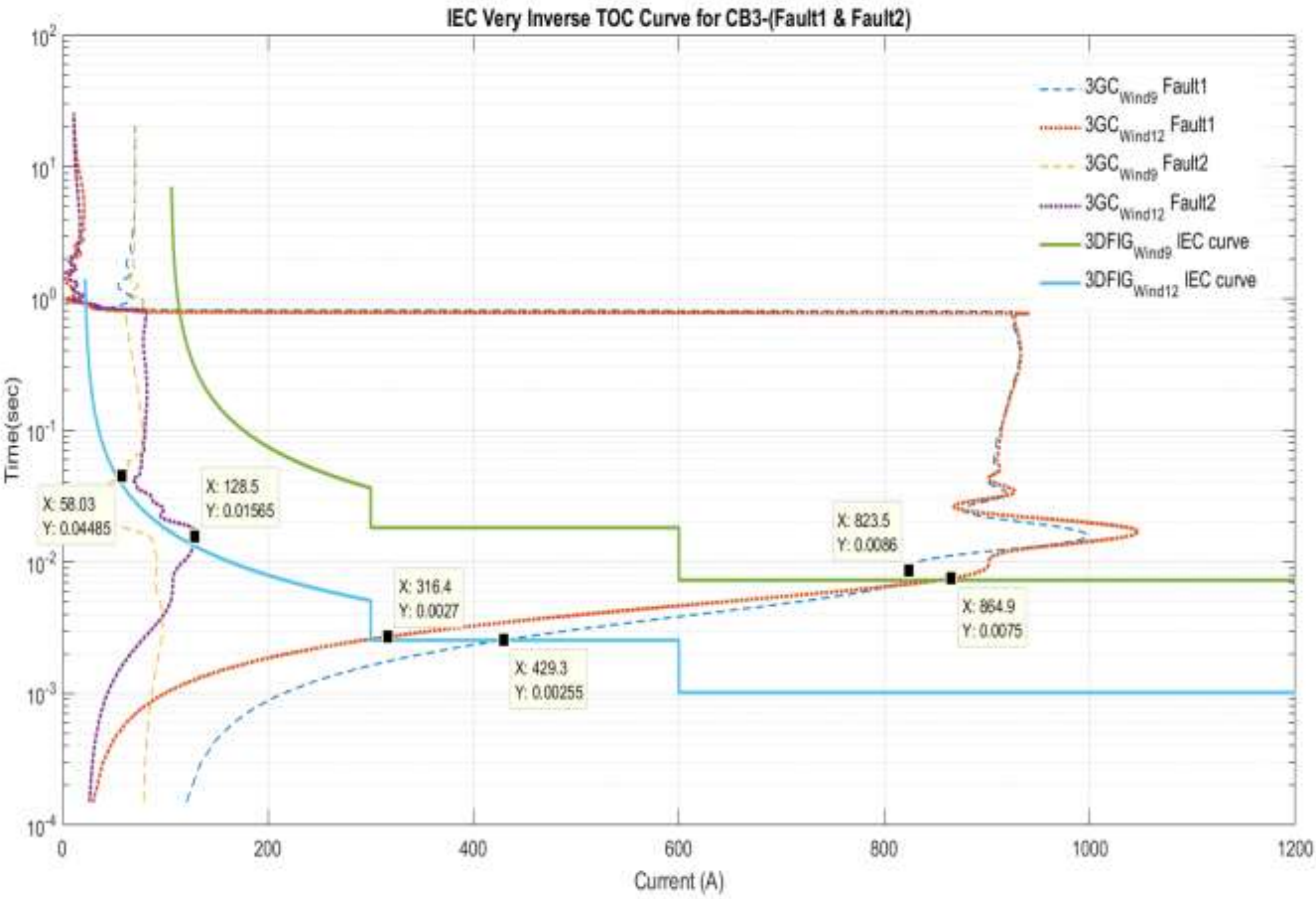

Figure 4.14 Comparison of the operation time for TOC curves at CB3 for Fault1 and Fault2.

Consequently, as shown in Figure 4.13 and Figure 4.14 it is important that the protection settings adjusted by considering different factors such as operation mode of the distribution network and location of the DERs which can be defined as downstream or upstream (relative to the distance from main grid connect) to their neighbouring CBs. In summary the fault current analysis is used to define certain parameters and factors that can be used for decision making on adjustment of the protections setting for specific operation condition within interconnected distribution network. However, using conventional fault current calculations cannot be reliable to highlight the effects of fault current contributions from DERs interconnected to the distribution network.

4.4 Summary

The importance of fault current calculation and its vital role for devising protection setting within conventional power system protection are discussed. Various fault current calculation methods including impedance method, symmetrical components analysis and IEC60909 standard have been identified as an effective and reliable approach in determining parameters for TOC protection settings within radial distribution network topologies. In opposition to conventional methods, investigation of the fault current behaviour based on dynamic modelling of the interconnected distribution network and DFIG system developed in Chapter 3 are presented as a reliable and accurate methodology to deal with complexities for determining adjusted TOC curve. To highlight the advantages of flexible and adaptive protection settings within interconnected distribution network, various parameters affecting the fault current contribution have been identified. For example, factors such as penetration level of DFIG systems, intermittencies in renewable energy sources (wind speed), grid-connected and Islanded mode of operation are taken into account to compare time domain behaviour of the fault current at each CB locations. In addition to that, evaluation of the functionality and performance of the TOC protection schemes are considered by plotting both time-domain response of the fault current and standard TOC IEC curves in a single graph. Basically, the results on comparing TOC curves are mainly used for introducing expert knowledge database to embed an automated heuristic decision making system to select appropriate group settings for TOC curves within protection IEDs of the protection system.

CHAPTER 5

MULTI-AGENT PROTECTION SYSTEM

In this chapter the proposed methodology for this PhD thesis is addressed which constitutes the core of the research study. The current chapter is developed based on two conference papers and one journal publication titled as ‘Integration of heuristic multi-agent protection system in distribution network interconnected with DERs’ which introduces a novel approach in devising protection system for interconnected distribution networks. The outcome for the published work is concerned with enabling protection system in interconnected distribution network by defining MAS framework for decision making support in dealing with complexities in operation of the DFIG systems. The process of decision making is defined based on exchanging knowledge between protection agents and applying heuristic rules to adjust protection settings in real-time. Thus, Chapter 5 embarks on detailed analysis and design of the MAS and decision making process where knowledge representation of the system and logic reasoning from human experts are central to establish proposed MAPS. The structure of the sections in this chapter is as follows. In the first section, some of the fundamental concepts associated with MAS development tools and Foundation for Intelligent Physical Agents (FIPA) standard specification for interoperability between MAS are discussed. In the second section, agent development software, JADE is adopted as a most commonly used FIPA-compliant software tool for developing MAS, while some important aspects associated with agent communication and agent behaviours are discussed. In the third section, designing methodology and steps toward establishment of a fully-fledged Multi-Agent Protection System (MAPS) have been discussed. Furthermore, as the core of the research study in this thesis, cooperation between different agent types and use cases for integrating heuristic knowledge in protection system are addressed. Finally, in the fourth section, for the sake of scalability and simplicity, a graphical user interface has been developed to facilitate the integration of the MAPS into power system in which power system components, agents and their behaviour are defined according to object-oriented programming paradigm. In section 5 summaries of the previous sections and their relevance to establish the MAPS are highlighted.

5.1 Multi-Agent System Infrastructure

Thus far, through literature review in Chapter 2 the topic related to MAS and its applications in operation of the future smart grids have been discussed for various research areas. However, establishment of MAS is reliant on solving some domain independent issues associated with communication between agents and deployment of core infrastructures for developing MAS [174]. This is because, researchers who are the end user to exploit MAS for various applications are required to support embedded generic services which are essential within the framework of the agent programming. On the other hand, implementation and development of these services require considerable time and detailed understanding of the operating system services, which can be out of scope for this research study. In order to avoid the aforementioned complexities for developing MAS, a unifying layer between the MAS application and operating system is required which is called middleware [175]. In fact, a middleware is a software, which resides between the MAS application and the operating system, network or hardware enabling efficient and easier application development. By using middleware software, developers can save from dealing with low-level and error prone platform (operating system) details by reusing programming interface codes for high-level services in variety of applications such as communication, data access and resource control [176]. In Figure 5.1, the role of middleware in developing a MAS platform has been illustrated [177].

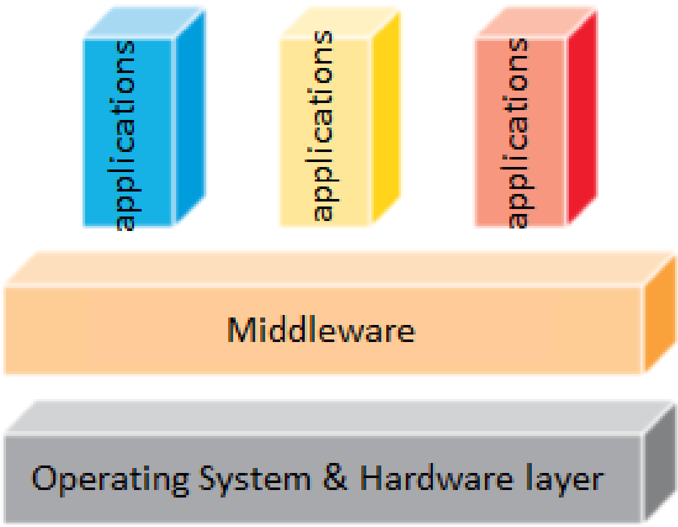

Figure 5.1 Arrangement of a middleware to establishment MAS platform [177].

In the literature, development of the MAS applications has been addressed through utilizing MAS middleware or agent platforms which basically reduce the time and complexity for developing MAS applications [177]. Many agent development platforms have been proposed which have used different approaches for supporting MAS applications [178]. However, in order to be aligned with the prospect of the Smart Grid operation and taking into account the importance of interoperability for an international standard for MAS, Foundation for Intelligent Physical Agents (FIPA) have been identified by IEEE Computer Society as reference standard for developing MAS applications within the field of power system engineering. Hence, the importance of MAS in establishing the proposed MAPS within this research project will be emphasised. In the next subsection , some main aspects related to agent-oriented programming and the standard framework required for developing MAS has been discussed [179].

5.1.1. Foundation for Intelligent Physical Agents (FIPA)

For development of MAS, software platforms and agent frameworks are the two key aspects which can affect the diffusion and interoperability in using MAS technology between different applications [174]. Thus, the idea of establishing a software platform addressing an open, stable, scalable and reliable architecture for utilizing MAS has been considered by many researchers in the field of MAS [178, 180]. Currently, with special attention to interoperability and compatibility, IEEE-FIPA has become an international standard to address issues related to software standards and agent-based programming [181]. Although during the evolution of FIPA standards many ideas related to agents and agent programming have been promoted to standard status, some still have not been developed or rejected. However, according to FIPA standard some key concepts related to agent platform have been highlighted which is discussed in the following [24, 182].

5.1.1.1 Agent Architecture

The FIPA abstract agent architecture is a reference model for common features that are critical and effective to allow interoperation between agent systems residing in separate and distributed environments [174]. Thus, there are particular aspects for an agent entity, which have to be adopted by software platform developers to provide necessary services or tasks within agent organization itself as per FIPA standard guidelines. Related attributes for abstract agent architecture highlighted within FIPA standard have been listed as follows.

- ***Agent Message***: The structure of message is a key for communication between agents in agent-oriented programming. Thus, FIPA has proposed Agent Communication Language (ACL) containing set of parameters, which allows effective communication between agents.

- ***Message Transport Service (MTS)***: The MTS supports a mechanism to transfer messages between the agents either within the same platform or different agent platforms.

- ***Agent Directory Service***: It is a shared information repository in agent platform where agents register their information about services they provide.

- ***Service Directory Service***: There are services which can be used to discover other services also a shared repository, but agents and services can be used to discover services.

Thus the aforementioned abstract architecture specifications are essential for agent development platform that are compliant to FIPA standards [183, 184].

5.1.1.2 Agent Management

Administration service for an agent is essential as it addresses agent’s life cycle within agent-oriented programming paradigm. Therefore, a reference model for managing FIPA compliant agents have been introduced where functionalities such as creating, operating and retiring of the agents is enforced to establish a normative framework for deploying agent within agent platform. Basically, the Agent Management (AM) has been specified as a concrete architecture for realization of abstract architecture defined by FIPA standard which is assumed as supervisory control in allowing access and use of agent platform by agents [174, 180, 185]. In Figure 5.2, the FIPA reference model for agent management has been illustrated in which physical infrastructure of agent platform has been distributed over multiple platforms constituting computers and support middleware software [180]. The internal design of the agent platform has not been specified as the subject for FIPA standardization.

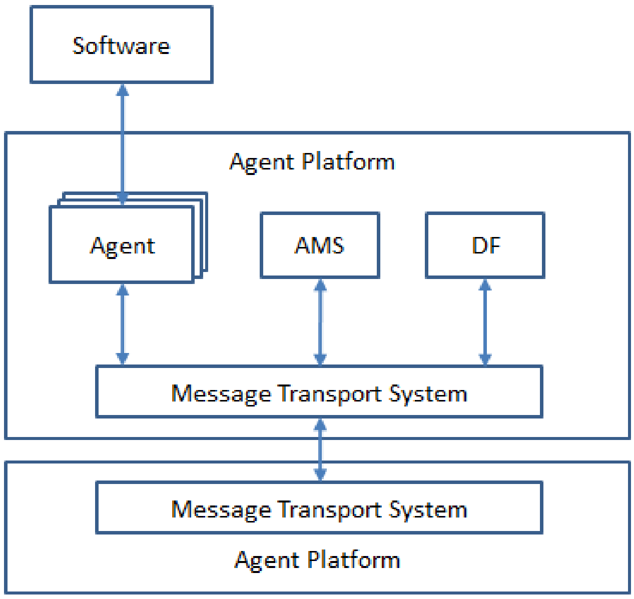

Figure 5.2 Agent management reference model according to FIPA standard.

According to FIPA specification, functionalities of agent management have been addressed through different elements, which are mandatory for any FIPA compliant agent platform. The FIPA specifications and corresponding tasks for each of the agent management components are listed with dot points [186].

- ***Agent:*** Contains computational process, which can communicate autonomously using agent communication language. In addition, each agent should have an owner and Agent Identifier (AID) which can be distinguished from other agents within the agent universe.

- ***Agent Management System (AMS):*** Mandatory component in any Agent Platform (AP), which supervises and control the access to any agent. There is only one AMS system in an AP, which keeps records of the agents AIDs and their transport address for supporting communication between agents.

- ***Directory Facilitator (DF):*** It is mainly used for providing yellow page services to other agents. Therefore, all the agents register their AIDs in AMS and can use the DF to query for services available within the other agents. The DF is an optional component of the AP and if it is addressed for the agent management system the aforementioned requirement needs to be implemented according to DF services in FIPA.

- ***Message Transport Service (MTS):*** It is a service for transportation of the messages between agents in an AP or in different APs [185].

5.1.1.3 Agent Communication

The ability for communicating and exchanging messages between agents are central for knowledge query and decentralized cooperation among different agents. However, to coordinate and share information among the rest of the agent communities, a potential infrastructure to offer flexible and effective communication language is imperative. Thus, to address this crucial aspect of the agent interactions, the communication part in FIPA standard has proposed an Agent Communication Language (ACL) which supports a mechanism for coordinating and sharing information between different agent platforms [187]. There are two main aspects related to ACL and its potential advantages for interoperability between different agent platforms, which are discussed in the next subsection.

5.1.1.3.1 FIPA Message Structure

In FIPA standard the ACL is a high-level language with primitive terms and concepts which supports collaboration and interactions (aka communicative act) required by MAS. To realize the actions required for agent interactions, a message structure wrapped in ACL is used for describing the context of message and its relevant information regarding the sender and receiver of the messages [183, 187]. According to FIPA standard, structure of the message is defined to contain set of parameters and elements which enable effective communication and interaction between FIPA compliant agents. In Figure 5.3, the message structure defined by FIPA standard has been illustrated where different elements of the message have been clearly integrated into FIPA message structure [174].

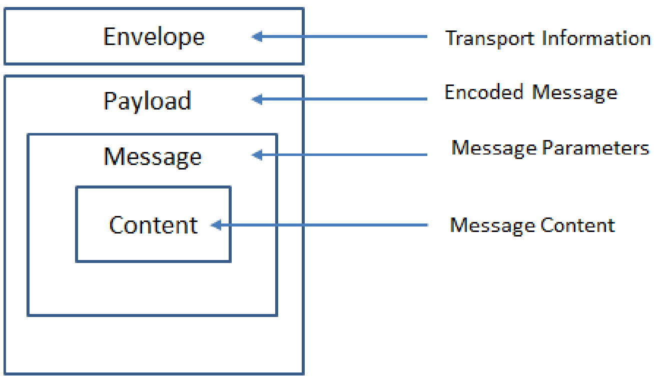

Figure 5.3 FIPA message structure for ACL.

As it is seen in Figure 5.3, each element in FIPA message structure consists of envelope and payload where the message envelope conveys information required for message transport service while message payload describes the actions in agent communication [188].

5.1.1.3.2 FIPA Communication Stack

As discussed in last subsection, FIPA-ACL message structure has a complex structure with different layers, which can be difficult to exploit in network-oriented medium (interface or infrastructure). For agent communication, ACL is used to exchange knowledge or information between the agents, but to transfer the ACL messages over communication networks transport protocols such as OSI and TCP/IP are required to support ACL via communication channel (network interfaces) at the data level. To supplement network-oriented model for ACL, FIPA standard has introduced a communication protocol stack based on OSI transport protocol where the application layer is separated into seven sub-layers application protocol [185, 187]. To provide a comparison between the OSI reference model, TCP/IP and FIPA-ACL protocol stack, Figure 5.4 has been illustrated. As seen in Figure 5.4, the application layer for TCP/IP protocol stack has been replaced with seven sub-layers within FIPA-ACL communication protocol stack [182, 187].

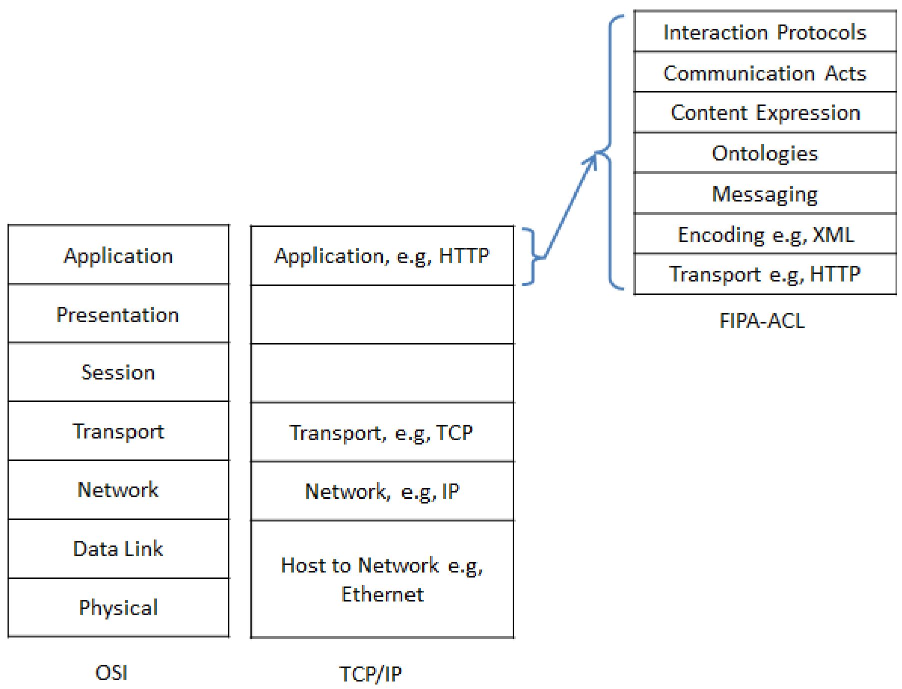

Figure 5.4 FIPA-ACL communication protocol stack.

Unlike OSI model, the services provided in FIPA-ACL application sub-layers are not restricted to be accessed by layers below, where each sub-layer in FIPA-ACL application layer is designed for specific services to support agent communications. The purpose of each sub-layers are explained as follows [174, 185].

- ***Transport:*** Is the lowest application sub-layer in FIPA-ACL protocol model in which HyperText Transport Protocol (HTTP) are used asynchronously to send communication messages between agents.

- ***Encoding:*** Utilized to transport messages between the agents in higher level data structures rather than byte encoded, although in the case of wireless implementation, string encoding or bit-efficient encoding can be used for encoding sublayer in FIPA-ACL protocol stack.

- ***Messaging:*** Specifies the data parameters such as sender and receiver names, message type, time-out for replies etc. The messaging structure is independent of the encoding sub-layer in FIPA-ACL protocol as it is applied to payload or content exchanged between agents.

- ***Ontology:*** References the terms in agent messages (FIPA-ACL) according to application-specific and conceptual model for a particular level of intelligibility/articulacy.

- ***Content Expression:*** Outlines predicates and logical formulas to form truth values from the ontology of the application domain.

- ***Communicative Act:*** Defines communication messages in terms of functions or actions to exchange attitudes in terms of beliefs and intensions.

- ***Interaction Protocol:*** Describes interaction sequences for information exchange between agents [188].

5.2 Agent Development Platform

Aside from technical aspects related to FIPA specifications and middleware-layer functionalities in development of MAS, there are some aspects of the agent technology which has not been addressed through FIPA standard and has been left for the platform developers to integrate their own specific features. In the literature, there has been number of software platforms for agent-oriented programming, which have been used for developing of the MAS such as FIPA-OS, agent Tool, JATLite and RETSINA, which support services and techniques for agent paradigm. However, successful realization of agent applications is dependent on availability of the appropriate tools and technologies such as programming languages, software libraries and development tools which can simplify the process of developing MAS [174]. In this research project, Java Agent Development Environment (JADE) has been used for developing the MAS due to its easy to use advantages and availability of the world-wide community support, which can further simplify the task of software development for agent programming. Basically, JADE is an open source agent development software based on JAVA object-oriented programming language, which provides set of APIs and core functionalities to simplify the agent-based programming. In addition, JADE is a FIPA compliant agent platform which guarantees interoperability between the agents in different environment provided that they are bounded to the same standard. Some of the concepts related to agent programming within JADE platform and technical terms for developing MAS are explained.

5.2.1. Platform Architecture

The architectural model underlying JADE platform is based on distributed system topology, where agents can be distributed on remote machines while they are able to communicate with each other. As shown in Figure 5.5, JADE platform is constituted of containers which are JAVA process, which provide run-time environment and library services for the agents inhibiting in the containers. Each instance of the JADE run-time environment is called a container and the set of all the containers create the platform. The distributed deployment of JADE run-time for each container and library services required by the agents in each container hide the complexities and diversities in operating systems from the software developers.

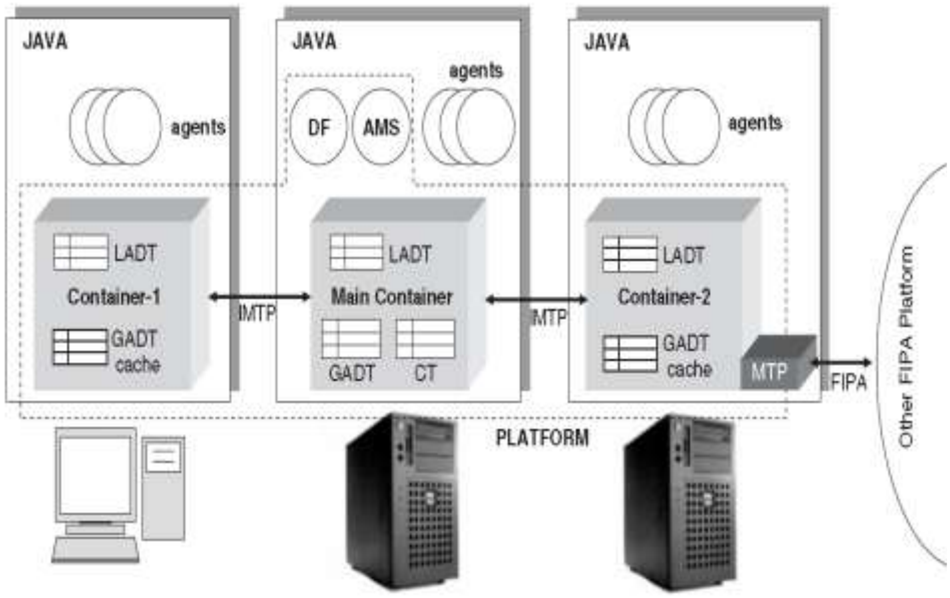

Figure 5.5 Architectural model of the agent containers in JADE platform [174].

The functional model described for distributed peer-to-peer application is based on launching a main container which also can be a bootstrap point of the platform. For each new container, which is created by the developer, the container is automatically registered to the main container by their specific identification names. As shown in Figure 5.5, the main container within the JADE environment has specific responsibilities to manage and register the transport address for all the containers. Moreover, aside from its Local Agent Descriptor Table (LADT) to register the agents within the main container, the Global Agent Descriptor Table (GADT) has to be created and managed within the main container, where all the agents in the platform with their addresses and their status are listed. Although the main bottle neck to the JADE agent platform is the failure of main container, the main replication service has been defined to ensure robustness to fully operate the JADE platform.

5.2.2. Message Passing

The ability to send and receive messages by agents is an essential characteristic of agent programming paradigm. Within the JADE platform, communication between agents is based on asynchronous message passing mechanism in that every agent has a message queue data structure receiving all messages from other agents ordered according to their arrival time. The process of message passing paradigm has been graphically illustrated in Figure 5.6 where each agent has a message queue similar to a mailbox that is defined and all messages received from other agents are arranged in sequence of their arrival. Although in message passing process each agent can independently prepare its message and send it to specific destination using JADE run-time environment, there is no dependency on availability of the sender or receiver at the same time. Also, for handling messages received from whenever a message is received to the queue, the agent will be notified and it is the programmer's choice to address agent's task to pick up the messages.

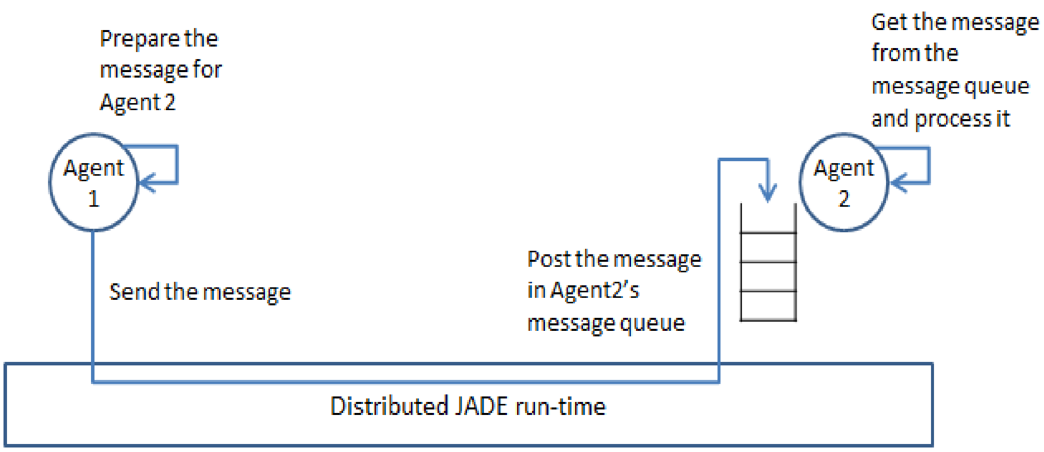

Figure 5.6 Asynchronous message passing paradigm for ACL.

Since the structure of the messages in JADE are object classes defined by FIPA-ACL including fields such as message types, time-outs etc. programmers can devise priorities to avoid burdening agents in dealing with synchronization for received messages. Therefore, in the JADE platform detailed complexities corresponding to encoding and parsing expressions for the sender and receiver agents are hidden in JADE run-time services. As a consequence of the advanced feature for message passing mechanism within JADE platform, communication between agents is only related to the application logic while converting back and forth between the formats to exchange message contents is an integrated service provided by the JADE runtime platform [174, 177]. Using JADE as the agent platform, the application programmers need to only focus on their application logic rather than engaging in complexities related to communications with other agents.

5.2.3. Task Execution

Ability to imitate human social behaviours is a key characteristic to agent paradigm, which has to be addressed in any agent programming software framework. In JADE platform, behaviours are defined as the tasks scheduled and implemented by each agents during its life cycle. Therefore, for software developers who are using JADE platform to develop their application software, understanding the execution and implementation of the agent behaviours are crucial in software development cycle. In JADE platform, agents can run several behaviours simultaneously in a single JAVA thread per agent, but execution of agent's behaviour is based on non-pre-emptive scheduling, which means that execution of behaviour cannot be stopped by another behaviour until its task is finished. However, the concept of cooperation between behaviours is denoted as the behaviour or task can be switched to other behaviour or tasks where programmers can define when to switch. In Figure 5.7, the agent thread path of executing behaviours have been illustrated by highlighting none pre-emptive (none-stoppable) nature of the task executed through their *action ()* and *done* () methods defined for the behaviour classes in JADE. It should be noted that the *setup ()* method in the flow chart in Figure 5.7 references to a single JAVA thread for each agent entity.

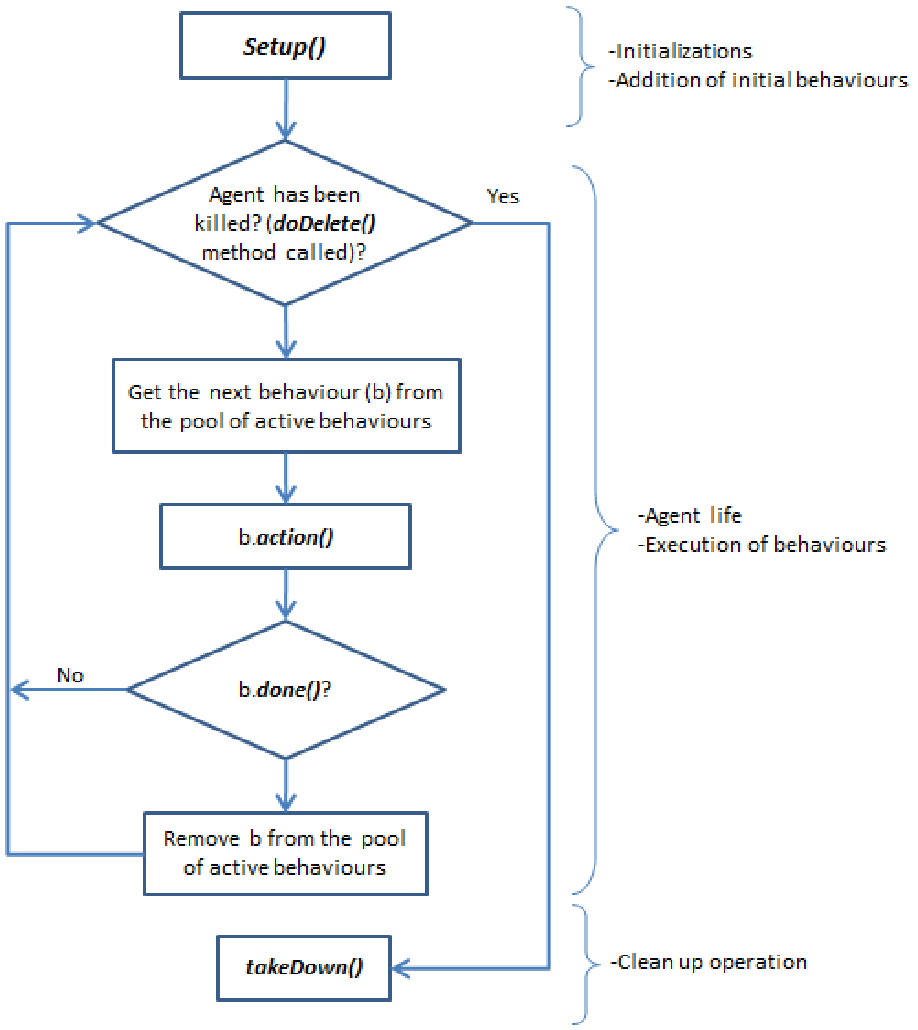

Figure 5.7 Sequence of task execution in an agent thread.

By adopting this type of the behaviour, some advantages are as follows:

- For each agent there is a single JAVA thread, which helps to reduce computational burdens in environment with limited resources.
- Using behaviour switching can improve the performance comparing to JAVA thread switching.
- It (agents) can avoid accessing the same resources between concurrent behaviours within a single JAVA thread.
- Possibility to store agent status, which allows agent persistency for later resumption of the agents task or behaviour [174, 177].

The proposed MAPS and its architectural details are discussed in section 5.3.

5.3 Integrating Multi-Agent Protection System

Thus far potential of MAS and its software framework, which can facilitate flexibilities in deploying autonomous and distributed agents to capture complex interaction within large network systems have been discussed. However, the main aim of this research study is to integrate these agents into protection system, as an effective means to assess power system situations and take actions co-ordinately towards a global desired goal. In general, the idea of using agents as distributed intelligent and autonomous entity can replace conventional protection IEDs in power system for enabling factor within interconnected distribution networks to deal with complexities of protection system. To establish the proposed MAPS within interconnected distribution network, developing an integrated environment considering both information and computational aspects of the system protection task is inevitable. As a matter of fact, implementation of MAPS is reliant on availability of software tools and appropriate level of data integration, which can represent the overall behaviour of the system in terms of credibility and accuracy. Therefore, much of this section is related to technical knowledge domain for developing MAPS, which is mainly concerned with how system operates and system architecture connects each of the constituents in the proposed system. In addition, development phases controlling the design process for MAS have been discussed through SDLC methodology, where common iterative procedures for problem solving have been used. For example, the process of designing protection agents based on MAS framework similarly follows SDLC methodology as the outputs can be integrated into power system protection applications [25]. Some of the technical details corresponded to system architecture, protection agents and interaction between protection IEDs within the proposed MAPS are explained in the next subsection.

5.3.1. System Architecture

To address feasibility and deployment issues corresponding to the proposed MAPS, system architecture is of critical importance to bridge the gap between different domains of the integrated system. The idea of sharing knowledge and cooperation between the protection IEDs as MAS is conducive to Smart Grid architecture. The utilization of ICT enables power system components to communicate their operating conditions or status through interactions between other electrical components in the system. Thus, similar to SGMA a layered-based architecture has been adopted for the proposed MAPS as different simulation domains can interact with each other while each sub-domain can be independently implemented [189]. In Figure 5.8, the two layers of MAPS have been illustrated which constitute the power system and agent layer. As shown in Figure 5.8, the arrows indicate interfacing two layers of power system network and protection agents highlight the data communications for simultaneous interaction between the two domains while each domain operates autonomously in parallel. Technically, the intelligence and resiliency of the MAPS is associated with architectural arrangements and co-simulation of power system components and agent domain protection system, where real-time simulation data can be exchanged between two domains.

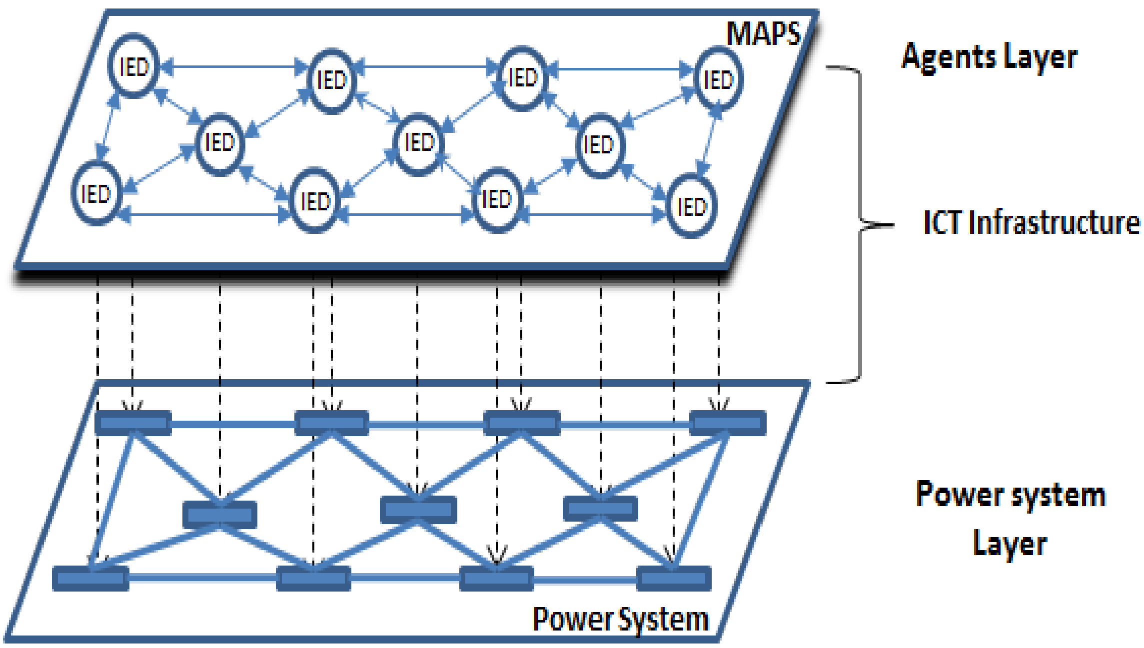

Figure 5.8 A layer-based architecture for establishment of MAPS.

In the agent layer, protection system based on MAS framework is developed where each protection IED constitutes three different agent types that are designed to fulfil protection task. Furthermore, to exploit knowledge sharing and communication between protection agents, JADE platform is used to support FIPA standard agent communication language. In Figure 5.9, the protection IED is devised to integrate MAS into system protection of the power system network has been illustrated. As seen in Figure 5.9, for MAPS each protection IEDs contains three different agent types and these are measurement, communication and coordination.

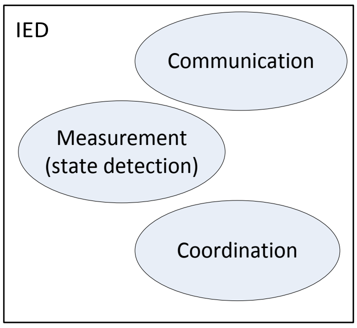

Figure 5.9 Arrangement of the protection agents into protection IEDs.

The advantage of defining IEDs architectures designated for three different agent types is to utilize agent-technology paradigm in distributed decision making and resilience in protection system within interconnected distribution networks. Moreover, the ability to introduce a common communication language to exchange information between protection IEDs can be well-matched for future power systems, which are large scales system with heterogeneous devices covering wide geographical area. Steps toward designing of the protection agents are discussed next.

5.3.2. Agent Development Methodology

Essentially, in FIPA standard the scope for MAS framework is confined to address a conceptual model and provide a normative reference model to deal with interoperability between agent development platforms, as it specifically focuses on agent structure and agent communication language. However, similar to any SDLC, adopting an agent development methodology for MAS is crucial, which not only can save time and cost but it also allows the developers to choose suitable organizational patterns that can further improve robustness, efficiency and reusability within the deployment of the agent entities. Unlike the SDLC for Object-Oriented programming, there are some technical aspects corresponding to MAS paradigm and their architectural organizations, which require specific attention during the analysis and design phases of MAPS. Generally, for planning phase, mainly literature review and research studies related to the MAS is pertinent as it has been already discussed in Chapter 2, but for analysis phase there are certain steps that has to be identified before proceeding to designing and implementation phases. In Figure 5.10, the steps taken during the analysis phase for development of MAPS has been illustrated as different aspects of agent paradigm and has been highlighted with the top to bottom approach. Although it is important to note that despite the top-down representation of the steps, analysis phase is a repetitive process where at each step certain requirements and deliverables are defined and interrelated for the next step or phase in the SDLC. Finally, the outcome from the analysis phase focuses on features and deliverables which are required by MAS such as scalability, interactions between agents, agent types and ontologies related to the protection system domain.

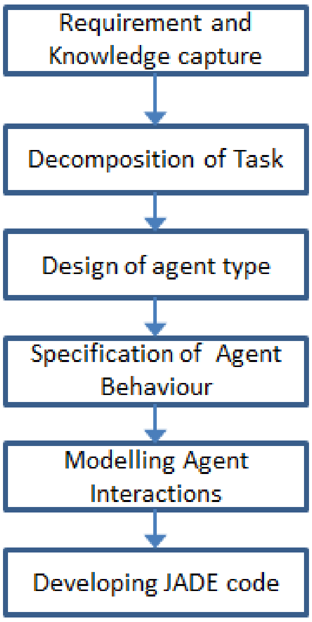

Figure 5.10 Steps adopted in design methodology of MAPS.

While in the analysis phase, logical links between the agents and solutions to the problem are investigated but identifying and understanding the capabilities of the agent software platform can play a crucial role for improving the scalability and interoperability of the proposed MAS. Therefore, during the design phase, limitations and constraints for developing the software agents are highlighted where prescribed interactions between agents are updated through repeated process between the analysis and design phase of the design methodology. Finally, the proposed scenario for integrating of MAS into protection system is implemented by developing a software application and graphical user interface (GUI) which manages deployment of the agents and synchronization of data communication between power system and agent domain system. In the following, steps taken through analysis phase of developing MAS including identifying agent types and their roles to fulfil protection task within agent domain paradigm has been discussed [111, 178, 190].

5.3.3. Protection Agents

As discussed earlier in subsection 5.3.2, agent development methodology identifying agent types and their roles to establish MAS for protection system constitute the main theme in analysis phase of the agent development. Thus, considering protection system task and potentials in introducing MAS, organizing (distributed protection sub-tasks) distributed protection agents, which can participate cooperatively in a collective decision making process is defined as the basis to initiate (setup) agents roles and responsibilities within a MAPS. In contrary to conventional protection approach, endorsement of agent paradigm and decentralized measurement is aimed to take into account different operational and topological variations into protection decision making as the protection complexities within interconnected distribution network are multifaceted and interdependent problems. In general, there are three key aspects (measurement, communication and coordination) in protection system task which can be defined as separate entities in the form of agent type/model to fulfil their associated roles through logical communication links. In this research for developing MAPS, there are three subtasks of measurement, communication and coordination which have been proposed as the key elements to address agents' types and responsibilities within MAS framework. Although within the conventional approach all the sub-tasks in protection system are tightly coupled to a specific decision making algorithm, dividing them into subtasks loosely coupled to interact autonomously in their environment provides a resiliency which is critical for protection systems in interconnected distribution network. In order to further illustrate the concept for proposed protection system based on MAS framework, Figure 5.11 depicts the roles and interaction between different agent types through Unified Modelling Language (UML) use case diagram. As seen in Figure 5.11, the three protection tasks mentioned earlier are represented as agents where they can communicate and exchange knowledge of their environment to collectively decide on an appropriate protection settings using expert knowledge database.

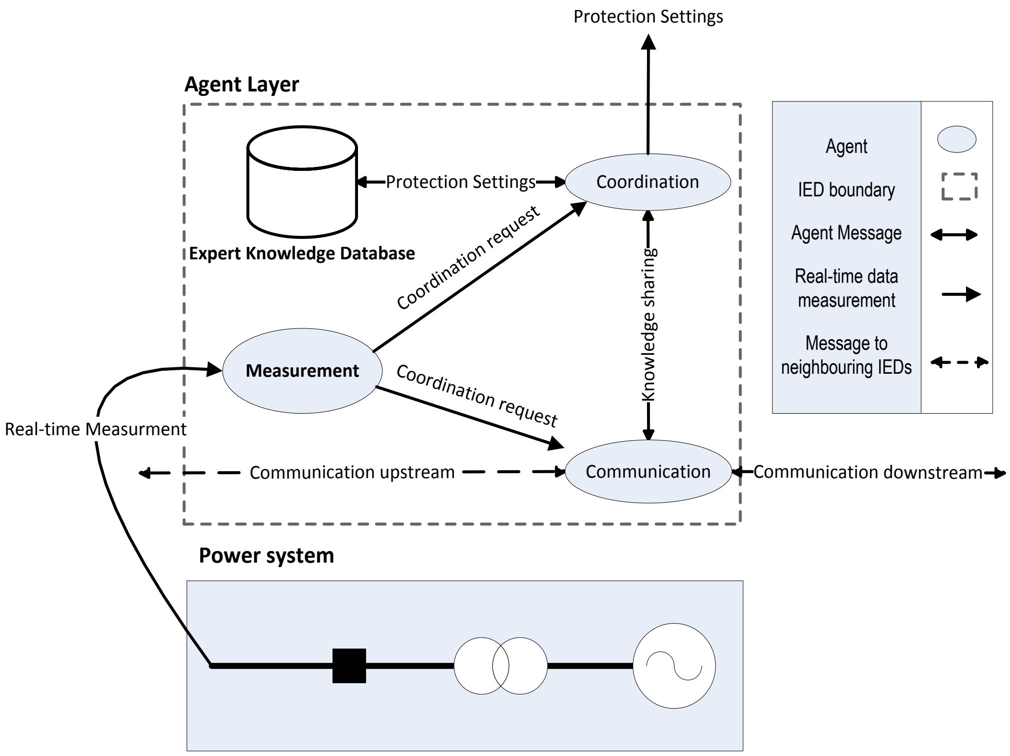

Figure 5.11 Use case representation for interaction between protection agents.

In the illustrated case diagram of Figure 5.11, the two domains of power system and agent layers have been specified with system boundaries, which identify the inputs and outputs from each sub-system. In addition, placing the power system and MAPS within the same UML use case diagram is to underscore architectural feasibility and arrangements of protection IEDs according to power system automation perspectives. Finally, in order to further clarify the roles and responsibilities of each agent in the proposed MAPS, some technical details related to protection agents' designs are explained.

5.3.3.1 Measurement (Transition Detection)

The main responsibility for measurement agent is to receive real-time measurement data and monitor the operation condition at the location of CB, where measurement for voltage, current are continuously observed for variation of the operation condition. In addition, measurement agent can send message for requesting adjustment of the protection settings to coordination agent. For development of the measurement agent, a JAVA class has been defined in which structure data including CB name, type of component that CB is protecting and measurement data variables such as current, power flow and voltage are assigned during deployment phase.

5.3.3.2 Communication

For communication agent, the task of knowledge sharing between neighbouring protection IEDs is fulfilled by sending request messages and receiving back replied measurement data from the requested CBs. Furthermore, the information received from the neighbouring protection IEDs are delivered to coordination agent for supporting decision-making process by incorporating additional information from system operation condition. In similar way, a JAVA class type is developed for communication agent where data structure allocated to hold CBs name for the neighbouring protection IEDs.

5.3.3.3 Coordination

The core of decision making and incorporating of the heuristic rules for adjusting protection settings in each protection IED is implemented in coordination agent. In fact, coordination agent demonstrates a distributed decision-making approach/entity where measurement information are collected and taken into account for evaluation against the heuristic knowledge that forms the reasoning basis for selecting proper protection settings from the existing setting groups in the protection IEDs. Although, in order to be able to develop a fully automated protection system based on the aforementioned protection agents, interaction protocol between different agent types has been devised, which can autonomously and interactively engage each agent type to address system protection. In Figure 5.12, the UML sequence diagram for interaction between the protection agents has been demonstrated.

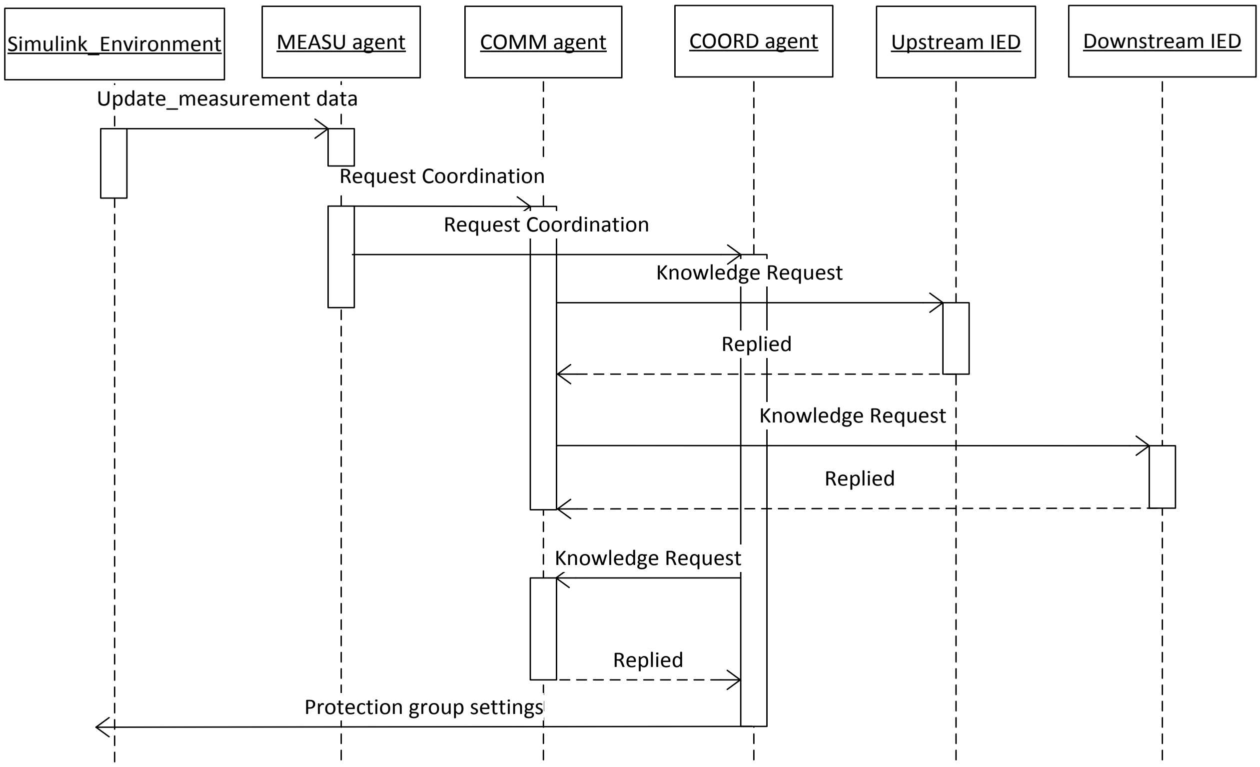

Figure 5.12 UML sequence diagram for protection agent cooperation.

5.3.4. Protection Ontology

Generally, in MAS environment agents work collaboratively to solve specific problems, which they have been introduced to. Therefore, having an effective communication language to ensure agents can understand each other is an imperative requirement for MAS to accomplish its global goals. Similarly, for the proposed MAPS the need for a structured and domain-specific communication language which can explicitly conceptualize the existing properties and relationships between the protection agent’s community, it is desirable to improve interoperability within the domain. An ontology-based communication language has been adopted for MAPS, where content of the messages exchanged between protection agents are defined according to vocabulary and semantics related to system protection engineering. This approach is particularly important since it improves semantic interoperability and scalability within the system consisting of heterogeneous and distributed agents such as MAPS as proposed in this thesis. In addition, considering interdependencies between different levels of power system operation adopting domain specific ontology for agent communication can promote a unified framework in power system automation [191, 192]. In Figure 5.13, integration of the ontology-based communication into agent communication language and its role to interpret/exchange knowledge between two different agents has been represented [193].

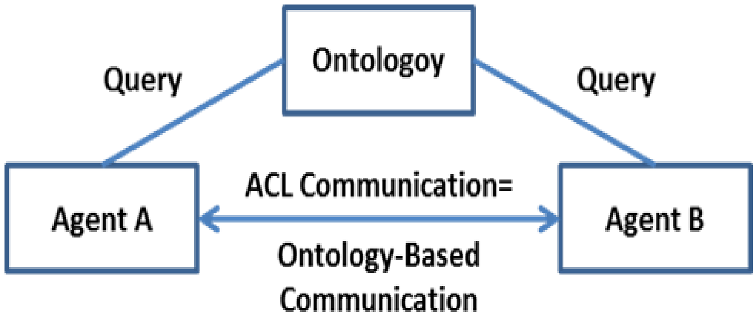

Figure 5.13 Interaction between agents within ontology-based communication language.

There are certain aspects related to semantics and knowledge sharing (acquisition) between agents, which have to be agreed by all protection agents in order to understand each other. Next, content elements for the protection ontology described for MAPS are discussed [63, 194, 195].

5.3.4.1 Predicates

In general, the predicate can express a fact regarding the message content of the agents, which can be true or false in the protection system ontology domain like Protect CB name, element type which shows specific CB_{name} protect, certain type of the element. For example CB_{DFIG} Protect wind turbine (WT) means the protection IED with the name of CB_{DFIG} protects a connection point at a DFIG wind turbine terminal.

5.3.4.2 Concepts

The concepts represent entities in the domain of study, involving data structures and some properties which independently can not be meaningful information for decision making however, in the context of agent message communication concepts can be considered as the objects that actions act on them. For example, the CB elements considered as concept within the protection system where for each CB its status, measurement data and type of the component it protects in the power system can be utilized as protection system knowledge. Actually, adopting the existing concepts within the protection system domain ontology can improve scalability and interoperability between protection IEDs.

5.3.4.3 Agent Actions

Agent actions are terms defined to indicate possible actions that can take place or requested by agents in a specific domain of study. For example, in the proposed MAPS the request for coordination or acquiring knowledge from the neighbouring protection IEDs can be represented as coordination and communication messages, which can independently be meaningful as Communicate to neighbouring CB nodes upstream or downstream.

5.3.5. Heuristic Decision-Making Approach

The process of decision making and deterministic algorithms for problem solving in power systems have been used in various levels to address optimal operation of the power system networks. However, within the context of the protection system and reliable operation of the power system, there are three main objectives such as sensitivity, selectivity and speed, which have to be simultaneously/concurrently managed to meet the reliability standards. Traditionally, deterministic decision making algorithm have been the core of conventional protection methods, where protective relays are simply defined with fixed decision boundaries and comparing local measurements from CTs and VTs against deterministic functions such as TOC curves, distance and differential protection functions as decision made to send trip commands [196]. Despite the well-established and successful practice for many years, in the course of prevailing uncertainties arising from interconnection of renewable energy resources into power system networks, deterministic problem solving approaches based on objective knowledge and formulae are not effective to meet the reliability standards anymore [196, 197]. On the other hand, with the advancements of ICT in power system infrastructure application of sophisticated and efficient decision-making algorithm, combining ICT elements and heuristic knowledge of the human expert have gained lot of attention in the modern power system era. In contrast to deterministic approach, heuristic techniques are defined as rule of thumbs taking both objective and subjective knowledge of the system to solve problems, which do not rely on formulae or closed form solutions [198]. Therefore, depending on the applications, the main advantage of integrating heuristics into decision making process is to reflect the intuitive knowledge about the solution of a problem, as it is not possible to quantify that in a formula. In the proposed methodology for integrating MAPS into interconnected distribution networks and according to fault current analysis investigated in Chapter 4, there are two elements concerned with the heuristic decision making; the first one is the operation states at each CB nodes and the second element is the parameters affecting fault current contributions.. In the next step detailed explanations about the state transitions and expert knowledge sharing between agents for developing heuristic decision making algorithm is presented.

5.3.6. State Transitions

In practice, steady-state loading current at CB location is the basis for devising protection settings as power flow direction and magnitude is approximately stable during normal operation of the power system. Unlike conventional radial distribution network, steady state load-generation balance within interconnected distribution networks endures uncertainties corresponding to availability of the renewable energy resources and topological changes during grid connected/islanded mode operation. Accordingly, selection of protection settings in interconnected distribution network is difficult to maintain protection system reliability as volatilities in normal operation conditions can initiate state transitions at certain CB locations. On the grounds of fault current analysis investigated in Chapter 4, operation state at each CB location can be related to available fault current capacity and bi-directional power flow, which are critical factors to choose appropriate protection settings under different operation scenarios of the interconnected distribution network. However, considering local measurements independently cannot be an accurate measure for devising protection settings since the topology and type of DER connected to the distribution network is also effective in fault current contribution at their neighbouring CBs. Therefore, the solution to avoid potential mis-calculation in devising protection settings based locally measured values at CB locations is to consider both characteristics of state transitions and topology of the connections with the neighbouring CBs as state diagram highlighting a unique operation condition to devise the proper protection settings. By following the same approach for the proposed interconnected distribution network operation, Figure 5.14 represents state transitions diagram for each CB locations, where connection with neighbouring CB nodes can be shown as downstream or upstream with respect to the type of neighbouring CBs (DER) connected and power flow directions.

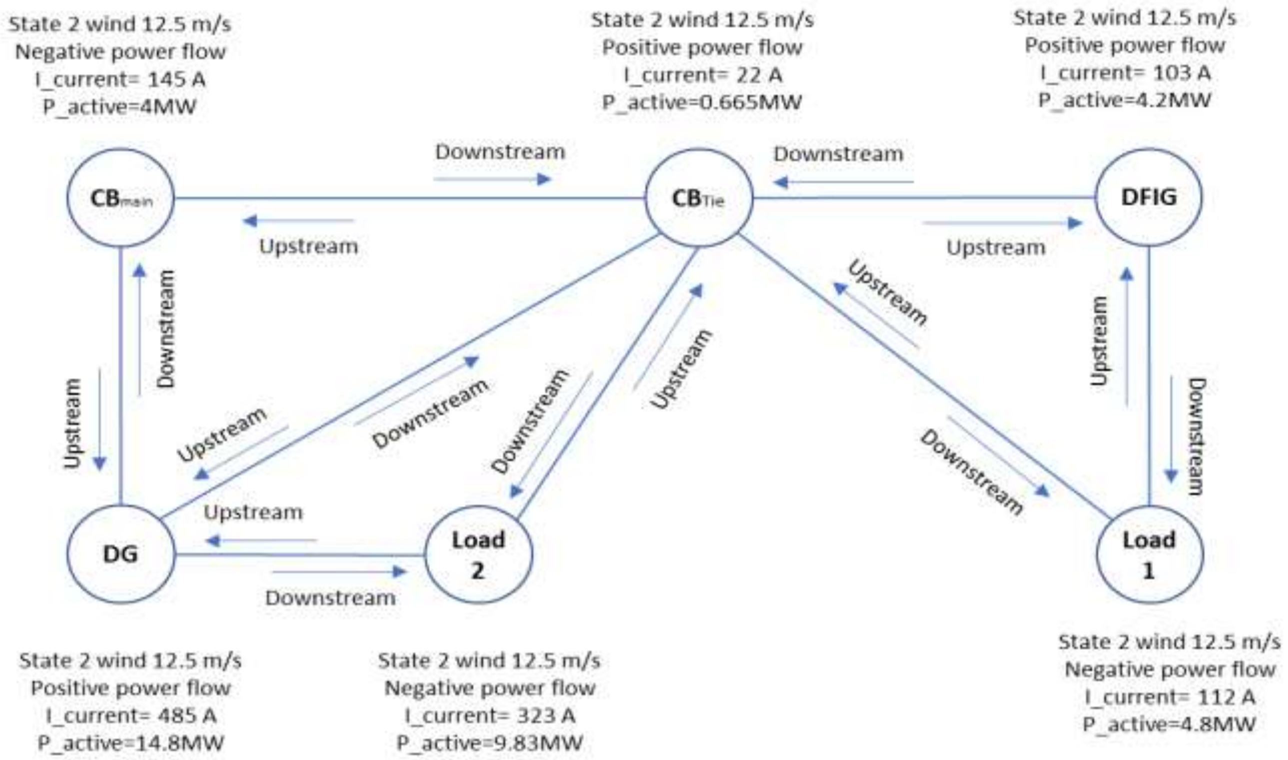

Figure 5.14 State transitions due to wind speed intermittency in interconnected network.

As shown in Figure 5.14, the DFIG system connected into distribution network system represent the grid-connected mode of operation in which changes of wind speed and number of DFIG system contributing to power generation are considered driving inputs to the state transitions. Consequently, it is obvious that depending on the wind speed variation volatilities in operating conditions prevail state transitions at each CB locations and furthermore the interconnected network can absorb (consumption mode) or deliver (generation mode) electrical power to distribution network through the main CB. Similar representation for state transitions with the variation of the DFIG operation conditions have been illustrated in Appendix C.2.

Similarly in Figure 5.15, the islanded mode operation of the state transitions at each CBs has been illustrated where depending on wind speed variation and number of DFIG system connected to the system state transitions can occur. Therefore, operation of the interconnected distribution networks can be represented through a state transition diagram, which identifies interdependencies between the neighboring nodes. Furthermore, to deal with the effect of non-deterministic inputs such as wind speed or increasing the number of DFIG connected into the distribution network, other information different from conventional CT and VT measurements are required for devising reliable protection settings. In the next step, information supported by knowledge sharing between different protection agents are defined as state transitions and network topology which constitute knowledge database for decision making process to select appropriate protection settings based on logic reasoning and expert rules.

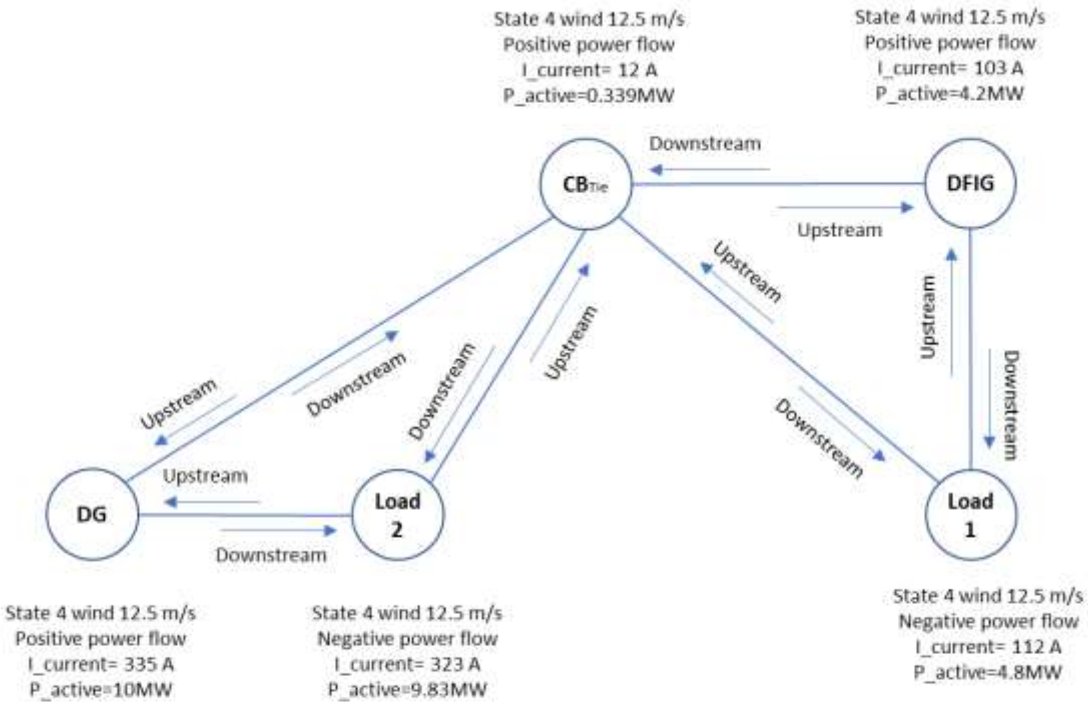

Figure 5.15 State transition of the interconnected distribution network (Islanded mode).

5.3.7. Expert Knowledge Database

Following the analysis of state transitions and interdependencies of neighbouring nodes on fault current contributions, in this section establishment of a decision-making process to perform automated actions for adjusting protection settings of the protective relays has been proposed.

Basically, the idea of integrating heuristic approach into protection system is to mimic human mind decision making process, in a limited way, for traversing limitations and challenges attributed to conventional system protection design. In this method, the two main elements of AI, MAS and expert systems are utilized to fulfil protection tasks where a novel approach based on specified semantics related to interconnected distribution network have been used for heuristic reasoning in protection system domain. Also, MAS is an enabling factor to form intelligent, autonomous and interoperable communication layer for knowledge acquisition and representation. Therefore, the first step adopted for developing (establishing) of the heuristic decision making is through collecting information from the system states and topological arrangements of each component which have been discussed in previous section. After that, the knowledge database system is used to represent the knowledge extracted from the operation condition of the system, which forms a framework to utilize expert knowledge and logic reasoning to adapt protection settings for each CBs. In Table 5.1, information related to state transitions and neighbouring nodes for each CB has been represented in the form of knowledge database for the interconnected distribution network described in Chapter 3. As seen in Table 5.1, the first column lists types of the component that each CB protects against the fault current, which is a critical factor for protection engineers when considering certain protection strategies. For example, protection CBs for load centres are usually passive and do not contribute for any fault in upstream or downstream of the network as their setting groups are limited to only ensure coordination with other CBs in the network. Also, in IED group settings column, number of group settings for different protection IEDs are represented, which are set for various fault current level at the CB locations. Symbols HH, H, HL and L indicate very high level, high level, medium level and low level settings for each setting groups. Also, letter D represents directional element is activated within a protection IED as it is used for specific CB types. Finally, the last two columns are related to topological connections between different CBs and their state transitions explained in subsection 5.3.6. Measurement values at each CB locations for each state have been listed in Appendix C.1 according to different operating condition of the DFIG system.

Table 5-1 Representation of the protection IED nodes for knowledge database.

System Knowledge Database			
CB_i Type	IED group Settings(levels)	Up/Down Stream	Transition States
DFIG	4 (HH,H,HL,L)	Upstream	4
Load(1)	2 (H,L)	Downstream	1
Load(2)	2 (H,L)	Downstream	1
Tie	4 (DH,DL,H,L)	Up/Down	4
DG	2 (H,L)	Upstream	2
MAIN	4 (DH,DL,H,L)	Upstream	2 (GC-IS)

As seen from Table 5.1, selecting protection settings from the information provided by expert knowledge database demands appreciable knowledge and ingenuity from the perspectives of protection engineering expertise as protection settings has to be adjusted accordingly with changes in the operating condition of the system. Therefore, the knowledge represented in Table 5.1 is required to be described in a form that is suitable for expert system rule engines and logical reasoning defined for expert knowledge database. Actually, the aforementioned process is addressed as knowledge engineering stage which plays a critical role to relate system operation conditions with the actions, which in this case is the selection of IED group settings. One of the important aspects proposed for developing the heuristic MAPS is to represent knowledge database in the form of descriptive logic by identifying a semantic domain for protection system in interconnected distribution network. Actually, within descriptive logic, knowledge of an application domain is structured in a well-understood hierarchical class, concepts and relationships, where rule languages can be applied for further deduction and prediction using logical reasoning. Hence, the adoption of description logic for representing system protection knowledge database, Figure 5.16 illustrates the proposed hierarchical classes and relationships between classes, subclasses and their roles. In Figure 5.16, ellipses identify both classes and subclasses where subclasses are linked to their higher level classes through (*is-a*) arrow links, also the dotted-line arrows represent the relationships (properties) between two classes. As can be seen in Figure 5.16, CBs class is defined as the main superclass in the class hierarchy, where the concepts of type, group settings and operating conditions (including Grid-connected/Islanded and Penetration levels) constitute subclasses of the CBs class.

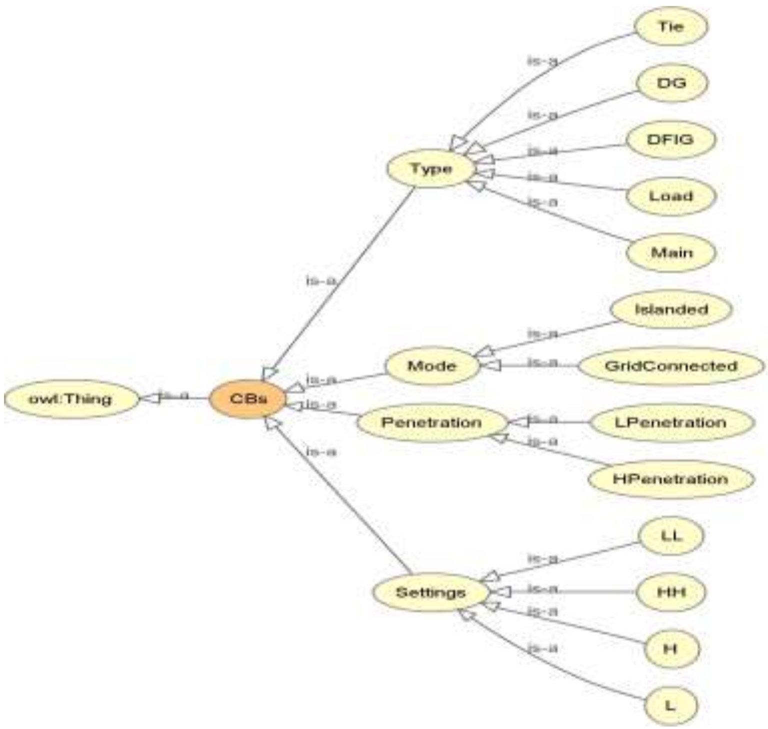

Figure 5.16 Class hierarchy for knowledge representation in descriptive logic reasoning.

Thus far, the approach for knowledge engineering and representing protection system domain is within Descriptive Logic (DL) semantics. However, one of the powerful features in building ontology knowledge base is to utilize reasoning services to extract hidden information from the explicit knowledge of the system. There are advantages that can be related for adopting DL reasoners to fulfil the MAPS, the first one is that automated reasoning process is matched for requirement of adaptive protection settings, where based the operation conditions at certain CBs, expert knowledge database agent can propose desired group settings. The second one is associated with the necessity of scalability and interoperability within modern power system, where the domain knowledge is separated from the reasoner or expert rule-base as the connection and disconnection of the DERs can occur depending on the planned or unplanned changes to the system, but the reasoner can still do its task using inference rules for knowledge database. In the architectural representation of the MAPS, expert knowledge database is identified as an agent which is communicated by coordination agents to update the protection group settings according to the variation of the operating conditions. As core for the rule-based reasoning, 4 rules for each settings group have been represented in Table 5-2. In Table 5-2 the first line for each rule is the syntax representation of the rule and the second line is the expert knowledge represented as the rule. In Appendix D.2 the Knowledge database for the MAPS has been represented in PROLOG.

Table 5-2 Rule-based reasoning for selection of the protection settings in MAPS.

(descriptive logic reasoning):
Rule1
HH ≡ (∀ CBs) ∩ (∃ is Grid-Connected.⊥) ∩ (∃ has_Upstream.DFIG) ∩ (∃ is Hpenetration.⊥) IF state is GC & has Upstream Type DFIG & (DFIG) in High State Then HH
Rule 2
HL ≡ (∀ CBs) ∩ (∃ is Grid-Connected.⊥) ∩ (∃ has_Upstream.DFIG) ∩ (∃ is Lpenetration.⊥) IF state is GC & has Upstream Type DFIG & (DFIG) in Low State Then HL
Rule3
L ≡ (∀ CBs) ∩ (∃ is Islanded.⊥) ∩ (∃ has_Upstream.DFIG) ∩ (∃ is Hpenetration.⊥) IF state is Islanded & has Upstream Type DFIG & (DFIG) in High State Then L
Rule 4
LL ≡ (∀ CBs) ∩ (∃ is Islanded.⊥) ∩ (∃ has_Upstream.DFIG) ∩ (∃ is Lpenetration.⊥) IF state is Islanded & has Upstream Type DFIG & (DFIG) in Low State Then LL

Finally, in Figure 5.17, the flow chart identifying steps to fulfil the proposed MAPS by integration of heuristic reasoning have been illustrated. As has already been explained from the perspective of architectural arrangement and protection tasks, protection agents are the driving factor in collecting information and extracting knowledge from the interconnected distribution network. The knowledge representation and reasoning services are bounded for expert knowledge database. As seen in Figure 5.17, the measurement values and input information such as device name, device type and operation mode data are provided by protection agents. To establish the stages required for implementing the MAPS, a software application based on JAVA programming language, JADE and logic programming (PROLOG) have been used to deploy protection agents and reasoning engines for heuristic decision-making process.

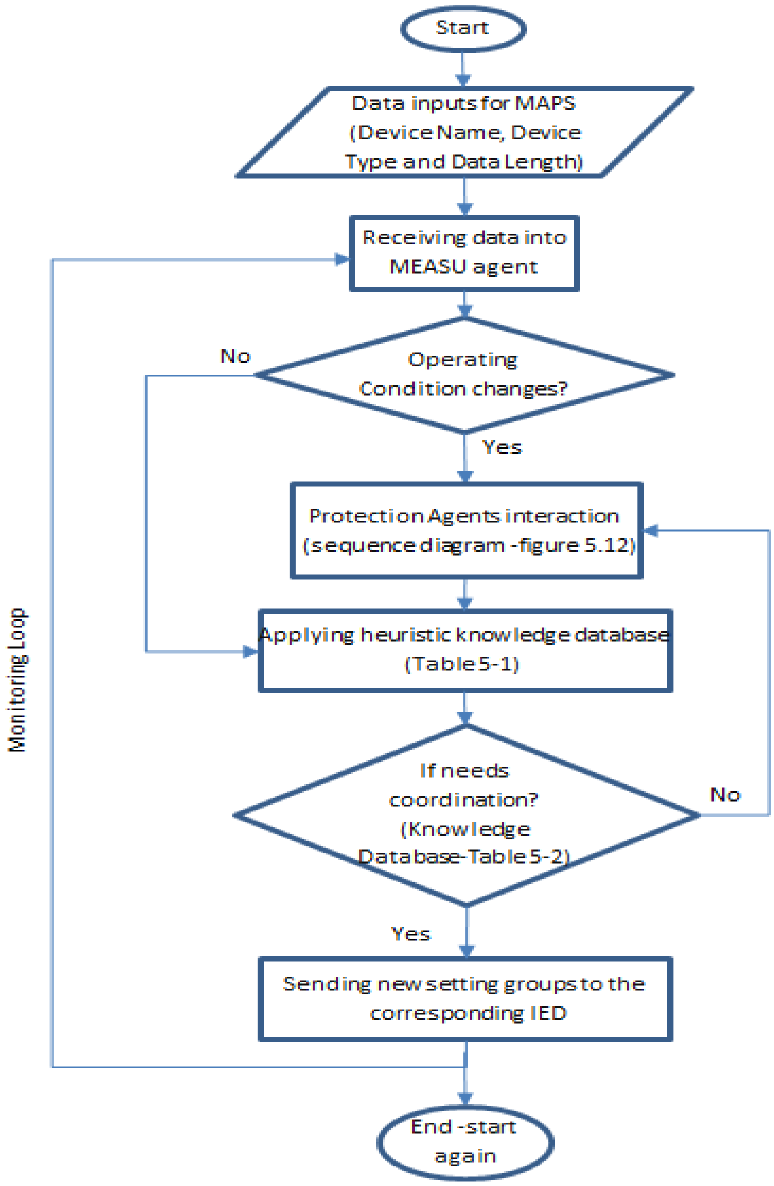

Figure 5.17 Flow chart representing MAPS monitoring loop and information.

5.4 MAPS Application Software

For implementation phase of MAPS, a software application has been developed, which performs specific tasks and functions allowing flexibilities for end users to deploy different elements of the proposed protection strategies. As there are different domains of simulation with various features and requirements with the proposed MAPS, development of the software application to provide a unified framework for interfacing between hardware and software elements of the simulation platform is critical to integrity and credibility of the simulation results. Thus, in this section, to ensure functionalities and services required for each subsystem of the MAPS, application software is explained in detail. The core of the MAPS software application is based on agent development software (JADE) while logic programming element (PROLOG) is wrapped in MAS framework to integrate heuristic decision-making process within the agent domain application. Although, there are other aspects related to agent deployment, synchronization between different domains and object-oriented modelling of the power system elements, which support establishing a unified architecture for developing MAPS. Different components of the MAPS application software are explained as follows.

5.4.1. Graphical User Interface (GUI)

For MAPS software, the GUI has been developed for user to provide required information for deployment of the protection agents within power system protection. In the first stage (form), the numbers of IEDs, which reside in the proposed interconnected distribution network, are collected. For the second stage (form), information for configuring data arrays and formatting the data exchanged between the Simulink environment and the multi agent system are requested from the user through an input window form. Figures 5.18 and Figure 5.19 show the input forms and message prompts designed for user to enter requested data for MAPS. As shown in Figure 5.19, the input data and information entered by the user is essential to build the architecture and arrangement of the IEDs.

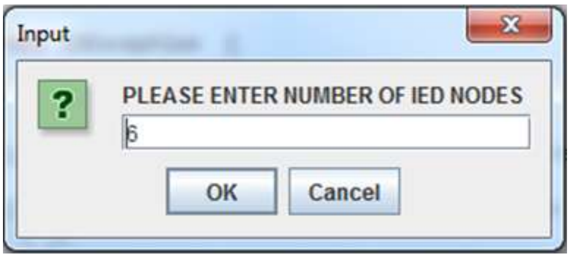

Figure 5.18 GUI for assigning number of protection IEDs.

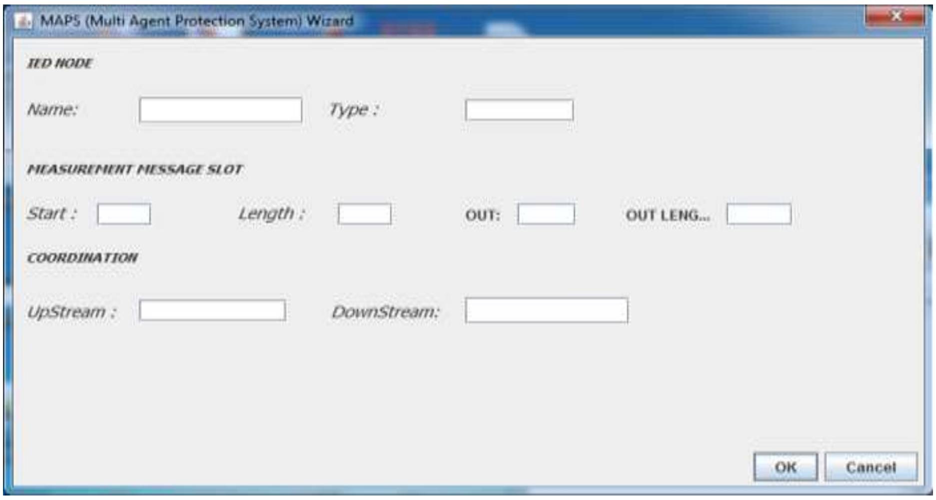

Figure 5.19 Graphical user interface to collect information for each specified protection node.

The input information in the MAPS form (Figure 5.19) is used to assign a name for each IED device. Also the type for IED device indicates the type of power system element/component protected by that specific IED node. In the measurement message slot the start and length of a data array are specified for each protection IED to access and read real-time measurement values received from power system simulation environment. Although depending on the type of IED node, different electrical quantities or operational characteristics of the nodes are assigned to be updated in the measurement message. Similarly, the output data array is specified by length of output array (OUT LENGTH) and start of the array (OUT) in the MAPS form. The output array is used to store and send group settings for each IED node as the outcome of the MAPS heuristic decision-making process. Finally, in the coordination section of the MAPS form information about the arrangement/location of each IED node and its neighbouring IED node are entered by identifying as downstream or upstream IED nodes. In the next step, based on the information collected from the MAPS GUI, the agents and protocol which have been devised for communication and exchanging measurement data between the MAPS and real-time power system simulation environment is explained.

5.4.2. Interfacing Agents

Interfacing agents are defined to ensure real-time data exchange between the two simulation environments. In fact, the inputs and outputs of each specific simulation domain have to be synchronized at each simulation step while SIMULINK and JADE are running independently. There are three different types of agents with different tasks which have been introduced to synchronize data exchange between the two simulation environments. Figure 5.20 illustrates the use of case for interfacing agents as data exchange between SIMULINK and JADE environment takes place. As shown in Figure 5.20, Synchronization, Measurement and Output are the three different agent types, which cooperate with each other to exchange real-time data between the two separate simulation environments. Tasks and behaviours of the interfacing agents are explained as follows.

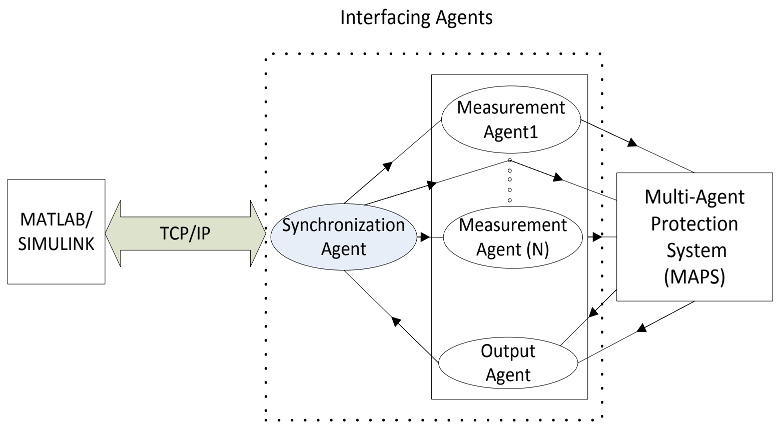

Figure 5.20 Establishment of the real-time data exchange utilizing interfacing agents.

5.4.2.1 Synchronization Agent

The task of Synchronization agent is to establish a TCP/IP communication interface and exchange simulation data between the SIMULINK and JADE. However, to ensure a real-time simulation framework, the inputs and outputs of the two simulation environment has to be updated in each time step of the simulation. Therefore, following the establishment of the communication link by Synchronization agent, data received from SIMULINK environment is sent to Measurement agent to update measurements data in agent layer within the JADE platform. On the other hand, data received from the output agent is sent to SIMULINK environment. The data exchange loop between SIMULINK and Multi-agent protection system is updated at each simulation time step. Figure 5.21 illustrates the sequence of exchanging data between Multi-agent protection system and SIMULINK environment. It should be noted that, the GUI explained earlier has been developed to allow users to configure interfacing agents for exchanging desired length of inputs and output data between the SIMULINK and MAPS.

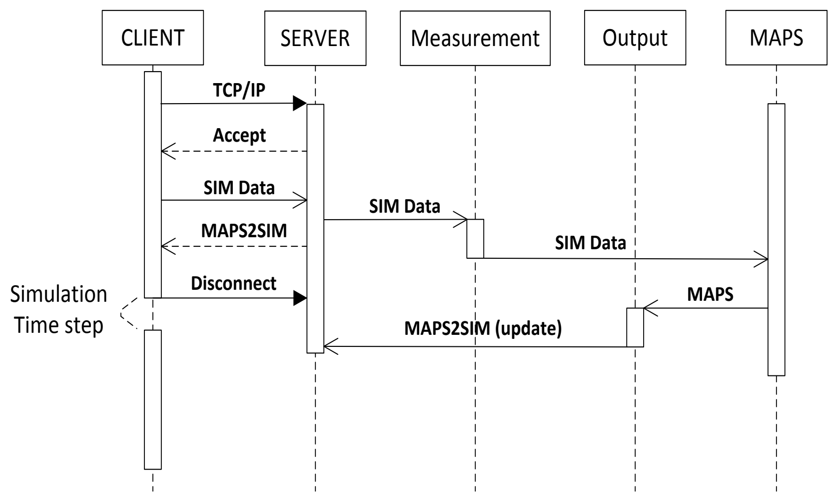

Figure 5.21 Sequence diagram representing message passing between interfacing agent.

5.4.2.2 Output Agent

Similar to measurement agents, the Output agent is a link between the Synchronization agent and the MAPS. However, the main objective for devising Output agent is to avoid bottleneck in data exchange between the Synchronization agent and the SIMULINK environment. Agents in JADE environment are run in separate threads and can receive multiple messages from other agents. Thus, for the Synchronization agent managing data exchange loop between JADE and SIMULINK, processing multiple messages and updating output data can affect the simulation speed and introducing delays in output data passed to the SIMULINK. In order to prevent delays in output data sending to SIMULINK, an Output agent is defined which receives output data messages from MA protection system and update the output data message. Consequently, the Output agent sends an updated output message to Synchronization agent to be sent to SIMULINK. Figure 5.22 illustrates the sequence of the messaging between the MA protection system and Output agent.

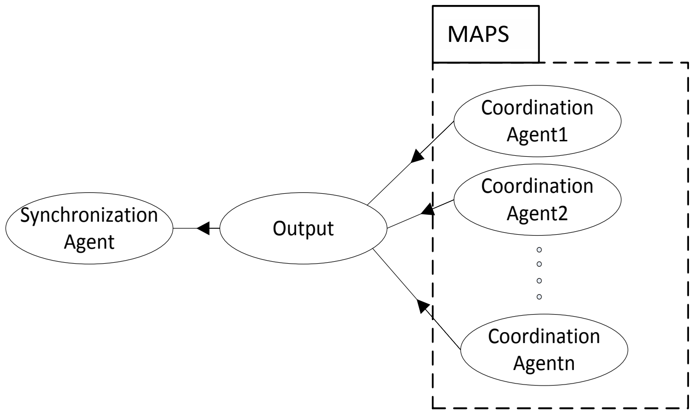

Figure 5.22 Procedure to update output from the MAPS into real-time simulation environment.

5.4.3. Object-Oriented Data Modelling

Having described protection agents as software entities interacting within the domain of the power system to/and capturing system information and events, modelling of the power system components as abstractions of system/relevant information to power system domain is essential to implement required services and operations of the smart grid paradigm. Therefore, a methodology that can introduce a systematic approach to develop relevant information model entailing extended heterogeneity of the modern power system is of vital importance to address scalable and maintainable database of information system. In developing the information model for power system components, the object-oriented paradigm has been adopted, which introduces important advantages such as interoperability and reusability/modularity to developed/proposed MAPS. Basically, in object-oriented approach, real-world elements can be modelled based on relevant information to the application domain. For example, information such as measurement data, device types or status information can be the attributes for protected power system components, which are placed in MAPS application. Thus, according to object-oriented approach each power system components such as CB, DGs and other elements can be defined as instance of classes where protection agents can access information associated with protection or protection related applications. In practical view the idea of object-oriented information modelling has been a key solution to define many advanced intelligent operational concepts such as self-healing, automatic restoration and etc, as power system automation and operation of smart grid paradigm are concerted with ICT elements. Consequently, for integration of MAPS into modern power grids, identifying the information for each element in a well-defined semantics within the field of the protection system is conducive to a flexible modelling of information based on hierarchy of the object-oriented classes. Thus, in the current information modelling for the power system components, a common class of electric component with attributes related to measurement values (for example voltage, current and power, etc) are defined as the main classes and the other electric components are defined as extension to electric device class [199, 200]. In Appendix D.1 associated classes and codes for each of the classes have been shown.

- **DFIG**

As an electric power generation system with renewable energy sources for generation of the electric power, Doubly-fed Induction Generators (DFIGs) are defined as a class of the electric device which in addition to common measurement values such as current, voltage and power , the operation slip of the DFIG system is important for specifying the operating condition of the DFIG component thus it (DFIG class) can be defined as a subclass of the electric device object with addition of data attributes of operation slip, generation mode etc.

- **DG**

Similar to DFIG system, DG system is modelled as electric power generation unit class where measurement quantities such as voltage, current, power are defined as data attributes used for state transition evaluation. Although there are other data attributes or properties related to DG system such as specifying control mode (frequency or voltage), these can be defined for identifying operation modes within hierarchical control system suggested for interconnected distribution networks.

- **CB**

For CB class the measurement values updated in time domain simulation are the voltage, current, active/reactive power and power flow direction. Also, status of the CB is defined as

Boolean attribute, which is used for connection or isolation of particular section of the distribution lines.

- **Load**

Load class is defined as subclass for the CB class with the same measurement attributes like voltage, current and power which is updated by real-time measurement values received from power system simulation environment. The class type is important for application of decision-making process as the expert rules take into account the CB type in their antecedent of their reasoning logics.

- **Main Grid**

The main grid is defined as a specific CB type, which shares the same data attributes within the CB class but it has its type as Main.

5.5 Summary

The focus in Chapter 5 has been mainly concerned with technical aspects related to development of the MAS and methodology of integrating heuristic approach to fulfil protection tasks under prevailing changes in the operation condition and interconnected distribution network. Thus, in the initial stage, detailed interaction for MAS such as middleware and services provided by JADE software is discussed where some of the concepts such as task execution for agent behaviours, information sharing and communication between the agents have been explained. Later, based on fault current analysis investigated in Chapter 4, different operating conditions and the topology of the connections of the DFIG wind farm is expressed in terms of expert knowledge database rules, which is used to support cooperative decision-making process between different protection IEDs. To implement expert knowledge database rules PROLOG (Programming Logic) has been used for determining coordination between the protection IEDs with communication of its local neighbouring nodes. Furthermore, for integrating the aforementioned steps in an autonomous and self-reliant way, application software and relevant software development methodologies were applied to facilitate implementing MAPS for real-time simulation framework. In the next chapter, verification and validation of the proposed MAPS based on functionality and performance of the protection system using simulation results is discussed.

CHAPTER 6
SIMULATION and RESULTS

The final stage in development and establishment of the proposed MAPS is associated with validation and analysis of the results in which evaluation of the protection system performance under real-world scenario is investigated. In this chapter a real-time simulation testbed has been developed to address the establishment of MAPS as Cyber-Physical System (CPS) within future power system context. Moreover, simulation results demonstrating functionality and performance of the MAPS are discussed and compared against conventional protection system. The research outcomes from this chapter have been presented in several technical papers and one co-authored journal paper. A conference paper titled "Real-time simulation framework for protection system in smart grid application" has been published on developing the testbed for MAPS which is reference for integrating ICT infrastructure into power system operation. Also plots and simulation results produced in this chapter have been used for other publication in Chapter 5 of this PhD research study. Initially in this chapter development of the testbed for MAPS is discussed in section 1 where architectural arrangements of different software and hardware tools are explained. In section 2, co-simulation technique for establishing real-time data exchange between protection agents and power system components is demonstrated. For section 3, HIL techniques and some technical details on configuring protection IEDs for online adjustment of protection settings through IEC61850 standard and GOOSE messaging is addressed. Section 4 explains experimental testbed with hardware equipment and devices used in VUZS laboratory to develop the real-time simulation platform for MAPS. Following that in section 5 simulation results including time domain plots and message communications between different agents in MAPS are discussed to identify and support the validity of the proposed MAPS for improvement of functionality and performance of the protection system in interconnected distribution network. Finally, in summary section some of the advantages and characteristics of the MAPS in dealing with various operation conditions within interconnected distribution networks are highlighted.

6.1 Testbed Development

Generally, in planning and study of power system protection, modelling and validation of the research outcomes are fundamental to ensure accuracy and consistency of the results in comparison to real-world process. However, considering state of the art computing, sensing and communication technologies embedded in operation of the modern power system, the need for up to date and reliable simulation techniques is becoming inevitable. In fact, the paradigm of Smart Grid architecture and interactions between subsystems of multi-domain physical environment has introduced various intricacies, where utilizing conventional simulation tools can compromise the reliability and consistency of the simulation results. Thus, the main focus of the research study in this thesis is on protection system and its operational performance, there are certain aspects related to modelling and validation of the proposed MAPS, which are critical to replicate system integrity including hardware interaction for producing accuracy required for development of the protection system. To deal with the aforementioned complexities, a testbed setup constituting different simulation tools and equipment has been developed in which, hybrid simulation techniques such as real-time co-simulation and HIL are adopted for implementing MAPS. In Figure 6.1, architectural layers constituting the simulation platform for implementing MAPS have been illustrated where protection agents, power system real-time simulation and HIL layer are interfaced via communication services of TCP/IP and IEC61850 GOOSE messaging. The two-sided arrows on the left in Figure 6.1 illustrate two duplex communication paths for data exchange between different layers of the MAPS sub-domains. As shown in Figure 6.1, real-time measurements and protection settings derived through heuristic decision making process between protections agents are exchanged between the two top layers of the MAPS architecture. Similarly, a separate connection path has been established between power system and HIL layers to exchange GOOSE messages for selecting desired protection settings in protection IEDs while trip signals published by protection IED are subscribed simultaneously open CBs within power system simulation layer.

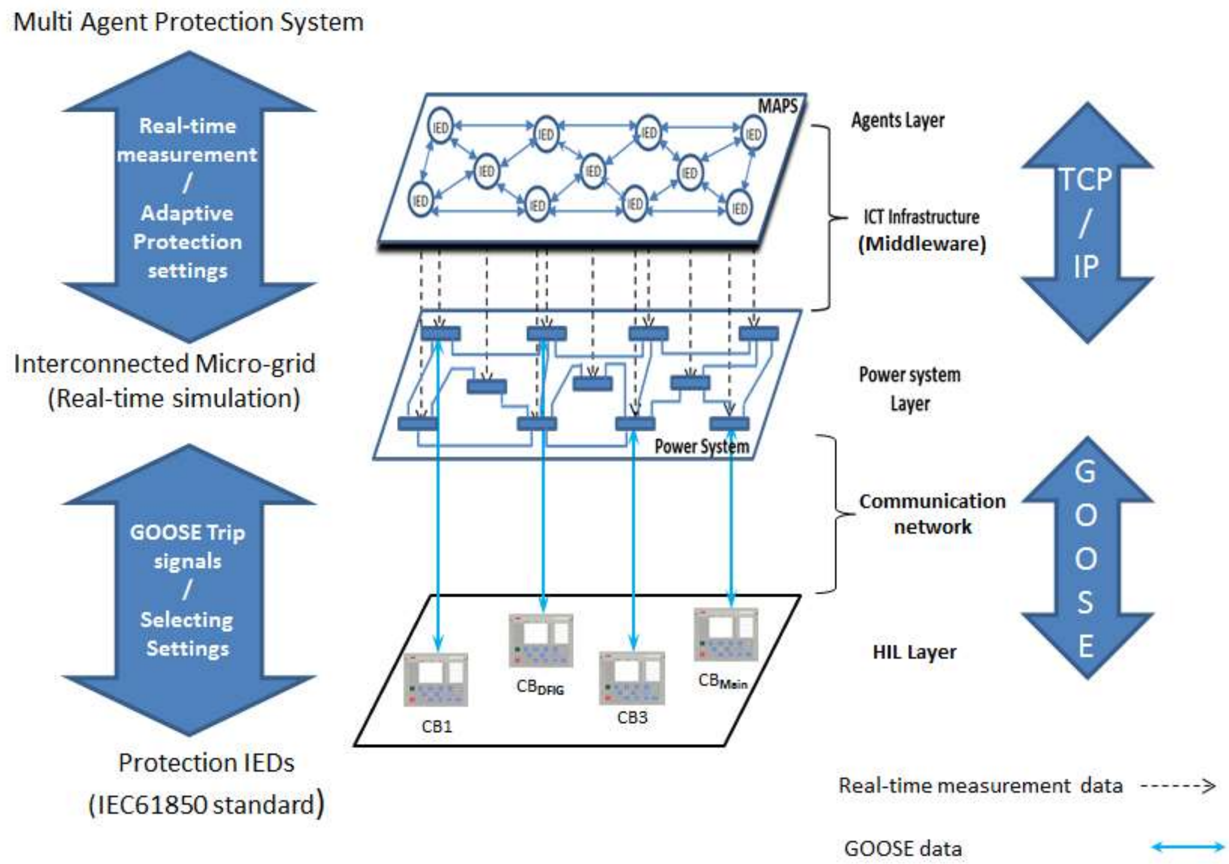

Figure 6.1 Architectural integration for MAPS test bed.

Finally, with respect to the architectural integration, for incorporating ICT elements into power system operation, there are different hardware and software tools, which have to be coordinated through different simulation techniques. In the next section (6.2), some of the technical details corresponded to each simulation techniques is discussed and the final experimental setup developed in VUZSS laboratory is demonstrated.

6.2 Real-Time Digital Co-Simulation

As discussed in section 6.1, one of the challenging aspects in verifying the functionality and performance of the MAPS under real-world operation scenario is the inclusion of interaction between different domain subsystems where separate simulation tools and solver engines are adopted. Although there are simulation tools for specific simulation domains, which has been optimized and improved through years of development, their simulation results are bounded to constrain on modelling and conditions of the particular aspect of study. Similarly, having introduced new equipment and improved functionalities for secondary system in power system operation such as CTs, VTs and protection IEDs, realistic modelling and simulation of the modern power is reliant on multiple simulation environments, where there are already well-established tools for modelling desired domain of study. From technical point of view, integration of several simulation software tools into one single software tool, which can take into account all the details and intricacies of the existing subsystem domains of study is not an easy task, if not possible at all [34]. However, as an alternative way for simulation of multi-domain heterogeneous physical systems, a hybrid approach based on simultaneously interfacing different simulation software tools and running the simulation process in real-time has been proposed, which is called co-simulation. Through literature [34-36], application of co-simulation has been highlighted as a cost effective and reliable method for research studies on modern power systems. Thus, in the current research study co-simulation approach for interfacing between continuous simulation domain of the power system and discrete event-based communication messaging services among protection agents is imperative. However, the requirement of precise timing for interaction between two heterogeneous physical environments is reliant on synchronization method, where real-time data from power system elements can be exchanged with the agent development environment as decision-making process takes place. Although, for conventional software tools timing of the simulation process is not critical as solver engines are bounded to solve specific physical phenomena, but for co-simulation between different software tools running in parallel, real-time synchronization of the processes have to be addressed using specific equipment rather than PC desktops. In general, utilization of real-time digital simulator for developing multi-domain co-simulation environment has become an important element in conducting research studies related to cyber-physical systems, where sophisticated hardware tools and ICT supports are required for synchronizing different processes. Basically, in comparison to conventional power system software tools, one of the advantages of digital real-time simulator devices are the capability of simulating any power system component based on fixed time-steps to the order of 50 microseconds which can guarantee accurate realization for interactions between different subsystems within a unified simulation framework. Therefore, given the required timescales and accuracy in producing time domain simulation for system protection studies, a digital simulator device (OPAL-RT OP5600) has been used to establish real-time co-simulation framework interfacing both power system and agent layers. In Figure 6.2, block diagram for different subsystems and the arrangements for interfacing each process using ethernet Network Interface Card (NIC) has been shown. As seen in Figure 6.2, the interconnected distribution network is separately simulated in single domain using MATLAB/SIMULINK solver engine as the measurement values are interfaced with the MAPS block (simulation domain) through TCP/IP synchronization methods utilizing Ethernet card embedded into simulator device. Similarly, to update group settings of the protection IEDs, the embedded NIC is configured for using IEC61850 communication protocol to exchange GOOSE messages between MAPS and the protection IEDs which constitute the HIL subsystem in the simulation testbed will be discussed later in this chapter.

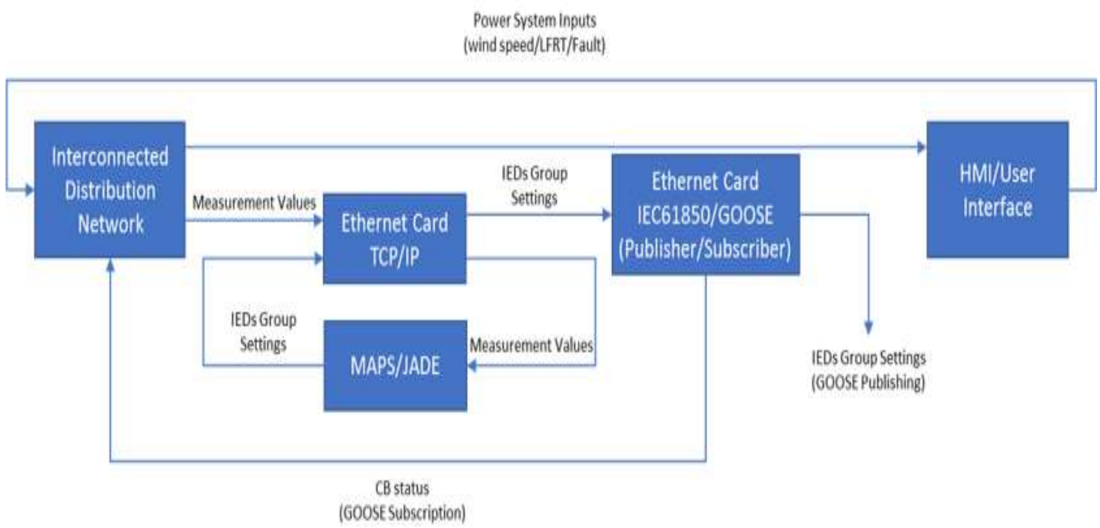

Figure 6.2 Block diagram representation of co-simulation between power system and MAPS.

6.2.1. RT-LAB/SIMULINK Real-Time Model

For developing co-simulation architecture proposed for the MAPS, requirement of real-time simulation is essential. Thus, to combine detailed modelling of the power system and flexible I/O capabilities of real-time digital simulator for interfacing with third party hardware/software, specific considerations related to preparation and deployment of MATLAB/SIMULINK model of the power system have to be performed. For this purpose, RT-LAB is used as a software tool which enables large scale power system models in MATLAB/SIMULINK to be distributed over multiple CPUs of the digital simulator and ensure fast execution of simulation time steps in a few microseconds. Moreover, the need to extend connectivity of the real-time simulation with the field equipment as shown in Figure 6.1 for HIL layer in the proposed MAPS architecture, developing RT-LAB model for the MATLAB/SIMULINK power system model is critical to represent holistic behaviour of the MAPS with respect to interactions between different layers of the platform architecture. In Figure 6.3, the RT-LAB model of the MATLAB/SIMULINK model of the power system has been illustrated where specialized block sets have been used to improve both performance and capability of the MATLAB/SIMULINK model to interface with external hardware/software tools. As seen in Figure 6.3, the solid red line boxes are the elements separating boundaries of SIMULINK model into sub-models distributed over parallel running CPUs while the dashed and dotted rectangles constitute inputs and outputs to the real-time power system respectively. As a consequence, the RT-LAB model developed for the real-time simulation on HILbox5600 real-time digital simulators has the capability to utilize MATLAB/SIMULINK for developing interconnected distribution network representing detailed simulation of Electro-Magnetic Transient (EMT) phenomena and dynamic behaviour of the connected DFIG system which is central in the system protection studies. In addition, real-time data from the power system can be interfaced to application software or field equipment for extending simulation platform for co-simulation techniques and HIL.

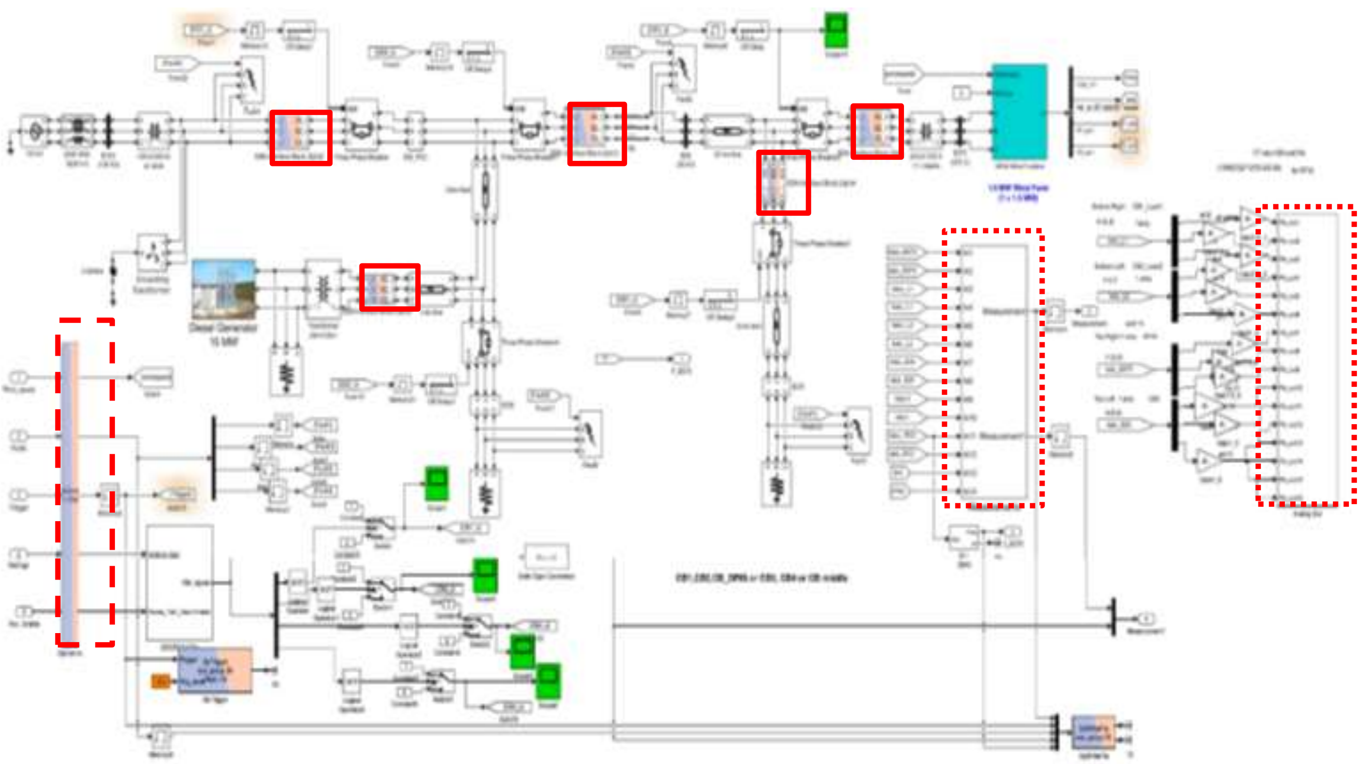

Figure 6.3 MATLAB/SIMULINK model developed in RT-LAB for real-time simulation.

Also, within the RT-LAB model, a user interface similar to HMI in real-time industrial process is provided, which constitutes a separate subsystem including graphical plots, ON/OFF switches and numerical input variables allowing the application of changes into running real-time simulation model. In Figure 6.4, a user interface window developed for monitoring and interaction with the interconnected distribution network has been illustrated. As shown in Figure 6.4 on the left dashed rectangle represents the input real-time measurement values received from the real-time model depicted in Figure 6.3, which are monitored in a time domain graph. The dotted rectangles on the right of Figure 6.4 represent ON/OFF switches and numerical input variables, which have been devised to apply fault scenarios and variations of wind speeds respectively.

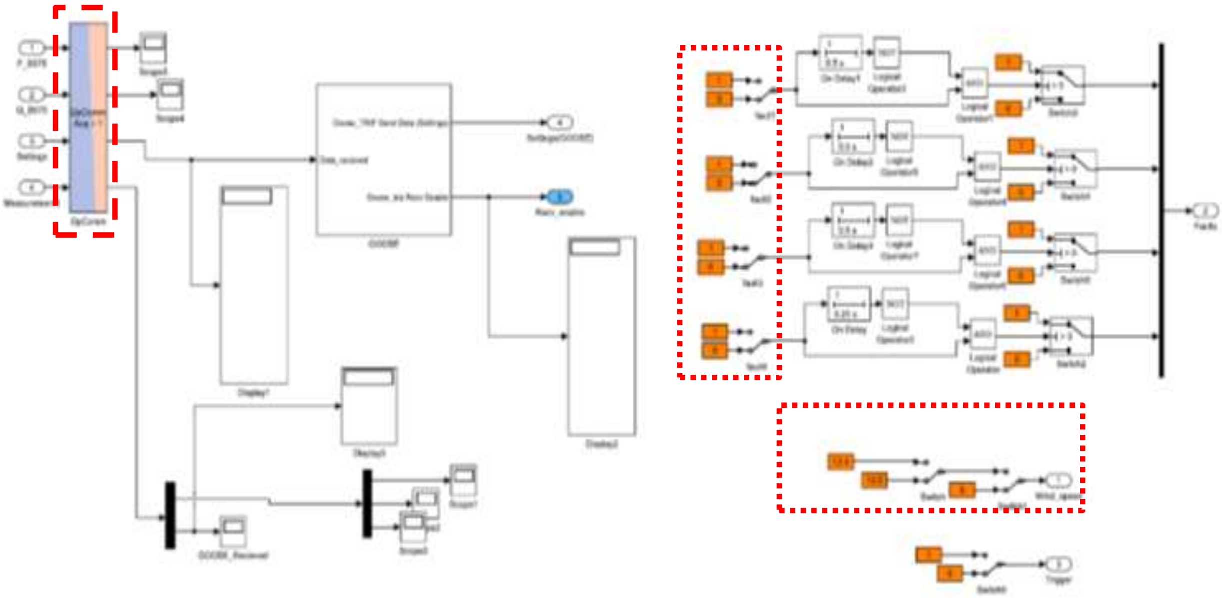

Figure 6.4 User Interface to apply changes in real-time within the RT-LAB simulation.

6.2.2. MAPS/JADE Software Agent Layer Platform

In the proposed MAPS architecture, application software constitutes the agent layer, where hardware platforms are used to support computational resources and communication interface between agents and external devices are established. However, there are considerations related to hardware and connectivity between agent containers, which have to be met for reliable performance of the MAS. Therefore, to implement MAPS software, a laptop is used as the hardware platform, which accommodates appropriate processing power and memory capacities as the computational tasks can increase exponentially depending on the number of agent instances. Moreover, multi-agent application programs are quiet complex with multi-threaded processes, which in general can be developed on laptops or PC platforms, since implementation of MAS for distributed modules in protection IEDs are not practical and cost-effective for a laboratory testbed. However, having said that the possibility to embed MAS into protection IEDs is dependent on successful deployment and laboratory tests, as large production numbers can reduce the costs for less expensive computational platforms (FIPA standard Multi-Agent Protection IEDs). Thus, in the current research study, limitations for agent layer are associated to the number of protection IEDs deployed within MAPS and hardware computational capabilities, where the agent containers are developed. Finally, there are libraries and APIs for supporting JADE runtime environment with built-in services, which hides complexities of tires from application developers. The hardware platform used for developing the agent layer is a laptop with Intel core i7 CPU, 500 GB SSD hard drive and 8 GB RAM and Windows 7 operating system. Also, the network card and Ethernet port (RJ-45) are used for interfacing agent layer with the other layers in the MAPS architectures.

6.3 Hardware In the Loop (HIL)

Generally, the state of the art ICT capabilities embedded into protection IEDs have been devised to introduce more functionalities and flexibilities into protection system in order to meet the requirement for protection system in modern power systems where applications, such as self-healing and adaptive intelligent protection schemes are implemented. However, given the heterogeneity within hardware and software design of each specific IEDs, complexity for detailed simulation and interaction between the protection devices cannot be a cost-effective solution, if it is not impossible. Therefore, as a relevant approach to deal with the aforementioned drawbacks where communication and data exchange plays a critical role, the application of HIL is integrated with co-simulation of the MAPS to establish a laboratory based simulation platform for studying and analysis of the advanced protection schemes such as MAPS. In fact, application of the HIL is necessary for assessing the performance of the protection system as there are other factors such as communication latency (timescale for protection IEDs), cybersecurity and interoperability between the protection IEDs, which may affect the overall performance of the protection scheme under real-word operation scenario [8]. In Figure 6.5, the proposed HIL based architecture to establish a simulation platform for MAPS has been illustrated which consists of the primary power system distribution network and the ICT infrastructure operating in parallel within different simulation domain/environment. As shown in Figure 6.5, OPAL-RT (OP5600) is utilized for real-time simulation of the power system network, where there are 6 protection IEDs from ABB (REF615) which constitute (for) the HIL subsystem and configured to interact with MAPS using GOOSE messaging defined in IEC61850 communication standard. The GOOSE messages subscribed by protection IEDs are pre-configured to activate desirable TOC curve within the protection IED depending on the output of the decision-making process from MAPS. In, each protection IED configured to SEND/PUBLISH trip signals back to the simulator box (OP5600) to open the corresponding CBs, upon detection of faults in the distribution network. Thus, it is important to note that the real-time interaction between protection IEDs as HIL and the power system components, in this case CBs, are takes place through communication network, which has been represented with red dashed line in Figure 6.5. For implementation of the real-world scenario for the proposed simulation platform, there are some details related to testbed components and accessories such as power amplifier unit, Ethernet switch and real-time simulation of the power system which are explained in the next section.

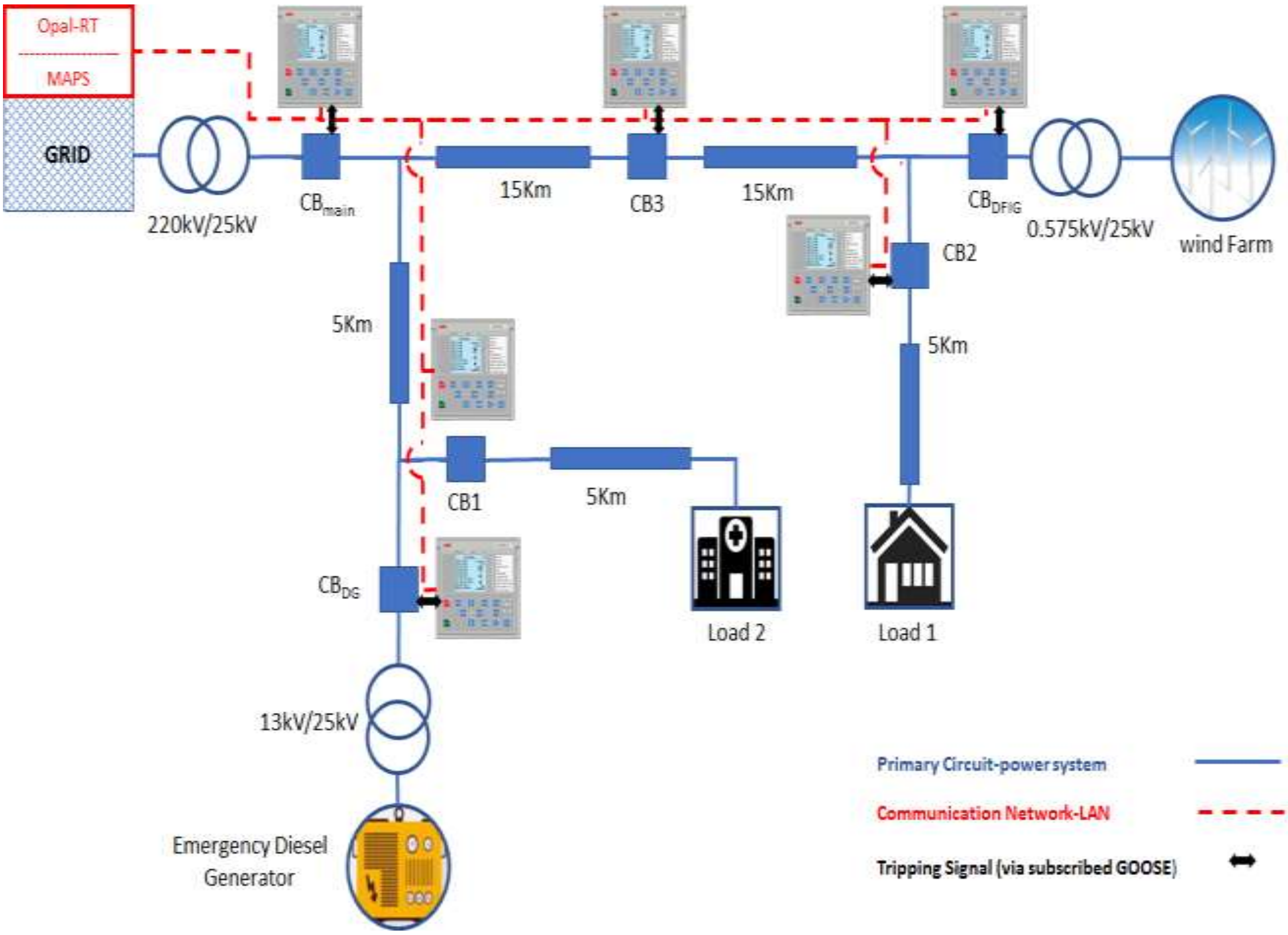

Figure 6.5 Proposed HIL architecture in MAPS.

6.3.1. Protection IEDs Configuration

For the HIL setup, protection IEDs constitute the main elements for interaction with both agent layer and real-time power system. Basically, unlike the old mechanical relays, modern protection IEDs have embedded advanced ICT capabilities, which enables desired functionalities matched for operation in sophisticated protection schemes as many of its functional parameters can be adjusted via online communication and remote communication links. For example, introduction of compatibility for IEC61850 standard has provided flexibilities for modern protection IEDs to dynamically change their operation configuration or settings envisaging a modern intelligent power system automation, which has significant effect on performance of the power system protection. Therefore, effective utilization of the modern protection IEDs rely on specific software tools and understanding the capabilities/availabilities of the IEC61850 standards with desired operation performance is essential. According to the HIL architecture and the operational task/role of the protection, IEDs within the MAPS architecture is related to changes in/selecting group settings of the IEDs and also configuring for TOC curves to operate and send trip signal through communication network using GOOSE. To do that PCM600 is a software tool that is provided by ABB for configuration of the REF615 IEDs to setup the protection settings such as turns ratio, configure trip signals and CT current levels. There are two main steps to configure the protection IEDs for performing desired interaction (publishing and subscribing to GOOSE messages) within MAPS architecture which are explained.

6.3.1.1 GOOSE Message

Basically, GOOSE messaging is a protection related communication services used in IEC61850 standard for time critical signals, such as trip signals within power system automation paradigm. To configure interaction between protection IEDs and MAPS, as seen the IEDs have been configured for two-sided interactions by PCM600 to PUBLISH/SEND trip signals for TOC protection function operating through the network as it is subscribed by OPAL-RT simulator to operate the CBs of the interconnected network in real-time simulation environment. The second GOOSE messaging published for protection IEDs for selecting appropriate group settings on-line in real-time operation of the power system. Therefore, using IEC61850 standard and GOOSE messaging, desired tasks and functionalities considered for future modern power system has been performed. As shown in Figure 6.6, two sets of GOOSE message have been configured into two specific batches to fulfil the required task of the protection IEDs as HIL for the proposed MAPS. The first batch for GOOSE messages is related to the operation of the TOC function and trip signals, which are published by the ABB protection IEDs to inform fault detection and send trip command. The first GOOSE batch is the control blocks configured as GOOSE messages each consists of three bits identifying the protection setting group for each protection IEDs and is published by OPAL-RT HILbox5600 in the communication network, while each ABB protection IED is subscribed to its corresponding GOOSE message. As a matter of fact, the process of configuring GOOSE messages for publishing over network can successfully perform the required task on the condition that it is subscribed by the receiver side or GOOSE message subscribers which in this case both OPAL-RT and ABB IEDs have to subscribe for GOOSE messages published by each other.

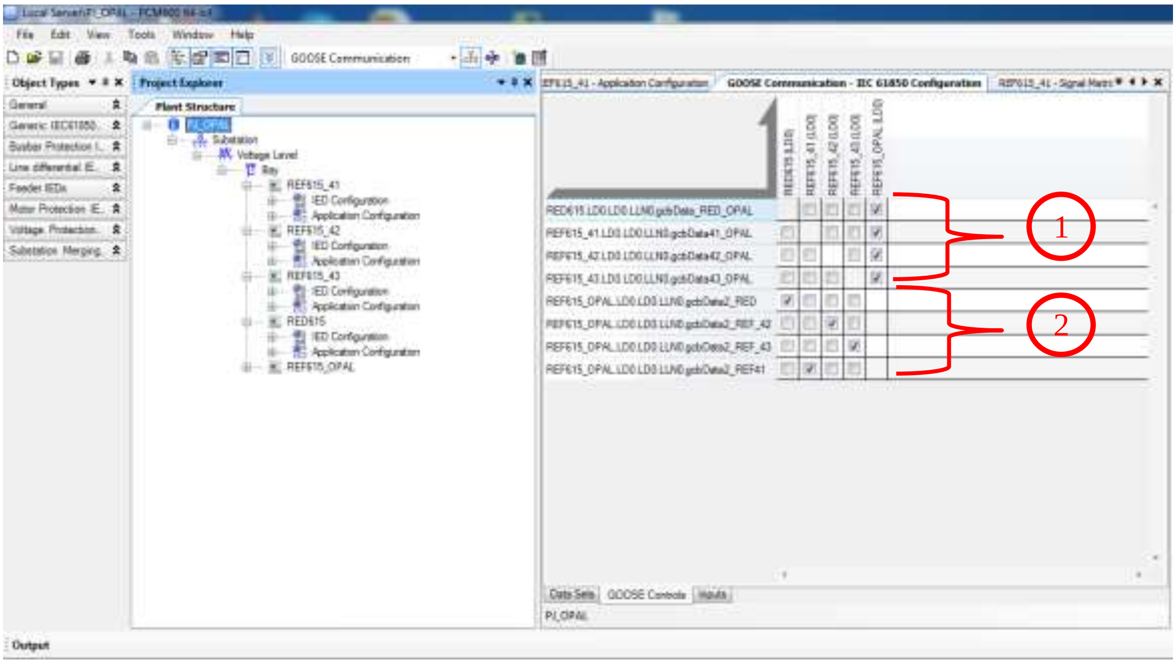

Figure 6.6 Configuring GOOSE messages for publishing and subscribing.

6.3.1.2 Application Function (Protection Function)

In PCM600 the application function option is used for connecting received GOOSE message as an input or to activate specific function block within the protection IEDs as the subscriber to published GOOSE messages. Thus, following the configuration for publishing GOOSE messages, protection IEDs have to be configured to subscribe for GOOSE messages published by OPAL-RT HILbox5600, which can activate different group settings according to the GOOSE control block in which the protection IED is subscribed to. Similar to GOOSE configuration process, the IED configuration tool (PCM600) is used to apply desired connection for application configuration within ABB protection IEDs. Thus, as seen in Figure 6.7, GOOSE receiving blocks labelled as first step to subscribe for the published GOOSE message and depending on the GOOSE message data frame different LEDs on the HMI face plate will be turned ON. For the second stage in Figure 6.7, the combination of the received GOOSE data bits are connected to the inputs of the protection IEDs group settings block for selecting appropriate protection settings of the TOC curves. There is a default setting and three inputs for different group settings in the protection IEDs which allow selection of 4 different TOC curves under various operating condition of the power system. Generally, the default value is specified by three zeros at the inputs of the protection group setting block, which identified the selection of group setting 1 but for all other non-zero inputs the selection of group settings of 2, 3 and 4 can be activated. It should be noted that Figure 6.7 represents application configurations for one protection IED as for other IEDs the same steps have to be taken.

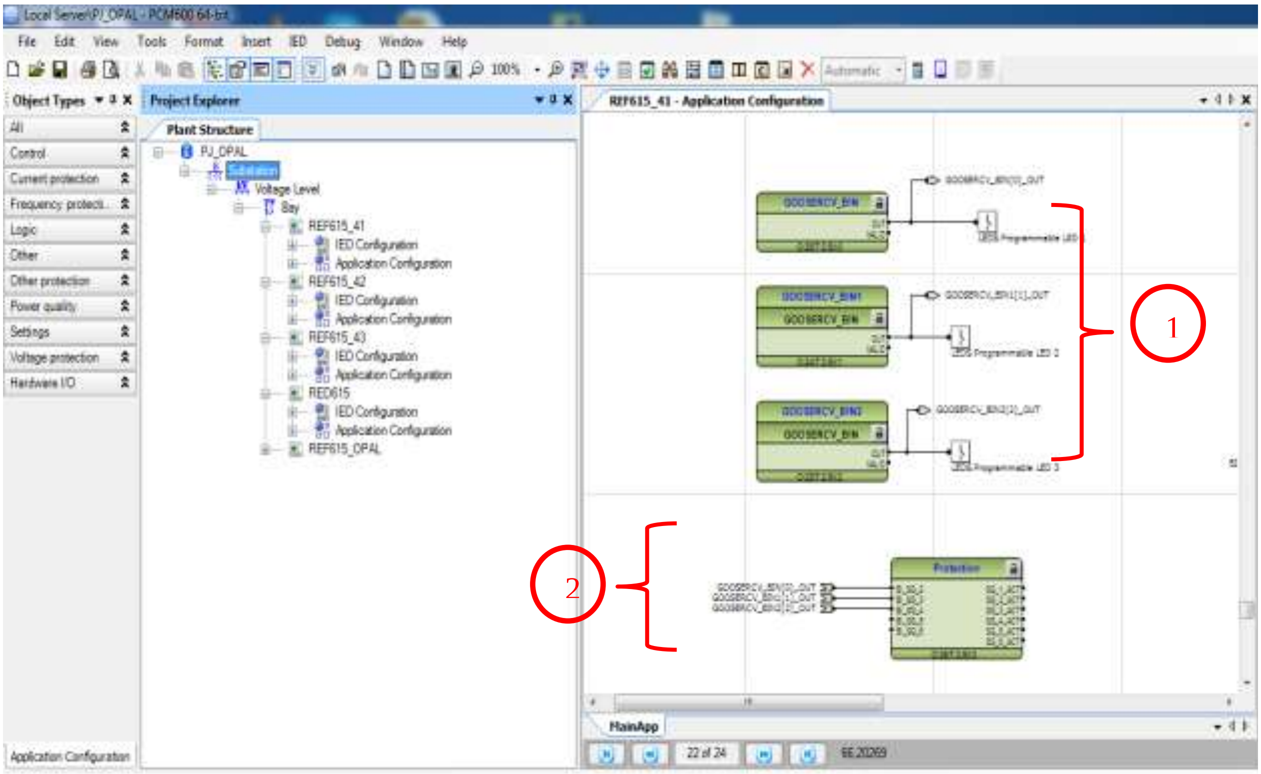

Figure 6.7 Configuring protection IEDs for online selection of the group settings.

6.3.2. Power Amplifiers

Generally, power amplifiers are used as test equipment for commissioning and testing operation and performance of the protection IEDs and their accuracy against protection settings within different protection schemes. However, in the case of using HIL amplifier, it is exploited to simulate power system signal conditions appropriate to inject 3-phase CT and VT signals into the protection IEDs terminals under the test. For HIL application, power amplifier is used in a closed loop architecture including OPAL-RT HILbox5600 and protection IEDs, where low level analogue signals from the Digital to Analogue (DA) cards driving the test unit power amplifier injects currents into IED terminals. The power amplifier is configured to receive low level signals and supply the amplified signals for evaluating of the protection IED and performance of the system protection schemes against real-time simulation of EMT signals. In the proposed closed loop architecture for utilizing the power amplifier, the process of CT and VT signal injection into protection IED terminals continues until the real-time simulation is terminated. There is a software tool, which is called F6 configurator to conform linearly scale low level signal inputs from the OPAL-RT DAO card into output signals injected to protection IED terminals. In the present scenario 3-phase CT currents for 4 IEDs are configured used for HIL configuration of the power amplifier.

Figure 6.8 Power amplifier simulator for injecting CTs and VTs signals into IEDs terminal - courtesy of Doble Engineering.

6.3.3. Network Architecture

Communication network constitutes the backbone for developing MAPS as data communication and messages between the different simulation domains are exchanged to enable a unified simulation framework. Basically, the interface between the different layers of the MAPS architecture is reliant on LAN and the Ethernet switch, which complement the closed loop of interactions to demonstrate holistic behaviour of the MAPS system under real-world operation scenarios. Thus, using the hardware related to LAN accessories can take into account technical aspects associated with data communication within real-time simulation platform factors such as communication delays and configuration of the network switch for cybersecurity and reliable network operation. Also, it can lead to holistic modelling and simulation approach for MAPS.

6.4 Experimental Setup

Finally, the proposed architecture which developed the testbed for experimental tests of MAPS is based on real-time co-simulation of power system components and ICT infrastructure consisting of communication network elements (Ethernet switch and Ethernet medium) and protection IEDs. Thus, to establish a real-world scenario for interaction between power system elements and IEDs within the power protection system, the concept of Hardware in the Loop (HIL) has been adopted to ensure real-time characteristics for the experimental testbed. In Figure 6.9, the entire system architecture of the power system and its LAN for data communication between IEDs have been represented. To simulate power system operation and its transient behaviour, a real-time digital simulator (OPAL-RT HILbox 5600) has been used for modelling power system components and their interactions within real-time constrains. In parallel to power system simulation, the power protection system is developed over a LAN where IEDs from ABB (REF615) are configured to communicate their data information using IEC61850 GOOSE messaging service. The data communication between real-time simulator box and IEDs in power protection system is through an existing NIC on OPAL-RT HILbox which supports IEC61850 communication standard.

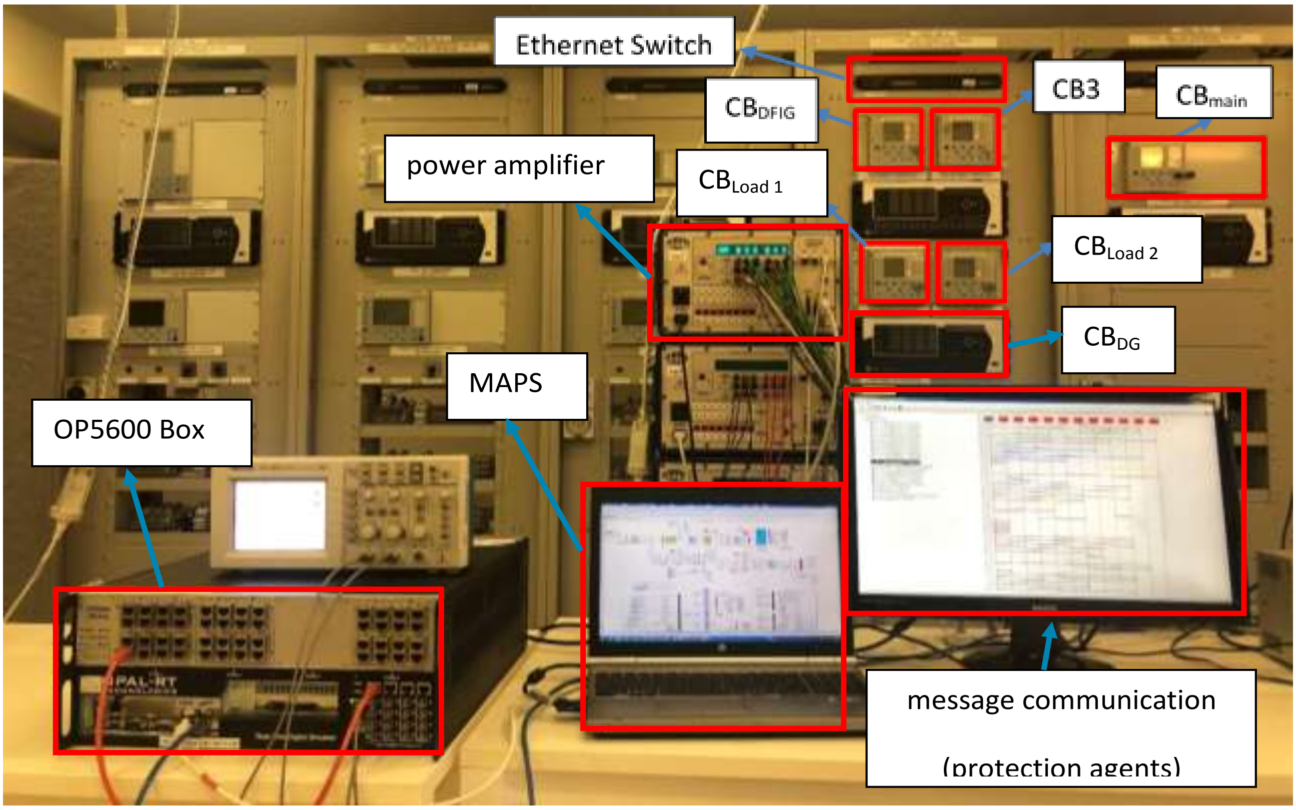

Figure 6.9 Developed testbed for the proposed MAPS in VUZS Laboratory.

6.5 Simulation Results

Aside from the designing and development part represented in Chapter 5, validation and assessment of MAPS under real-world scenario is a critical step to establish the main objective of this thesis. Basically, there are two aspects related to the performance of the MAPS, one is concerned with protection scheme performance considering adjustment in the group settings, functionality of the protection system and selectivity in operation of the protection IEDs. The second aspect is related to agent cooperation and messaging communication between protection IEDs, which share their knowledge towards a global goal of isolating faulty line sections utilizing distributed decision-making process. As a result, evaluating the holistic behaviour of MAPS is obtained through appraisal of effective coordination between protection system tasks and embedded heuristic decision-making engine/approach based on MAS. In the next subsections, simulation results from the developed testbed are investigated to highlight the performance of each integral element of the proposed MAPS.

6.5.1. System Protection Performance

Functionality of the protection system is dependent upon detecting faults and isolating the faulty section as system stability is maintained due to timely operation of the CBs in distribution network. Therefore, for evaluation of the MAPS performances, different operating scenarios are proposed and compared with conventional protection system approach, where the adaptability of TOC curves with respect to operation condition and tripping times are highlighted as the parameters improved through cooperative/distributed reasoning. Basically, with respect to fault current analysis discussed in Chapter 4 and variations in fault current contribution levels, the two main critical scenarios in operation of the interconnected distribution networks are transitioning from grid-connected to islanded mode and interconnection of DFIGs system leading to variation of the fault current contribution due to intermittencies in available wind speed. In the next stage, using the developed testbed to capture holistic behaviour of the MAPS, scenarios corresponded to each operation modes are presented real-time simulation plots.

6.5.1.1 Grid-Connected

As discussed in Chapter 4, for various operating scenarios, due to higher fault current levels in Grid-Connected mode operation conventional methods are used for setting TOC curves under different group settings where the pick-up values are fixed for approximately two times of the loading/normal condition. However, that can be a drawback in conventional approach with respect to interconnected DFIG systems as variation of the wind speed can increase the loading current to encroach into pick-up current zone of the protection IEDs due to the infeed current from the DFIG system. In order to represent the effect of the wind speed on protection system, Figure 6.10 illustrates variation in average wind speed from 9m/s to 12.5 m/s as the input to DFIG system interconnected into distribution network developed in chapter 3.

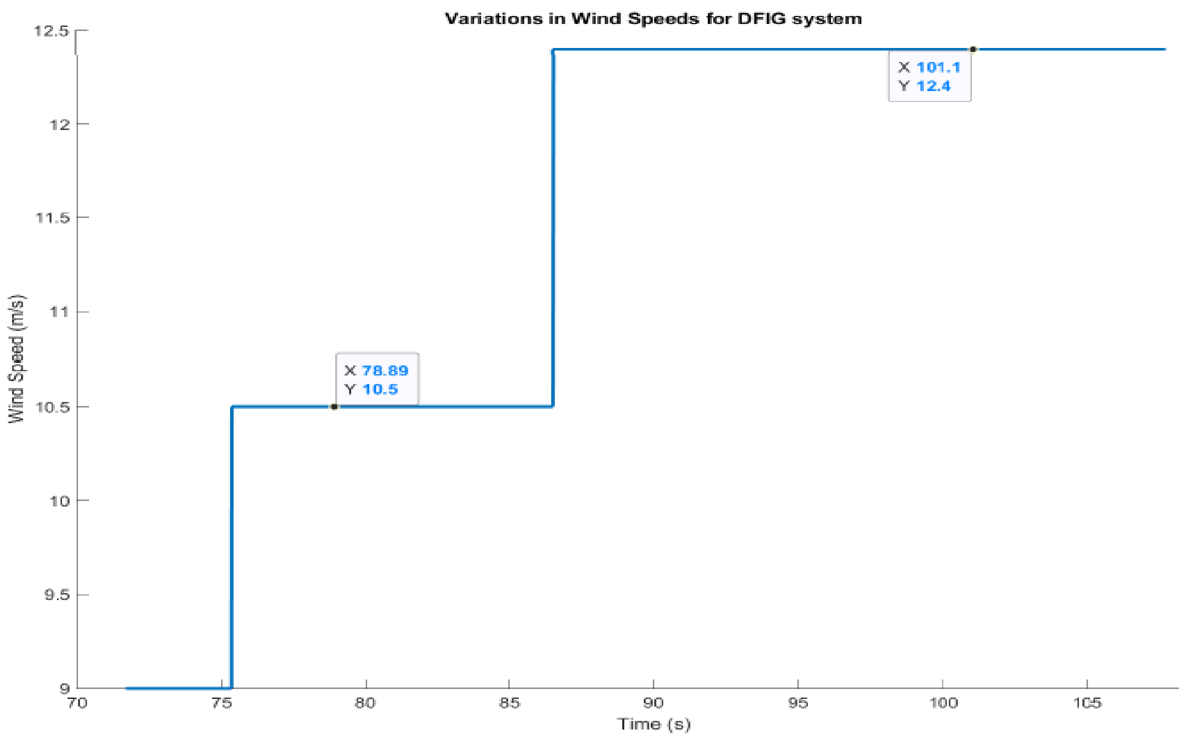

Figure 6.10 Variation of the wind speed as the input for DFIG system.

In consequence of increases in wind speed, control system in DFIG system extracts the maximum power from the wind speed profile, which feeds CB_{DFIG} with higher power generation capacity leading to rise in loading current and subsequent false tripping. As seen in Figure 6.11, the real-time simulation for loading current of DFIG system with HIL protection IEDs have been illustrated to highlight occurrence of the false tripping as the current increases due to increase of wind speed. It can be seen from Figure 6.11, DFIG system operates under normal condition, however the drawback in the fixed settings for the protection IEDs causes false tripping disrupting infeed current from the DFIG into distribution network.

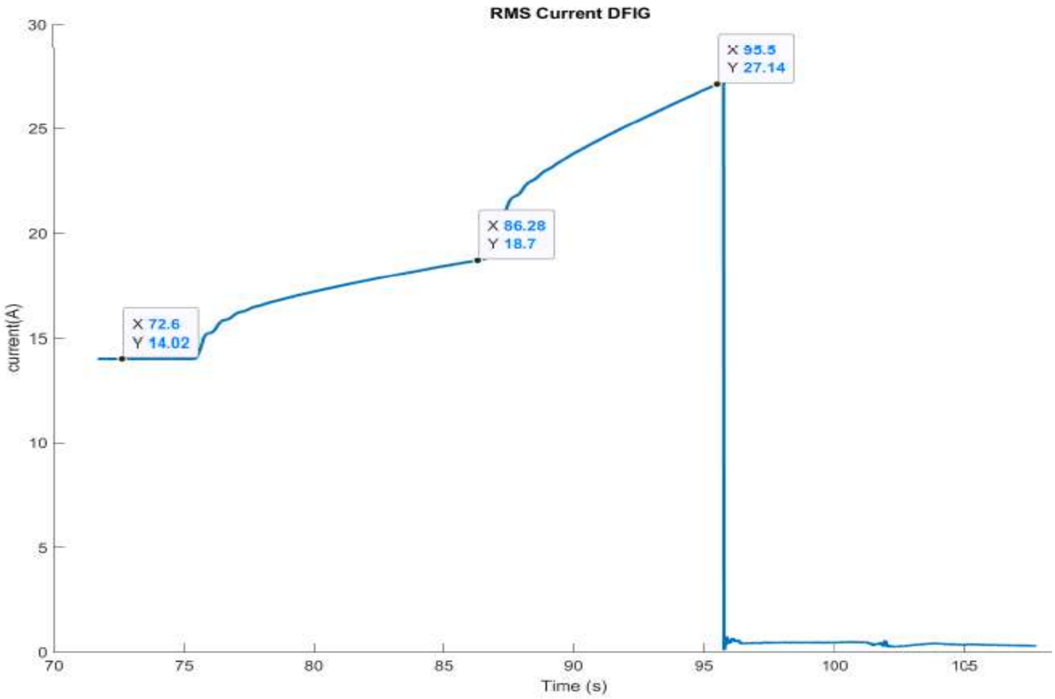

Figure 6.11 False tripping at DFIG connection point due to variation in wind speed.

Aside from false tripping, which can affect reliability of the protection system at the connection point of the DFIG system, variation in operating condition of the DFIG system can further introduce mis-coordination between protection IEDs within interconnected distribution network. For example, in regard to any fault upstream or downstream to DFIG system protection coordination can be affected by contribution of fault current from DFIG system leading to mis-coordinated tripping and indiscriminate selectivity within protection system. To illustrate the impact of fault current contribution from DFIG system, two 3-phase fault scenarios at downstream (F1) and upstream (F2) of the DFIG system at the lateral feeder have been chosen to investigate potential indiscriminate tripping due to connection of DFIG system into distribution network. In Figure 6.12, both fault current at CB1and CB_{DFIG} with the maximum wind speed of 12.5 m/s has been illustrated, where contribution of DFIG fault current at CB1 is identified and compared in time-domain simulation.

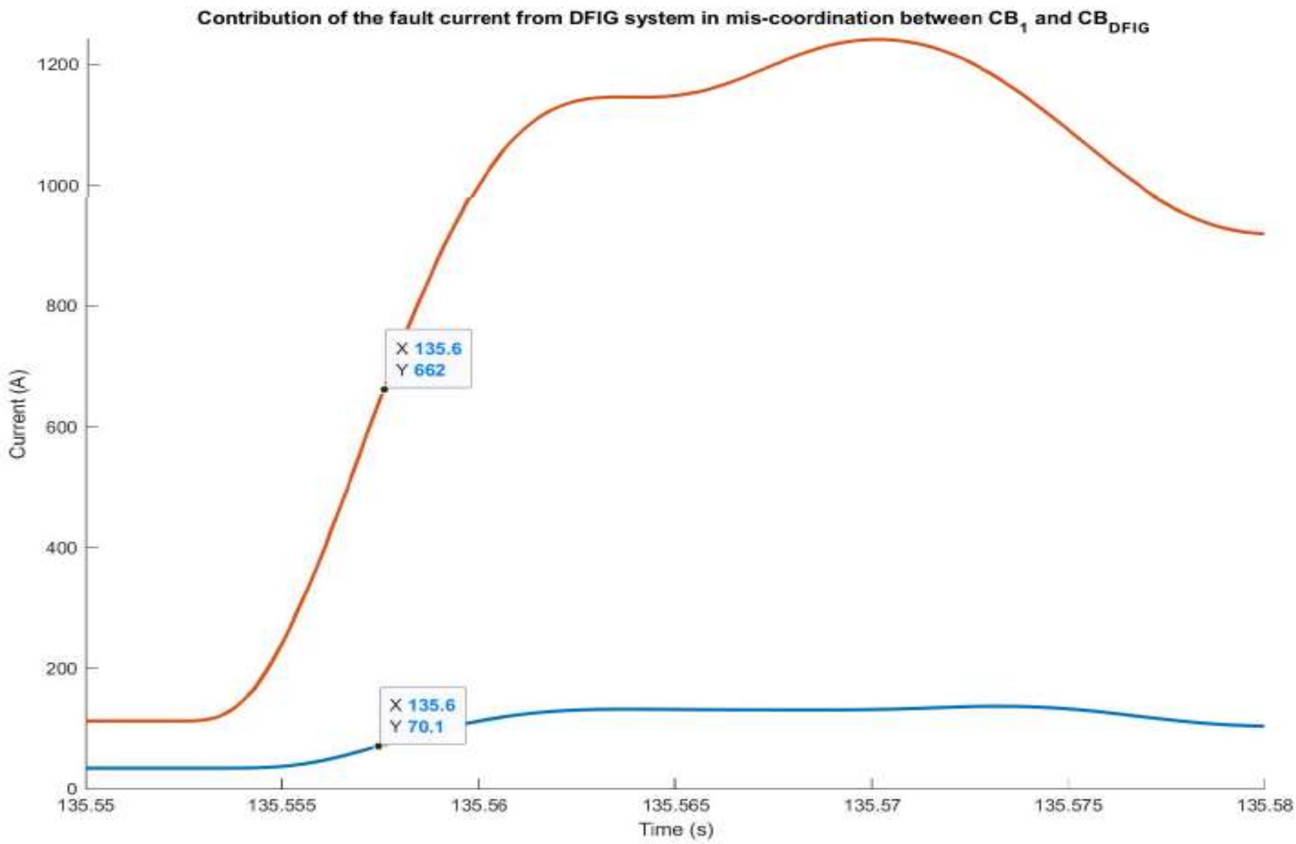

Figure 6.12 Contribution of fault current in downstream DFIG.

As shown in Figure 6.12, the data points on the fault current curves provide a comparison for fault current contributed by DFIG system (blue curve) at CB1 location (orange curve) which has been specified in real-time domain. It is worth mentioning that the fault current curves are related to grid-connected mode with 1 DFIG system where contribution of fault current level from DFIG can approximately increase the fault current at CB1 by 12% causing faster tripping time for disconnection of the CB1. As regards the timing of the trip signals for the protection IEDs at CB1 and CB_{DFIG}, Figure 6.13 compares tripping times in a real-time HIL simulation platform, where protection settings are fixed for two times of the loading current compared with normal operating conditions (Grid-connected and wind speed of 12.5 m/s for DFIG system). As shown in Figure 6.13, delayed operation of the CB1 (orange colour) has led to tripping of the CB_{DFIG} , which simultaneously affects system protection selectivity and undermine system stability within the interconnected distribution network. Considering similar scenario for CB2 with different operation and penetration level of the DFIG system for fault in upstream in Fault2 locations, real-time HIL simulation for trip signal and their timings can be shown for highlighting possible mis-coordination between protection IEDs.

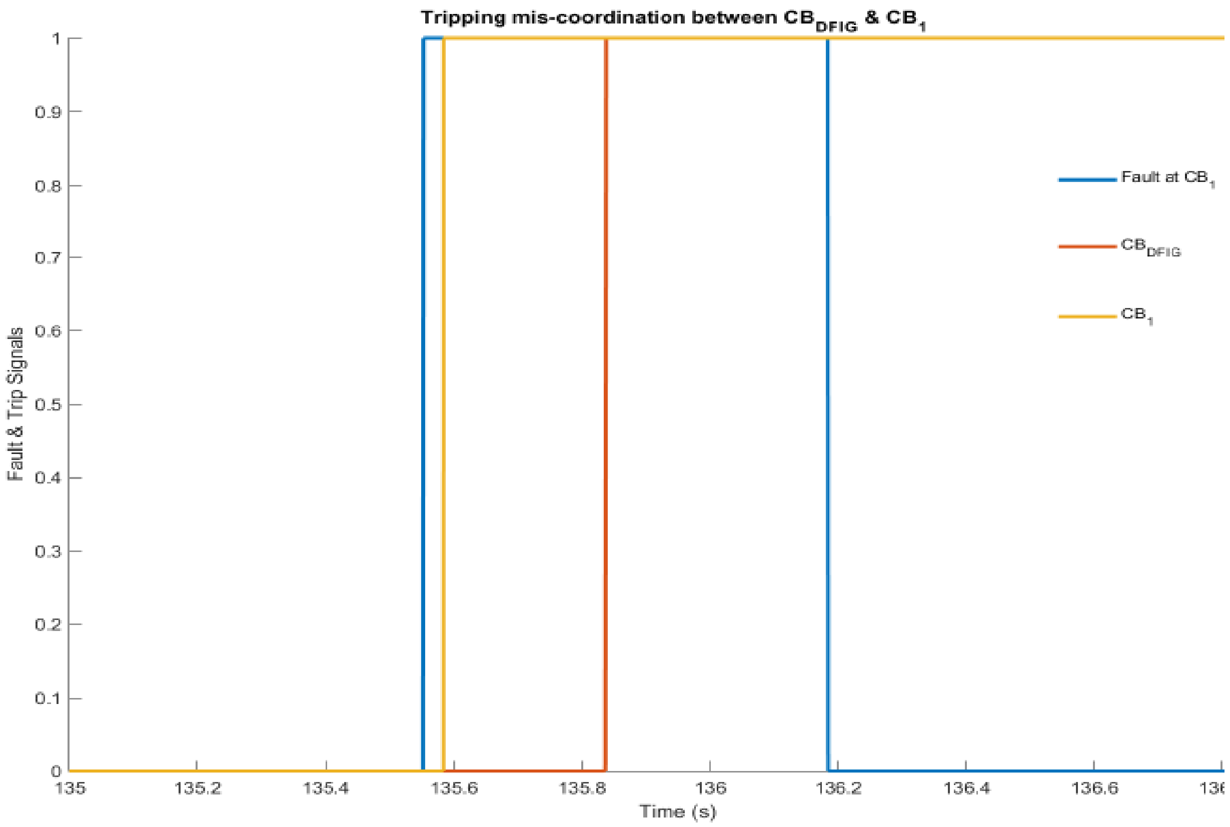

Figure 6.13 Mis-coordinated tripping time between for downstream fault at CB1.

In conclusion, for connection of the DFIG system variation in wind speed or operation slip have adverse impacts in conventional protection system performance, where false tripping and mis-coordination between protection IEDs degrades power quality and system stability within interconnected distribution networks.

6.5.1.2 Islanded

For interconnected distribution network, islanding mode of operation is of critical importance as the main goal for interconnecting DERs is to increase power system reliability during the time of grid-connected, where local loads are supplied by local power generation units. Consequently, investigation of the protection system performance under islanding mode is essential to utilize potentials of connecting DG and DFIG system into distribution network. As discussed in Chapter 4, fault current levels under islanded mode operation are weakened due to removal of main grid capacity for contribution of fault current and reduced mass inertia for interconnected DERs. Therefore, calculation of the protection settings based on contribution of high level fault current from the main grid is not reliable to meet functionality and performance required in the protection systems. To further investigate the shortcomings related to conventional protection settings, a 3-phase fault scenario for Islanding mode operation of the distribution network including DG and DFIG system as local generation units is considered to compare timings of trip signals at each CB locations in real-time HIL simulation. As shown in Figure 6.14, time-domain response for the fault current seen at each CB location has been plotted where F2 (Fault2) at the upstream of DFIG system is applied during the islanded mode of operation. It is obvious from Figure 6.14 that protection IEDs at CB2 location has not detected the fault as the fault current level is sustained for the whole duration of the fault (0.5 second). However, as the protection IED at CB2 fails to isolate fault within the desired time interval, CB_{DFIG} operates and disconnects DFIG system from the distribution network. This is the effect of sympathetic tripping caused by delays in tripping CB2 during the islanded mode of operation where fault current at CB2 are sensitive to fault current levels devised for the grid-connected mode.

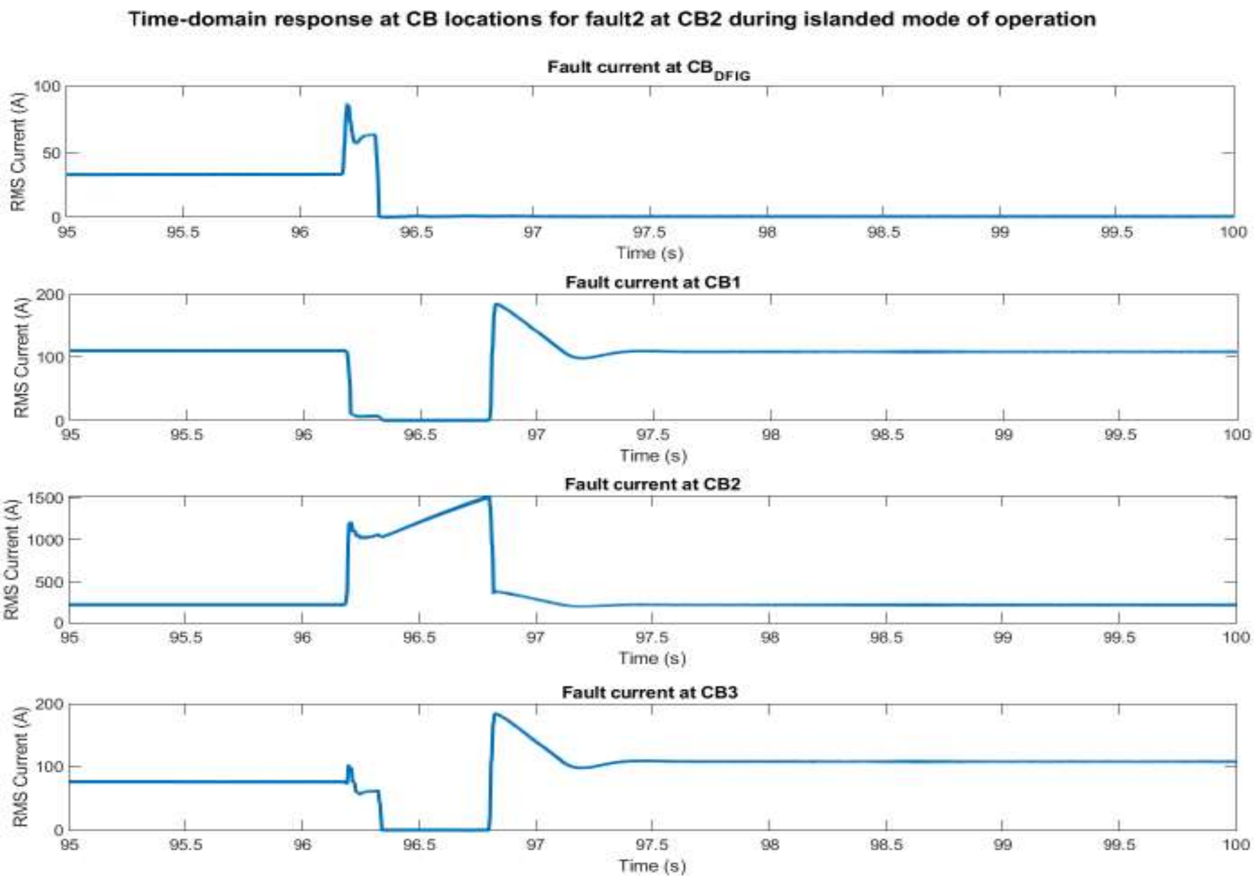

Figure 6.14 Sympathetic Tripping of the CB at DFIG connection point.

The trip signals representing the CB statuses for F2 (Fault2) applied during islanded mode of operation and the fault duration has been shown in Figure 6.15. According to CB trip status at CB2 location it is obvious that the protection IED fails to detect and isolate the fault section due to inaccurate protection settings devised for grid-connected mode of operation. However, protection IED at DFIG connection point has reacted to the upstream fault and has opened CB_{DFIG} sympathetic to a fault at CB2.

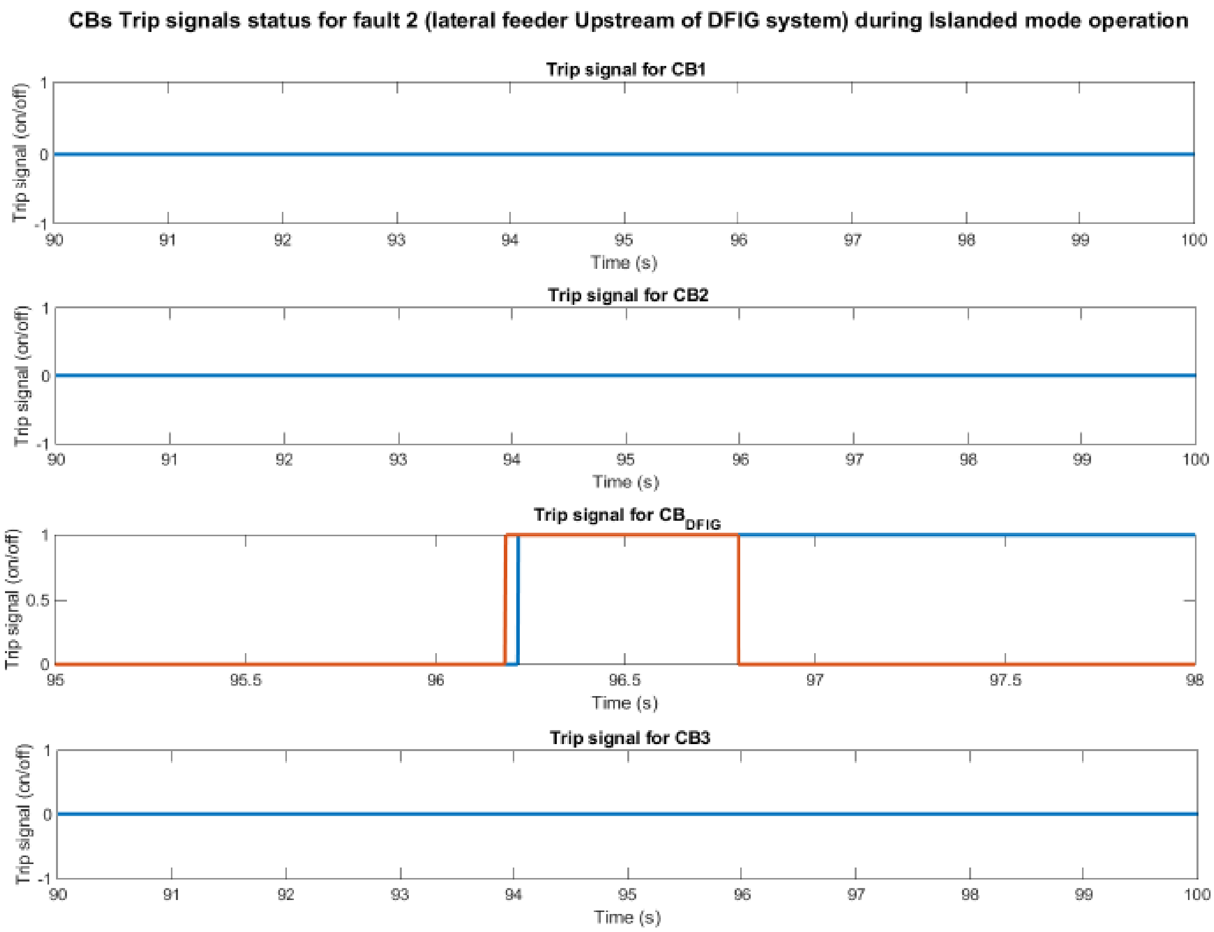

Figure 6.15 CB status representing sympathetic tripping at DFIG connection point.

Technically, protection settings for islanded mode of operation have to be adjusted according to the operating condition of interconnected distribution network, where variation of the wind speed and number of connected DFIG systems (penetration level) have to be taken into account.

6.5.2. MAPS Performance

Having integrated the heuristic decision making into protection system based on MAS, protection settings can be adjusted according to information and knowledge updated from the operating condition of the system through communication between different protection IEDs in the distribution network. Basically, the proposed MAPS utilized to fulfil protection system task is a knowledge database devised with respect to fault current analysis explained in Chapter 4, where set of rules are adopted to change pre-configured group settings for TOC curves within the protection IEDs software. Therefore, to evaluate the performance of MAPS against conventional approach in devising protection settings, various scenarios associated with operating condition of the interconnected distribution network are demonstrated to highlight satisfactory operation and practical implementation of the proposed protection system. Similar to previous section for the first scenario, intermittencies in availability of the wind speed for DFIG system operation is studied where MAPS is capable to automatically adjust the protection settings according to operating slip (wind speed) of the DFIG system. For operating condition under different wind speeds, Figure 6.16 illustrates the increase in generation current from DFIG system where the wind speed is stepped up from the minimum limit of 9m/s to the maximum level of 12.5 m/s. As seen in Figure 6.11, while the wind speed increases, protection IED at DFIG connection point does not trip and consequently the infeed current has reaches to 34 A, which is proportional to MPPT control scheme devised for DFIG system. However, for conventional protection system in Figure 6.11, the protection IED is tripped for 27.4 A, where there are no faults in distribution network.

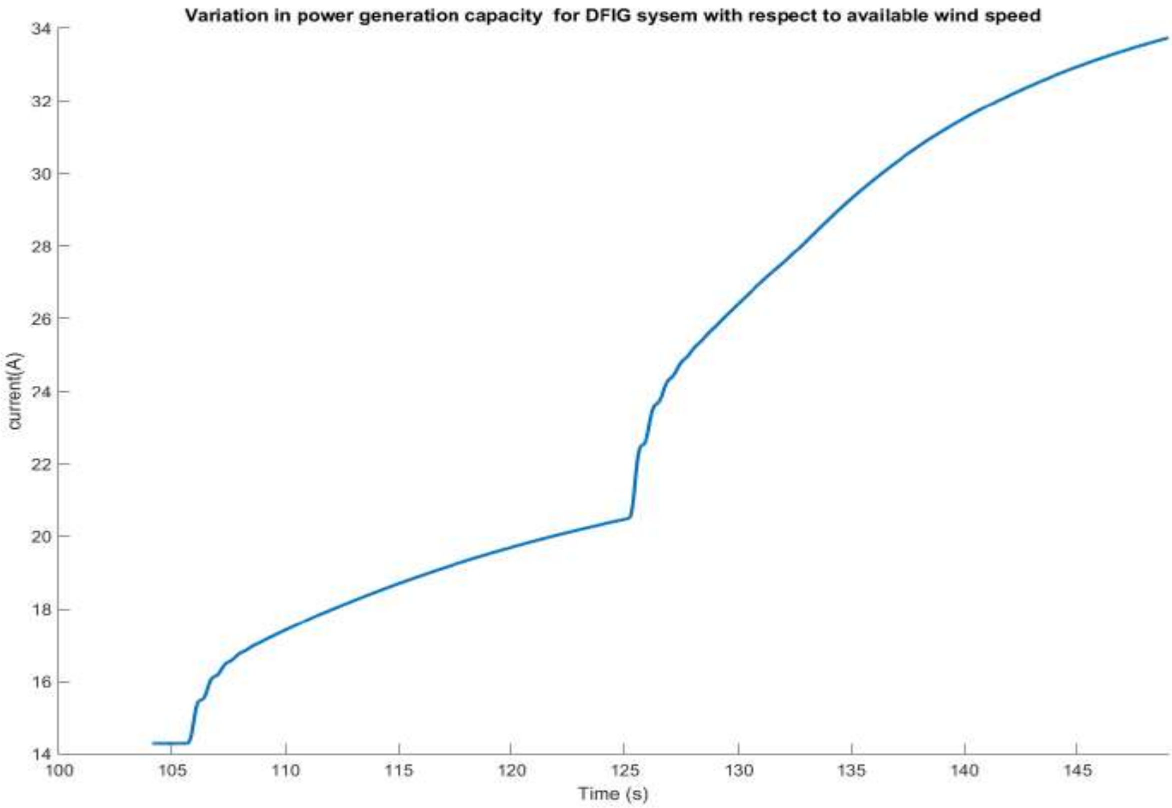

Figure 6.16 Rise of infeed generation current from DFIG system with increment in wind speed.

Thus, the advantage of the MAPS embedded into the protection IED for DFIG system is related to real-time monitoring of the operating condition including voltage, current and operation slip of the DFIG system are defined as states, where certain protection settings are chosen to meet the reliability in timely operation of the protection IED. To enable the adjustment for protection settings within the protection IEDs, different group settings are configured with respect to possible operating conditions of the DFIG system, which under specified operation condition is activated to perform protection task. Therefore, the aforementioned scenario for changing the protection settings of the DFIG is shown in Figure 6.17, where upon the changes in operation slip (wind speed) the coordination agent in MAPS applies relevant group settings to avoid false tripping of the protection

IED at connection point of DFIG system. Basically, for all protection IEDs, there are 4 group settings defined with binary state values specified by 3 zeros (000) as default group setting or setting 1 which is for the minimum wind speed available for DFIG system and the rest are setting 2 (100), 3 (010) and 4 (001). In Figure 6.17, the group setting 2 is shown to be activated by MAPS as the operating condition in DFIG system varies.

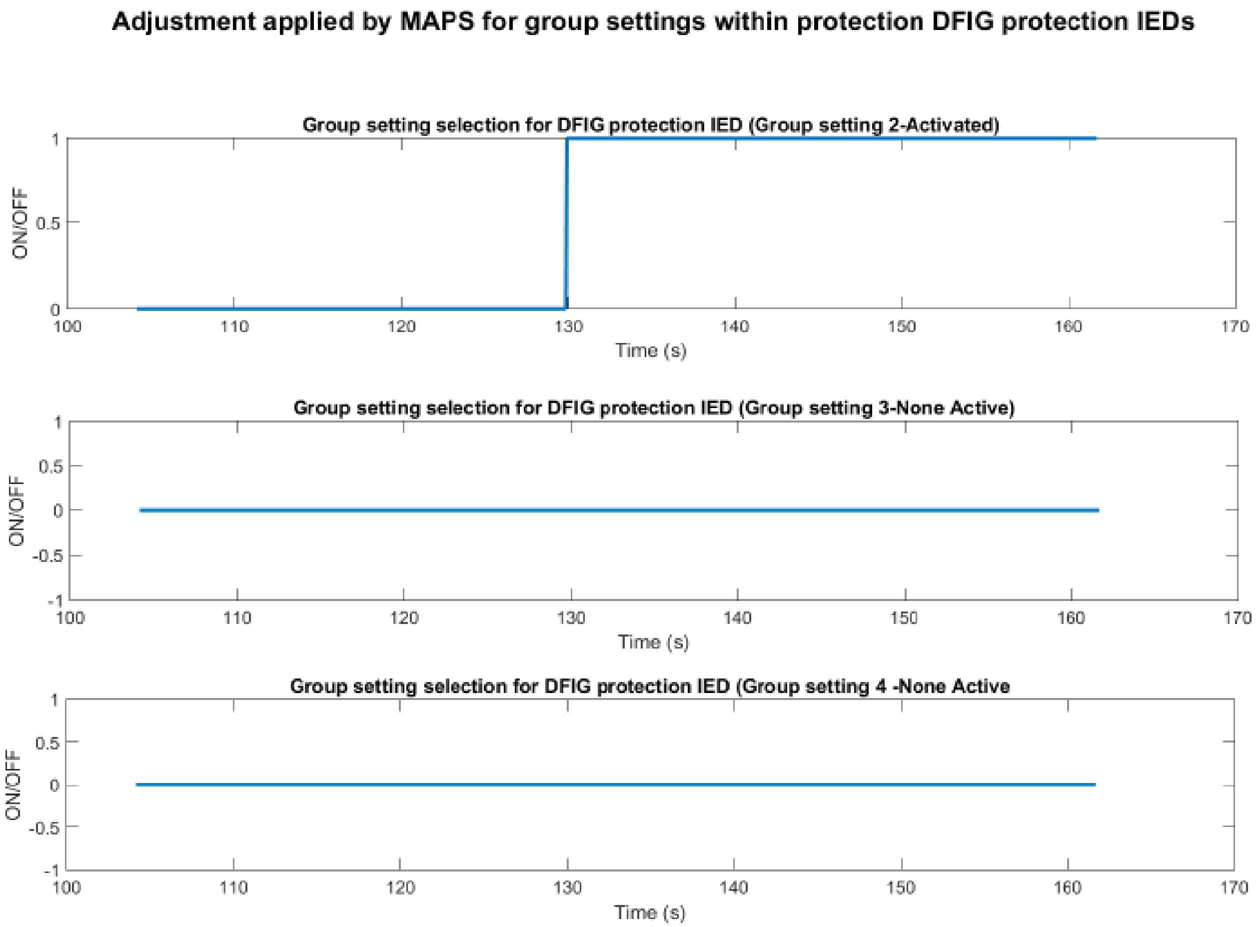

Figure 6.17 Adjustment in group settings for protection IED at DFIG connection point.

For the second case, to evaluate the performance of the MAPS under islanded mode of operation, a 3-phase fault scenario upstream to DFIG system at CB2 location F2 (Fault2) is applied, where protection issues corresponding to low level fault current and low mass inertia of the islanded mode of distribution network are key factors in selection of the group settings in the protection IED. In this scenario, cooperation between different protection IEDs are highlighted as the capability of the MAPS to determine the operating state for each protection IEDs by identifying the transition states from their upstream and downstream IEDs. Therefore, to illustrate the effective strategy adopted by MAPS, time domain response of the fault scenario for each CB locations have been plotted in Figure 6.18. As shown in Figure 6.18, the fault current at CB2 is isolated while the islanded power system recovers to its normal operating condition. In relation to MAPS performance to adjust appropriate group setting for protection IED at CB2, it is the task of protection agents and their cooperative behaviours, as discussed in Chapter 5, to share knowledge about their operation states with the neighbouring IEDs. However, depending on the CB type decision making to adjust group settings within the protection IEDs can be selected based on operating condition of the device itself, similar to DFIG system which is a power generation unit. But for CBs protecting passive systems such as loads or CB ties, selection of the protection group settings are reliant on distributedness of the MAS and its potentials to identify the topology of the interconnected distribution network through exchanging messages with upstream and downstream protection nodes.

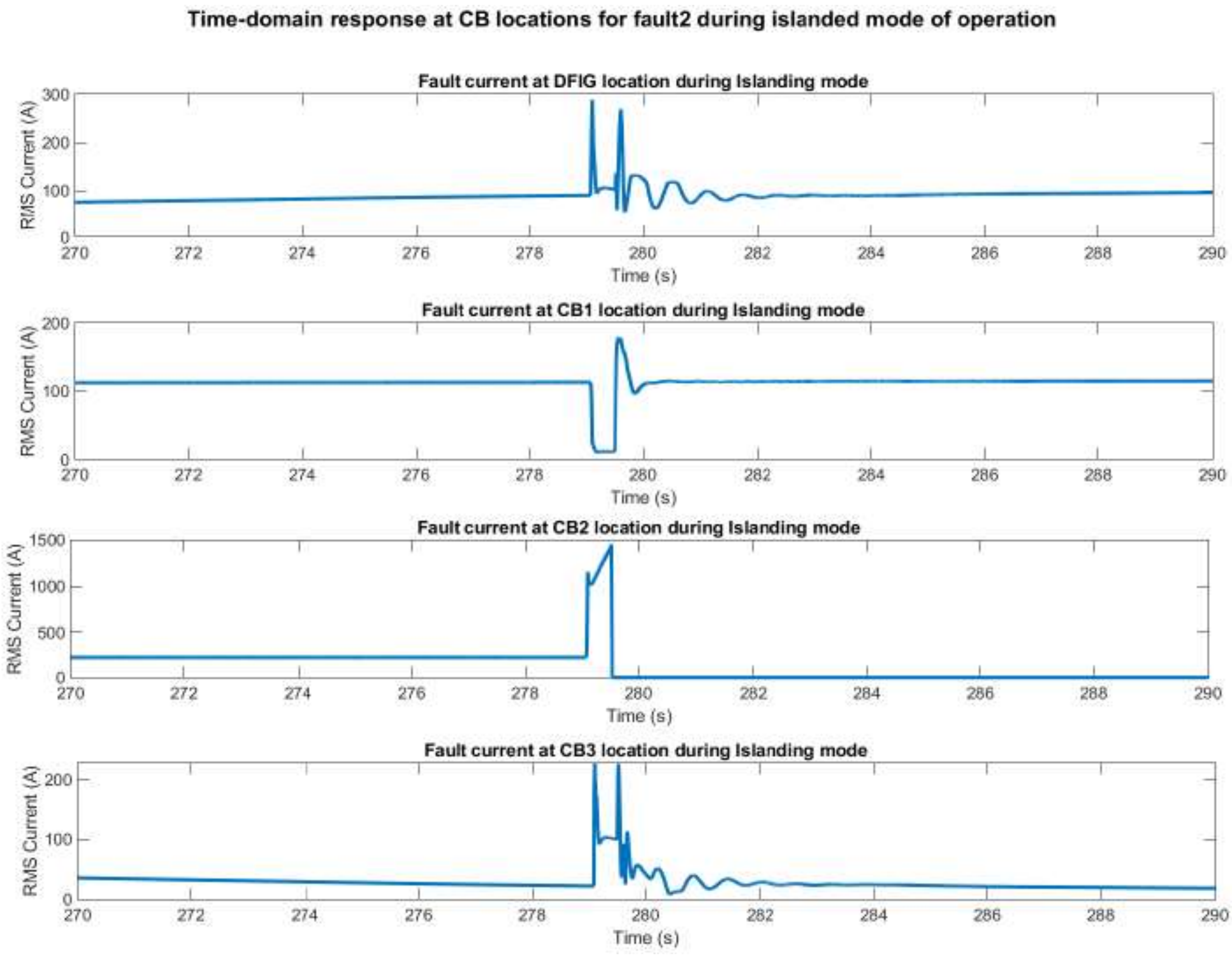

Figure 6.18 Real-time response at various CB locations for Fault2 during islanded mode.

In addition to the time-domain response of the fault currents at different CB locations, CB status for the HIL protection IEDs has been illustrated in Figure 6.19. It can be seen that protection IED at CB2 has operated in a timely manner and has sent trip signal to isolate faulty section at CB2. In Figure 6.19, the orange solid line represents fault duration at CB2 location and the blue line corresponds to the trip signal received from the protection IED configured as HIL for operating on CB2.

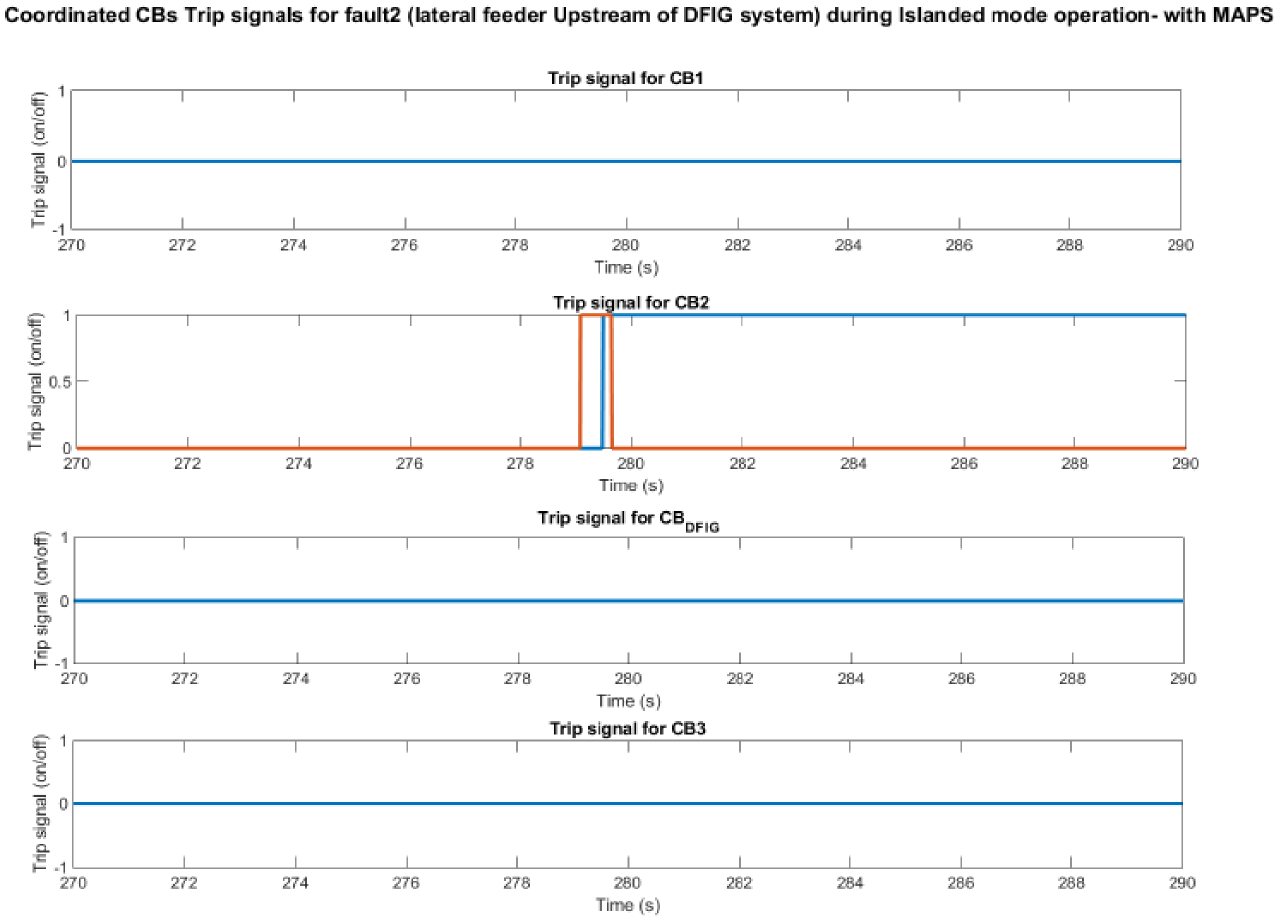

Figure 6.19 Trip signals received from HIL protection IEDs.

6.5.3. MAPS Messaging

Having represented the functionality and performance of MAPS for adjusting protection settings in protection IEDs, taking into account the operating condition in the interconnected distribution network, the proposed methodology is reliant on message passing and cooperative communication enables knowledge sharing between different protection IEDs. Therefore, in this section co-simulation between the MAS and real-time simulation for power system domain have been investigated to demonstrate the messages exchanged with in MAPS framework. To represent the track of messaging related to different scenarios for various operating conditions of the distribution network, a graphical user interface tool from JADE software has been utilized to log sequence of messages between protection agents and the interfacing agents. The process of distributed heuristic decision making based on agent messages are described in the next section.

6.5.3.1 Knowledge exchanges

As explained in Chapter 5, distributed characteristics within interconnected distribution network highlights the importance of the data communication and knowledge sharing between different elements of the power system. Thus, as a basis for development of the MAPS realization of the agent behaviours to address protection tasks allocated to agent types can be represented through agent messaging, which constitute the services and functionalities required for fulfilling protection system within interconnected distribution network. With respect to real-time data communication between the MAPS and power system distribution network, the roles of interfacing agents consisting of synchronizing agent (SYNCH_AGENT) and output agent (OUTPUT_AGENT) are defined for sending real-time measurement data and receiving protection settings as a two way communication via SYNCH_AGENT. In Figure 6.20, the messages exchanged by interfacing agents to establish the co-simulation between real-time digital simulation and MAPS have been highlighted by an enclosed dotted rectangle. Also, in Figure 6.20, SYNCH_AGENT and OUTPUT_AGENT are represented with solid line circles and their activity sequence line where the sender and receivers for the messages are illustrated by grey and blue arrows respectively. As seen from Figure 6.20, the destination for real-time measurement data are measurement agents embedded within MAPS protection IEDs as their detailed architecture illustrated in Chapter 5. For output agent, the destination of the messages containing the protection settings for each protection IEDs is the synchronizing agent, which sends protection settings as a TCP data frame to real-time digital simulator.

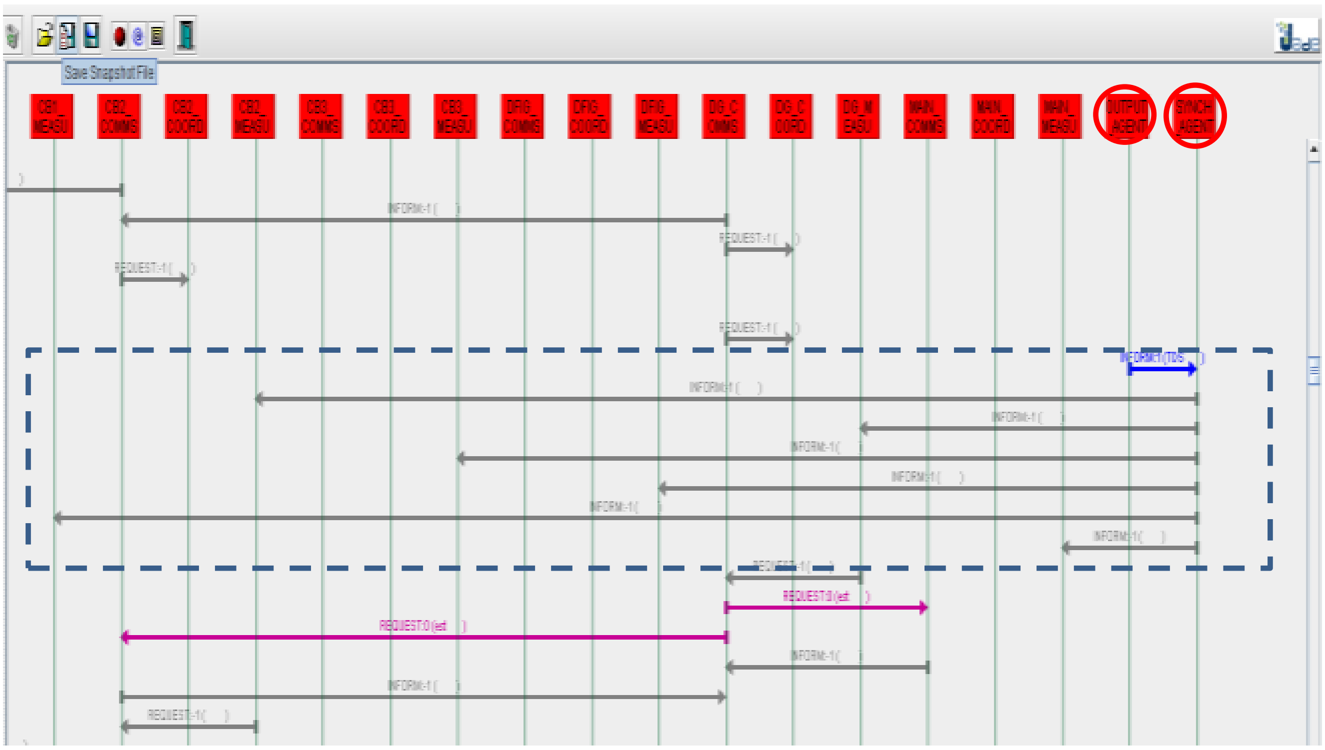

Figure 6.20 Messages representing real-time measurement data exchange within MAPS.

Aside from the interfacing agents, which are developed for synchronizing the co-simulation process between the MAPS and real-time simulation of the power system, protection agents constitute the core of adaptation and coordination process to automatically change protection settings in the protection IEDs. Therefore, to illustrate the process of messaging and knowledge sharing between protection agents, Figure 6.21 is used to graphically represent message types and message sequences exchanged during variation of the operation condition in DFIG system. As can be seen in Figure 6.21, the dotted line rectangle encloses the communication and coordination messages between the protection agents of the DFIG system. The sender for both communication and coordination messages in DFIG protection system is the measurement agent, which continuously monitors the operation condition of DFIG system and send a coordination message in the case of detection of any changes in the operation slips of the DFIG. The communication message sent from the measurement agent is to inform the communication agent to share the current operating condition with the neighbouring IEDs for the purpose of the coordination of the protection settings in the upstream and downstream protection IEDs. In Figure 6.21, the coordination message has been represented with yellow arrow and communication message is specified with a grey colour arrow.

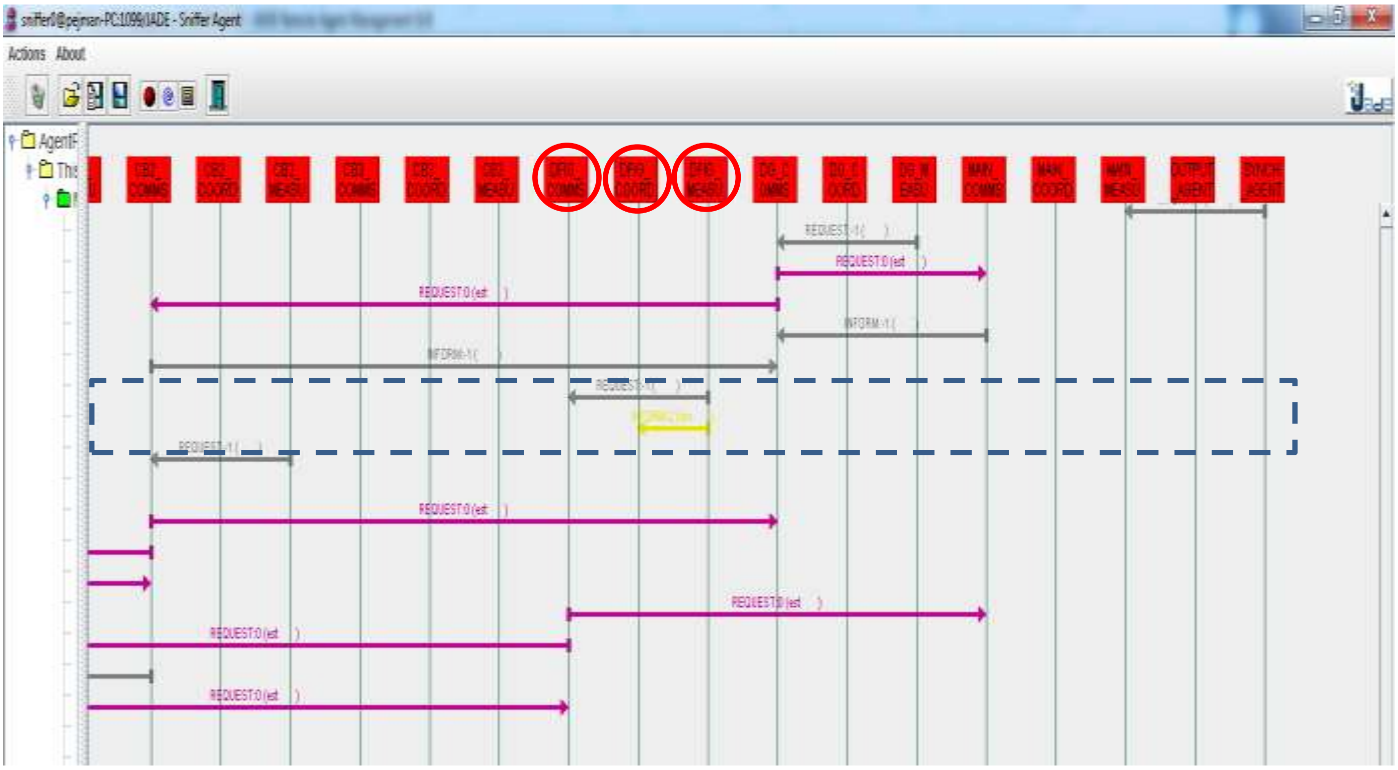

Figure 6.21 Messages exchanging between protection agents developed in MAPS.

Finally, it is worth mentioning that although MAPS have been developed to represent the real-world scenario for interaction between protection agents and power system component based on real-time data simulation, the timing for the message sequences represented in Figure 6.21 are not accurate since MAPS has been developed in a centralized approach using a laptop with multi-threaded CPU capabilities. However, in the case of the real-world implementation for MAPS each protection IED can be a separate platform (hardware) for protection agents but it is obvious that while the MAPS simulation results are satisfactory in the developed real-time data simulation frame work, hardware implementation of the MAPS IEDs can have much better performance to meet the required reliability within power system protection field.

6.6 Summary

In this chapter, architectural arrangement and development of a real-time simulation for the proposed MAPS is represented. Various simulation techniques and hardware equipment with their configurations interfacing over a communication network are explained to capture holistic behaviour of the MAPS. In addition to that and specifically two main simulation techniques constituting integral part of the developed testbed called co-simulation for interfacing or integrating MAS into power system and hardware in the loop to establish real-time interaction within a multi-domain research simulation study have been conducted. Finally, to validate the performance of the proposed MAPS, protection scenarios for grid-connected and islanded mode of operation have been evaluated to prove viability and effective integration of the heuristic protection scheme/algorithm for interconnected distribution network with renewable resources such as DFIG wind turbine. Also, from the perspective of the agent communication and cooperation between different protection nodes and the track of message exchanging among different agents are shown in user interface environment developed using JADE software tool.

CHAPTER 7
CONCLUSIONS

In this PhD research project, some of the critical aspects related to operation of the interconnected distribution networks and technical challenges for developing a reliable protection system have been investigated. Thus, within the context of the future power system operation and introduction of Smart Grid paradigm, a novel protection system based on MAS have been developed where protection settings can be adjusted automatically based on heuristic decision making between protection IEDs. According to research project objectives certain outcomes can be highlighted as the contributions to the existing body of knowledge in power system protection. In the first stage time domain modelling of the interconnected distribution system with DERs such as DFIG and DG system has been developed as parameters such as variability in wind speed and islanding operation mode have been introduced to ensure real-world scenarios has been addressed. Additionally, analysis of the fault current contributions under different operation conditions of DFIG system has been investigated and time domain representation of the fault currents have been compared with IEC TOC curves. Finally, for the proposed methodology protection system based MAS have been developed where protection IEDs are defined as a MAS with different agent types and various tasks. The core attributes of the MAPS are defined on cooperation between protection agents within each protection IEDs and further capability for sharing knowledge between protection IEDs within the interconnected distribution network. Also decision making process based on heuristic reasoning of the human mind has been integrated to automate the selection of the protection settings as an online adaptive protection system within the interconnected distribution network. Verification of the results demonstrates technical feasibility and reliable performance of the MAPS for protection system in interconnected distribution networks. According to the proposed methodology some of the outcomes established for protection systems in interconnected distribution network are listed as follow:

- Development of the Interconnected distribution network with DFIG and DG system
    1. Detailed time domain simulation of the DFIG and DG system including their control loops have been developed to address complexities relevant to fault current analysis and protection system studies.
    2. Input variables such as wind speed and transitioning from grid connected to islanded mode have been introduced within time domain simulation to match realistic operation of the interconnected distribution network in real-world scenario.
- Analysis of fault current behaviour under various operation conditions

1. To study and design for protection system complexities of the fault current behaviour with connection of DERs in this case DFIG system has been studied where different wind speeds and number of the DFIGs connected to the distribution levels
2. For distribution network interconnected with DFIG system fault current characteristics such as maximum fault current and fault current level can vary differently depending on the wind speed and number of the DFIGs connected into distribution networks
3. the effect of the fault location c, there are certain parameters in interconnected distribution network which are

- Development of the MAPS in future power distribution networks
  1. Complexities in protection systems for interconnected distribution network requires support information from wide area to ensure decision making
  2. Definition of protection tasks based on agent types can improve scalability and extensibility of the protection system which is essential for development of the
- Decision making under new operation paradigm
  1. Introduction of the protection strategies based on AI and heuristic reasoning have the potential to embed advanced self-adjusted protection systems within interconnected distribution network and smart grid paradigm
  2. With the concept of smart grid and interconnectivity between different layers of the power system operation conventional protection function have to be supported by information relation to operation condition of the power system network
- Future smart grid and simulation framework
  1. Establishing a simulation framework is critical for credibility and validity of the solutions within smart grid paradigm.
  2. Simulation techniques such as co-simulation and HIL are important to develop testbeds for evaluation of the modern grids performances.

In this research thesis, chapters have been organized to consecutively establish the main objective of the study, which are concerned with the integration of heuristic multi-agent protection system into distribution networks. In Chapter 2, different approaches in protection system and solutions in devising reliable protection settings within distribution network interconnected with DERs have been investigated. In addition to that, architectural arrangements for implementation of the protection system utilizing ICT have been addressed via SGMA where different simulation techniques have been defined for evaluation of the proposed MAPS. Having identified research gaps in literature review, in Chapter 3, a typical distribution network interconnected with DFIG systems have been developed to investigate time-domain simulation and transitions in operation conditions of the distribution network by considering intermittencies of the renewable energy resources. As a crucial step for devising protection settings including selection of TOC IEC curves within protection IEDs, analysis of fault current and fault current contribution under different operating scenarios are studied in Chapter 4. Additionally, Chapter 4 contributes to the identification of certain characteristics/attributes and properties in interconnected distribution network which are utilized to represent expert knowledge through supporting decision making based on sharing this information with one another between protection IEDs. In Chapter 5, the core of research study is explained as protection IEDs are identified as protection agents, which are capable of cooperation with neighbouring protection IEDs to fulfil protection task within interconnected distribution network in a distributed decision making process. Also, further to performing protection tasks under specified operation scenario the embedded expert knowledge system in protection agents enables adjustment of the protection setting with respect to transitions of the operating condition of the interconnected distribution network. Finally, in Chapter 6, results of the proposed MAPS are evaluated by developing a real-time testbed platform taking into account holistic modelling and simulation approach to ensure the functionality and performance of the protection system are comparable under real-world operation scenario. The main achievements and novelties of this PhD research studies are highlighted as follows in section 7.1.

7.1 Accomplishments and novelties

Interconnecting of DERs into distribution network has been considered as an effective solution for cleaner and cheaper electric power supply in ever increasing electricity consumption trend. However, complexities arising from decentralization of the energy resources have introduced substantial challenges into power system protection, which is the most critical factor for reliable and safe operation of the power system. In parallel to the present transition in power system operation, digitalization of the power system through deployment of ICT infrastructures have highlighted new possibilities for protection system where ICT elements and human-like intelligence are exploited to fulfil complicated protection strategies. Thus, in light of digitalization of power system operation and promotion to integrate power system solutions based on reference architecture such as SGAM, protection system based on MAS paradigm has been proposed to address protection challenges due to interconnection of DERs into distribution networks. Although applications of MAS have been considered in various domains within power supply industry but in this PhD research study protection system and its critical role in delivering reliable and secure electric power supply has been the focus to integrate MAPS into interconnected distribution networks. Thus, given the advantages of MAS with capabilities to interact within a large-scale, interdependent and heterogeneous environment similar to future power system networks there are three aspects associated with the proposed MAPS which can be identified as novelties and contribution in the field of power system protection. In the next subsection, heuristic decision making, development of MAS framework for protection system and establishment of a real-time simulation platform to evaluate the research outcomes under real-world operation scenarios have been discussed with their importance to improve protection system within the context of the future power supply industry.

7.1.1. Heuristic Decision Making Strategy

Typically, the process of decision making for system protection is reliant on deterministic approach in devising TOC curves with predetermined setting parameters, which are calculated based on detailed simulation and investigations of the fault current levels within distribution network. Although through literature [67, 80], it has been tried to extend the above conventional approach to restore system protection reliability within interconnected distribution network, these attempts have been mainly limited for certain topology or configuration of the connected DERs, which in turn have not been adaptable/flexible to accommodate prevailing changes within the operating condition of the DERs. Consequently, in this research study in conjunction with distributed knowledge sharing between neighbouring protection IEDs, expert knowledge database is used to select proper protection settings according to the operating condition of the interconnected distribution network. In fact, the principle of the proposed MAPS relies on cooperative behaviour between different protection agents with information collection regarding the upstream, downstream and type of the allocated protection IEDs are inquired. Practically, the distributed architecture devised for MAPS is mainly attributed to MAS paradigm and its deployment in each protection IEDs while decision making is performed through expert knowledge database composed of information obtained through protection agents and rule-based reasoning system.

The main innovations demonstrated for proposing MAPS are the scalability and automated flexibility within the protection system as the adjustment in group settings of the protection IEDs takes place through ICT infrastructure embedded in the modern power system networks. In addition, the use of heuristic/rule-based reasoning has been adopted to improve the process of decision making for large scale interconnected distribution network as heterogeneous power system components such as DERs are interconnected in various topological configurations.

7.1.2. MAPS Application Software Development

In many research papers [24, 27, 111], application of MAS in system protection have been addressed through architectural arrangements of different agent types and their specific tasks fulfilling a devised protection schemes in a centralized decision making algorithms where agent message passing is simplified as input variables. Thus, for the software developed in the aforementioned centralized algorithms, the concept of agent paradigm is mainly implemented in a single-threaded application software, where not only data communication traffics as an important aspect of ICT infrastructure within the protection system are neglected, it is also impractical to ensure interoperability within power system automation in modern power systems. Consequently, the procedures for evaluation and assessment of the aforementioned proposed protection schemes are only confined to simulation software tool and power system environment with no communication interface with external third party elements (multi-domain cyber-physical systems).

In this research project, an innovative approach for development and deployment of the MAPS have been adopted in which JADE software tool has been used to embed protection agents as individual autonomous entities executing simultaneously in separate computational threads. As a result of that, the application software for MAPS is developed based on multi-threaded architecture, which allows establishing the proposed MAPS according to embedded hardware and software tools required within real-world operation scenario. In addition, using JADE for developing MAPS facilitates desired interoperability and scalability within the protection system, which is important factor to deal with large-scale power system networks interconnected with heterogeneous power system components. Actually, the interoperability between protection agents deployed by MAPS application software is rooted in compliance of JADE with FIPA standard and protection ontology defined for ACL messaging based on communicative act.

7.1.3. Developing smart grid simulation platform

In the phase of validation and assessment for the functionality and performance of the proposed MAPS, a simulation framework based on Smart Grid paradigm has been adopted which highlights the feasibility of testing the proposed scenario under real-world operation scenario. As a matter of fact, future power grids are dependent upon interaction between power system elements and ICT infrastructure, where sophisticated protection schemes can be integrated to improve reliability in protection system within interconnected distribution network. Thus, given the multiple physical domain involved in Smart Grid operations and requirement for a time domain simulation applicable for protection system studies, a holistic approach to reproduce different physical domains within the timescales of milliseconds have to be established for accurately validating the simulation outcomes. Presently, the topic of simulating cyber-physical systems is an important joint research area within power system engineering and ICT Computer Science, where various simulation techniques such as co-simulation and HIL are adopted to replicate real-time interactions between hardware and software elements within Smart Grid operation context. The innovative approach selected for developing MAPS is to integrate both software and hardware elements with respect to existing communication standards, where possibility of a scalable solution according to available off the shelf's products can be exploited. For example, in the current PhD research, three main simulation domains including continuous time domain power system components, event-based ICT infrastructure and external analogue input signal have been synchronized to imitate real-world interactions between all the sub-domains in the system. In summary, integration of the agent technology, IEC61850 communication protocol and real-time simulation of DERs models have been utilized to establish real-time scenario for a heuristic protection system where protection settings are automatically adjusted on-line to maintain power system reliability within a distribution network interconnected with DERs.

7.2 Scopes For Future Work

From technical point of view, research areas associated with future power system studies are covering a wide range of interdisciplinary branch of science which overlaps power system modelling, ICT infrastructure, AI and business management as interdependent elements in the field. Basically, with the new emerging concept of SOS engineering and introduction of Internet of Thing (IOT) technologies, conducting a valid and credible research study within the field of modern power systems is conditioned to understand different layers and their interactions affecting protection system performances. For examples, taking into account different layers involved in SGAM, complexities in developing system protection is increased as the operation of protection IEDs to clear any fault in the distribution network can affect dynamic stability of the power system through embedded hierarchical control systems, which may further trigger sympathetic tripping of the other healthy line sections. While in this research study integration of heuristic MAPS into interconnected distribution network have been addressed taking into account the primary control loops of the DERs as the only control strategy to maintain stability of the system, but under hierarchical control strategy for interconnected distribution networks considering interactions between different layers of power system automation is critical to address reliable and effective protection scheme. Hence, to improve future research studies, there are a few points that can be highlighted as critical to further enhance practicality of the solutions for power system protection within interconnected distribution networks. Suggestions for future work are as follows:

1. Control Layer

In relation to control system for interconnected distribution networks, there are multiple criteria such as frequency control, voltage control, power flow control etc., which are operating simultaneously within the power system network. Therefore, depending on the predicted complexities in the future power system, integration of embedding different control layers can reflects better accuracy in evaluation and assessment of the protection system performance with respect to cascaded events and sympathetic tripping as it is critical to large scale blackouts.

2. Comprehensive integrated simulation framework

The importance of the simulation framework for research studies on power system protection in interconnected distribution network is crucial since new modern technologies in power system equipment are reliant on communication standards and interoperability between different power system automation layers. Therefore, a comprehensive simulation framework considering data communication traffics and its corresponding delays are essential as the performance of the protection schemes rely on quick response to isolation of the faulty section to avoid any damages and instability in the power system operation.

3. Internet of Things (IOT)

Having envisaged the protection system for future power system as a network of protection IEDs which are capable to interact and exchange data/information between each other, introduction of IOT framework it can further embed flexibility and intelligence into decision making process/algorithms for protection systems in interconnected distribution networks. However, establishment of IOT framework for protection system applications relies on different layers including sensor (CTs and VTs) layer, aggregation/gateway layer (collecting and managing data-include measurement, CB status etc.), processing engine (cloud) layer and application (enterprise) layer. Thus, considering each layer within the IOT framework can introduce research topics related to protection system such as data modelling, interoperability and communication services, big data analysis, automatic/on-line knowledge representation and knowledge engineering within protection system domain.

4. Cyber Security

With the introduction of the protection system network and communication infrastructure the prospect of cybersecurity threat can be an issue for safe and reliable operation of the power system network. However, given the characteristics of the communication protocols to exchange real-time data for protection system applications such as GOOSE, SV and etc. applying cyber security measures/algorithm may have adverse effect on speed and performance of the protection system communication. Therefore, in case of network based protection system study on different cyberattack detection algorithms and possible effect on communication delays with in protection system network has to be conducted for addressing both cybersecurity and protection system performance of the future power system networks.

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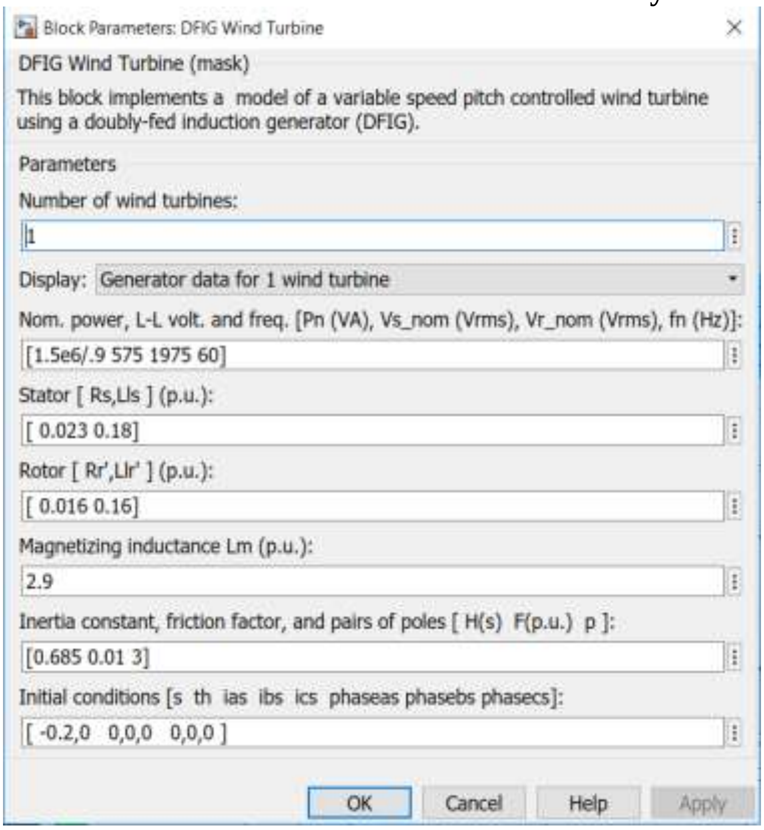
APPENDIX A

A.1 Simulation Data

Snapshots of the simulation data for DG system including SM, control systems, Diesel Engine and speed governor from MATLAB/SIMULINK Simpower system toolbox [201, 202].

Table A.1-1 Parameters for WRIM in DFIG system.


Block Parameters: DFIG Wind Turbine

DFIG Wind Turbine (mask)

This block implements a model of a variable speed pitch controlled wind turbine using a doubly-fed induction generator (DFIG).

Parameters

Number of wind turbines:

1

Display: Generator data for 1 wind turbine

Nom. power, L-L volt. and freq. [Pn (VA), Vs_nom (Vrms), Vr_nom (Vrms), fn (Hz)]:

[1.5e6/.9 575 1975 60]

Stator [Rs,Lls] (p.u.):

[0.023 0.18]

Rotor [Rr',Llr'] (p.u.):

[0.016 0.16]

Magnetizing inductance Lm (p.u.):

2.9

Inertia constant, friction factor, and pairs of poles [H(s) F(p.u.) p]:

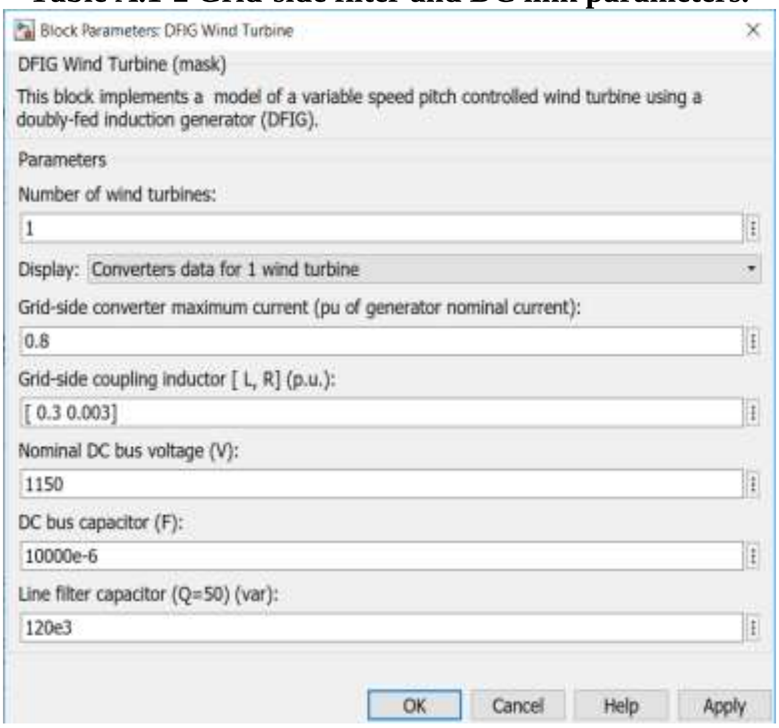
[0.685 0.01 3]

Initial conditions [s th ias ibs ics phaseas phasebs phasecs]:

[-0.2,0 0,0,0 0,0,0]

OK Cancel Help Apply

Table A.1-2 Grid-side filter and DC link parameters.


Block Parameters: DFIG Wind Turbine

DFIG Wind Turbine (mask)

This block implements a model of a variable speed pitch controlled wind turbine using a doubly-fed induction generator (DFIG).

Parameters

Number of wind turbines:

1

Display: Converters data for 1 wind turbine

Grid-side converter maximum current (pu of generator nominal current):

0.8

Grid-side coupling inductor [L, R] (p.u.):

[0.3 0.003]

Nominal DC bus voltage (V):

1150

DC bus capacitor (F):

10000e-6

Line filter capacitor (Q=50) (var):

120e3

OK Cancel Help Apply

Table A.1-3 Drive train and turbine parameters.

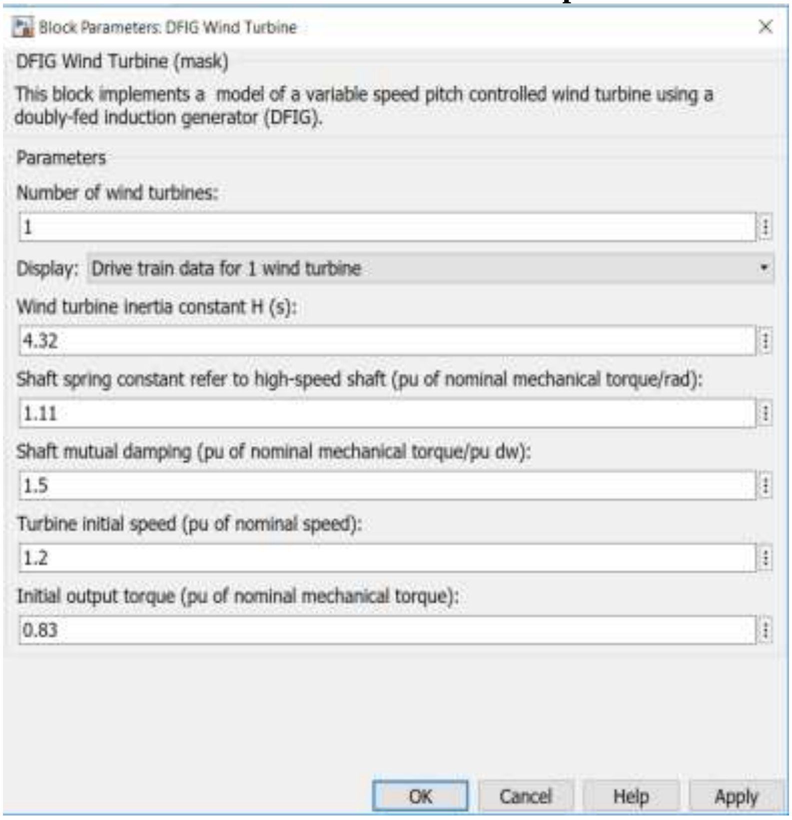


Table A.1-4 Synchronous machine parameters for DG system.

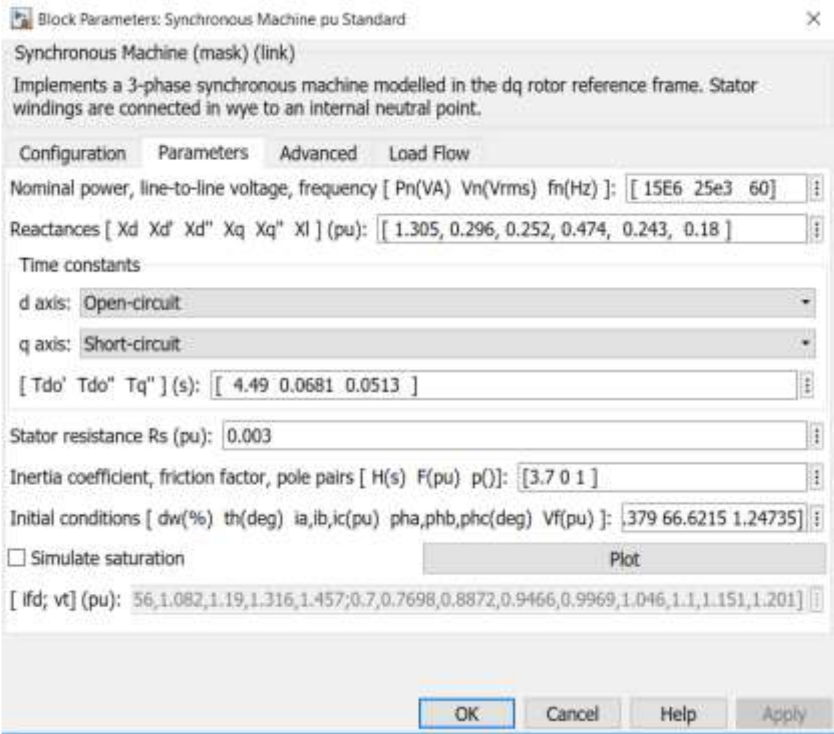


Table A.1-5 Control parameters and time constants for DG governor.

Block Parameters: Diesel Engine Governor

Diesel Engine Governor (mask)

This block implements a diesel engine and governor system:
1st and 2nd inputs: Desired and actual speed (pu)
Output: Diesel engine mechanical power.Motor inertia should be combined with generator.
Controller transfer function:
Hc=K.(1+T3.s)/(1+T1.s+T1.T2.s^2)
Actuator transfer function :
Ha= (1+T4.s) / [(s (1+T5.s)(1+T6.s)]
Motor :
Time delay Td

(See reference in Tutorial Session 5)

Parameters

Regulator gain K:	29
Regulator time constants [T1 T2 T3] (s) :	[0.01 0.02 0.2]
Actuator time constants [T4 T5 T6] (s) :	[0.25 0.009 0.0384]
Torque limits [Tmin Tmax] (pu) :	[0 1.1]
Engine time delay Td (s) :	0.024
Initial value of mechanical power Pm0 (pu) :	1

OK Cancel Help Apply

Table A.1-6 Control parameters and time constants for DG Excitation system.

Block Parameters: Excitation System

Excitation System (mask) (link)

Implements an IEEE type 1 synchronous machine voltage regulator combined
to an exciter.

The output of the block is the field voltage vfd, in pu, to be applied to the Vf
Simulink input of a Synchronous Machine block.

Connect the Vd and Vq measurements signals of the Synchronous Machine block
(signals 9 and 10) to the Vd and Vq inputs of the Excitation System block.

Parameters

Low-pass filter time constant Tr(s):	20e-3
Regulator gain and time constant [Ka() Ta(s)]:	[300, 0.001]
Exciter [Ke() Te(s)]:	[1, 0]
Transient gain reduction [Tb(s) Tc(s)]:	[0, 0]
Damping filter gain and time constant [Kf() Tf(s)]:	[0.001, 0.1]
Regulator output limits and gain [Efmin, Efmax (pu), Kp()]:	[-11.5, 11.5, 0]
Initial values of terminal voltage and field voltage [Vt0 (pu) Vf0(pu)] :	[1 1.2473]

OK Cancel Help Apply

Table A.1-7 Configuration and parameters for Three phase two windings Transformer.

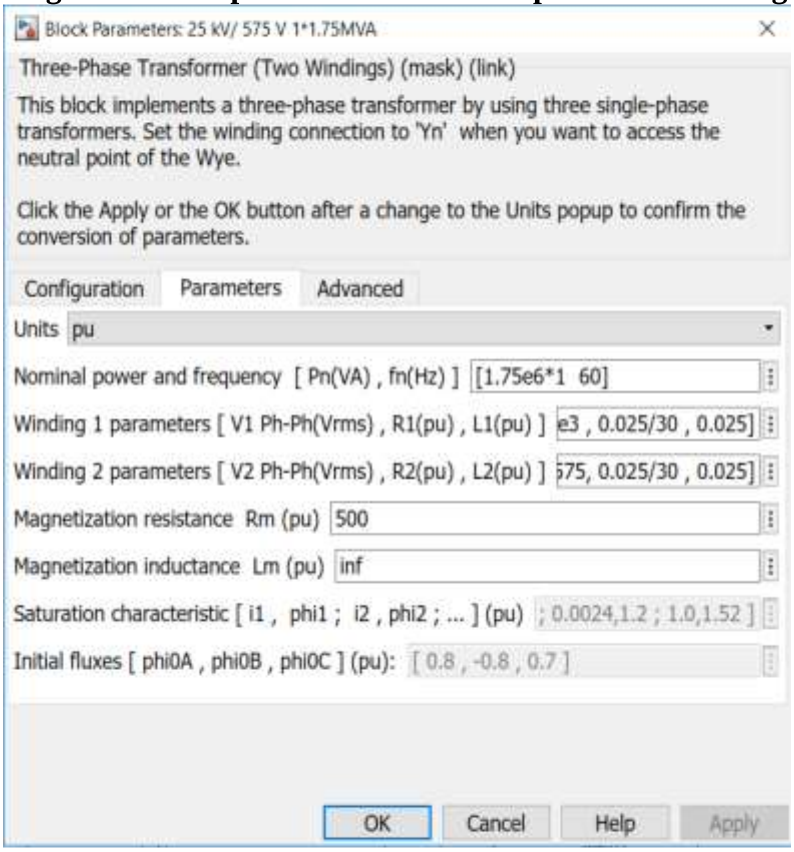
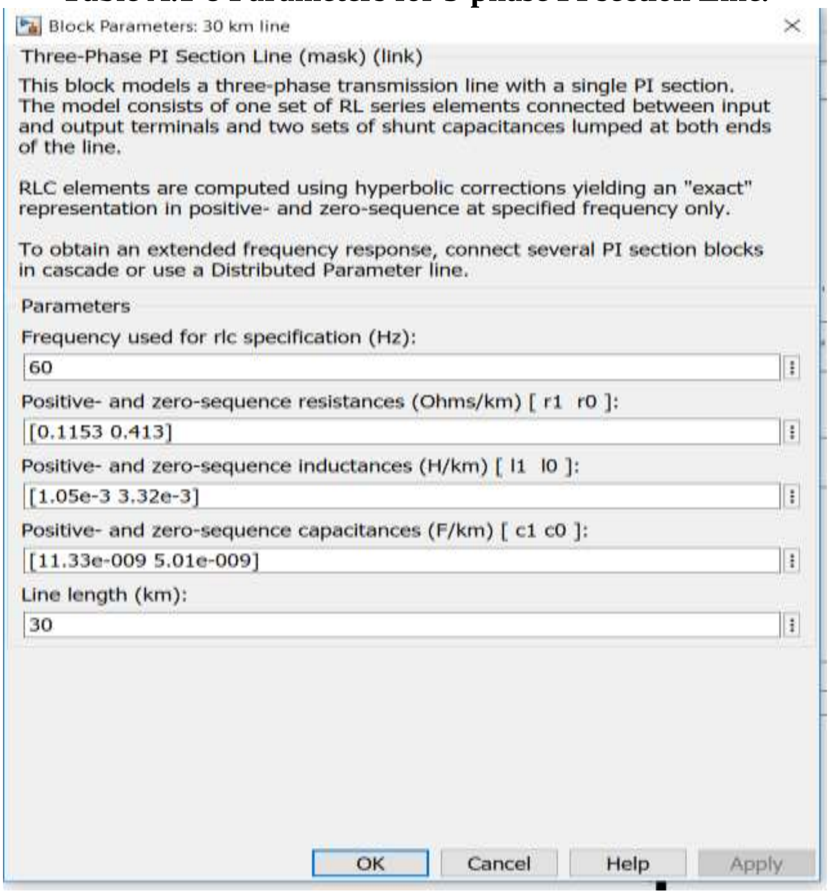


Table A.1-8 Parameters for 3-phase PI section Line.



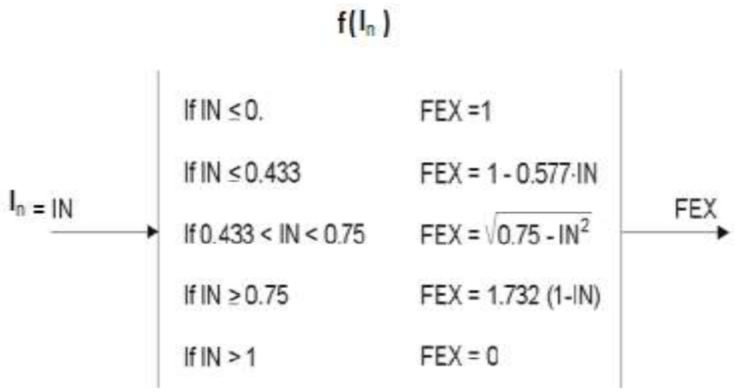
A.2 Excitation System Parameters (IEEE AC type1)

Below represents table of parameters and variables corresponded to the IEEE AC type1 excitation system illustrated in in Chapter 3 of section 3.6.4.2

Table A.2-1 Parameters, factors and gains for IEEE AC type 1 Excitation system.

K_A	Voltage regulator gain
K_C	Rectifier loading factor proportional to commutating reactance
K_D	Demagnetizing factor, a function of exciter alternator reactance
K_E	Gain for exciter circuit
K_F	Gain for stabilizing circuits
T_A	Time constant amplifiers
T_B	Voltage Regulator Time constant
T_C	Voltage Regulator Time constant
T_E	Time constant exciter
T_F	Time constant for stabilizing circuits
K_A	Voltage regulator gain
K_C	Rectifier loading factor proportional to commutating reactance
K_D	Demagnetizing factor, a function of exciter alternator reactance

Table A.2-2 Parameter ranges and Rectifier Regulation Characteristics for IEEE AC type1.

Parameters Range	Rectifier Regulation Characteristics f (I_n)
$0 < TR < 0.49$ $0.02 < TE < 2$ $0 < TB < 19.99$ $0 < KF \leq 0.3$ $0 < TC < 19.99$ $0.02 < TF < 1.5$ $0 < KA < 999.99$ $0 \leq KC \leq 1$ $0 < TA < 9.99$ $0 \leq KD \leq 1$ $0 < VAMAX \leq 15$ $0 < KE \leq 1$ $0 \leq E1$ $0 \leq SE(E1) < 1$ $-15 \leq VRMIN < -0.01$ $E1 < E2$ $0 < VRMAX \leq 15.0$ $SE(E1) < SE(E2)$	

APPENDIX B

B.1 IEC60909 Voltage Factors

IEC 60909 Standard defines internationally accepted method to calculate fault current within three phase power systems. In this method two levels of the fault current based on different voltage factors (Table B.1-1) are derived. According to the IEC60909 standard the maximum fault current level is used to devise the equipment ratings while the minimum fault current is corresponded to protection settings and protective relaying. Having said that the procedure to calculate the fault currents in IEC60909 standard relies on certain characteristics of the electric network which can be generalized in table formatted data and formulas simplified for power system engineers who are not specialized in power system protection. The procedure for calculation of the fault current in IEC60909 is defined in steps as follows:

1. Calculation of the equivalent voltage at the fault location with respect to the c factor listed in table B.1-1 accounts for
   a. Voltage variation in space and time (decaying wave/transient, DC and AC components)
   b. taking into account the transformer tappings
   c. sub-transient behaviour of generators and motors
2. Determining and adding up sequence impedances (all the three impedance sequences, positive, negative and zero) for upstream fault
3. Using symmetrical component from table B.2-1 to determine short circuit current based on the type of fault
4. As the RMS values of the fault current ($I^{``}$) are calculated other parameters such as maximum peak values of the short circuit current can be determined.

Table B.1-1 Values for Voltage Factor c in IEC60909 standard.

Rated voltage U_n	**Voltage factor C for calculation of**	
LV (100 to 100 V)	I_{SC} max	I_{SC} minimum
If tolerance + 6%	1.05	0.95
If tolerance + 10%	1.1	0.95
MV and **HV**		
1 to 550 kV	1.1	1

B.2 IEC6009 Fault Current Factors

Since in the procedure for calculation of the fault current under IEC60909 standard requires derivation of the sequence impedances including zero sequence, positive sequence and negative sequence impedance, Table B.2-1 lists the RMS fault current for various fault types.

Table B.2-1 Short-Circuit values depending on the impedances of given network in IEC60909.

Type of short-circuit	I''_k General situation	Fault occuring far from rotating machines
Three-phase (any Ze)	$I''_{k3} = \frac{c\,Un}{\sqrt{3}\,\lvert Z_{(1)}\rvert}$	$I''_{k3} = \frac{c\,Un}{\sqrt{3}\,\lvert Z_{(1)}\rvert}$
	In both cases, the short-circuit current depends only on $Z_{(1)}$, which is generally replaced by Z_k the short-circuit impedance at the fault location, defined by $Z_k = \sqrt{R_k^2 + X_k^2}$ where: R_k is the sum of the resistances of one phase, connected in series; X_k is the sum of the reactances of one phase, connected in series.	
Phase-to-phase clear of earth (Ze = ∞)	$I''_{k2} = \frac{c\,Un}{\lvert Z_{(1)} + Z_{(2)}\rvert}$	$I''_{k2} = \frac{c\,Un}{2\,\lvert Z_{(1)}\rvert}$
Phase-to-earth	$I''_{k1} = \frac{c\,Un\sqrt{3}}{\lvert Z_{(1)} + Z_{(2)} + Z_{(0)}\rvert}$	$I''_{k1} = \frac{c\,Un\sqrt{3}}{\lvert 2\,Z_{(1)} + Z_{(0)}\rvert}$
Phase-to-phase-to-earth (Zsc between phases = 0) **(see fig. 5c)**	$I''_{kE2E} = \frac{c\,Un\sqrt{3}\,\lvert Z_{(2)}\rvert}{\lvert Z_{(1)}Z_{(2)} + Z_{(2)}Z_{(0)} + Z_{(1)}Z_{(0)}\rvert}$	$I''_{kE2E} = \frac{c\,Un\sqrt{3}}{\lvert Z_{(1)} + 2\,Z_{(0)}\rvert}$
	$I''_{k2EL2} = \frac{c\,Un\,\lvert Z_{(0)} - aZ_{(2)}\rvert}{\lvert Z_{(1)}Z_{(2)} + Z_{(2)}Z_{(0)} + Z_{(1)}Z_{(0)}\rvert}$	$I''_{k2EL2} = \frac{c\,Un\,\left\lvert \left(\frac{Z_{(0)}}{Z_{(1)}}\right) - a\right\rvert}{\lvert Z_{(1)} + 2\,Z_{(0)}\rvert}$
	$I''_{k2EL3} = \frac{c\,Un\,\lvert Z_{(0)} - a^2 Z_{(2)}\rvert}{\lvert Z_{(1)}Z_{(2)} + Z_{(2)}Z_{(0)} + Z_{(1)}Z_{(0)}\rvert}$	$I''_{k2EL3} = \frac{c\,Un\,\left\lvert \left(\frac{Z_{(0)}}{Z_{(1)}}\right) - a^2\right\rvert}{\lvert Z_{(1)} + 2\,Z_{(0)}\rvert}$

Symbol used in this table:
- phase-to-phase rms voltage of the three-pase network = Un
- modulus of the short-circuit current = I''_k
- symmetrical impedances = $Z_{(1)}$, $Z_{(2)}$, $Z_{(0)}$
- short-circuit impedance = Zsc
- earth impedance = Ze.

APPENDIX C

C.1 Measurement Values

Based on the time domain simulation for the interconnected distribution network which developed in Chapter 3, measurement values for RMS current and active power at each CB locations have been listed in Table C.1-1 to Table C.1-6. As it has been shown each table is associated for certain operation condition for DFIG wind speed including number of DFIG system connected and wind speeds. It should be noted that the measurement values are derived based on steady state normal operation conditions under different operation scenarios as aforementioned. Therefore, the normal loading measurement values from these tables have been the based for devise protection settings in TOC protection schemes. Additionally each table can identified certain operation condition at each CB location which in turn for the transitioning states based on various scenarios related to DFIG system operation conditions.

Table C.1-1 Measurement values at different CB locations with 1 DFIG (wind speed 9m/s).

Wind speed 9m/s (1DFIG)			
CB names (IEDs)	Type	RMS Current (A)	Active power (W)
DFIG	WT	630*0.023	-5.9E5
CB1	Load1	109	-4.43E6
CB2	Load2	227	-9.5E6
CB3 or B25	CB	96	3.96E6
CB DG	DG	265	13.68E6
CB Main	CB	0.0157 pu	-355

Table C.1-2 Measurement values at different CB locations with 1 DFIG (wind speed 12.5 m/s).

Wind speed 12.5m/s (1DFIG)			
CB names (IEDs)	Type	RMS Current (A)	Active power (W)
DFIG	WT	1571*0.023	-1.5E6
CB1	Load1	109	-4.43E6
CB2	Load2	227	-9.5E6
CB3 or B25	CB	73	3.16E6
CB DG	DG	300	12.8E6
CB Main	CB	0.0233	-801

Table C.1-3 Measurement values at different CB locations with 3 DFIG (wind speed 9 m/s).

Wind speed 9m/s (3DFIG)			
CB names (IEDs)	Type	RMS Current (A)	Active power (W)
DFIG	WT	1839*0.023	-1.75E5
CB1	Load1	109	-4.5E6
CB2	Load2	227	-9.57E6
CB3 or B25	CB	68	2.87E6
CB DG	DG	295	12.66E6
CB Main	CB	0.025 pu	-907

Table C.1-4 Measurement values at different CB locations with 3 DFIG (wind speed 12.5 m/s).

Wind speed 12.5m/s (3DFIG)			
CB names (IEDs)	Type	RMS Current (A)	Active power (W)
DFIG	WT	4500*0.023	-4.39E6
CB1	Load1	109=112	-4.7E6
CB2	Load2	227	-9.5E6
CB3 or B25	CB	73	3.9E5
CB DG	DG	237	10.24E6
CB Main	CB	0.0233	-846

Table C.1-5 Measurement values at different CB locations with 6 DFIG (wind speed 9 m/s).

Wind speed 9m/s (6DFIG)			
CB names (IEDs)	Type	RMS Current (A)	Active power (W)
DFIG	WT	3666*0.023	-3.55E6
CB1	Load1	109=112	-4.7E6
CB2	Load2	227	-9.7E6
CB3 or B25	CB	28	1.21E6
CB DG	DG	256	11.01E6
CB Main	CB	0.028 pu	-1165

Table C.1-6 Measurement values at different CB locations with 6 DFIG (wind speed 12.5 m/s).

Wind speed 12.5m/s (6DFIG)			
CB names (IEDs)	Type	RMS Current (A)	Active power (W)
DFIG	WT	8944*0.023	-8.9E6
CB1	Load1	109=112=115	-4.97E6
CB2	Load2	227.9	-9.73E6
CB3 or B25	CB	90.22	-3.8E6
CB DG	DG	140.9	6.024E6
CB Main	CB	0.0233	-777.3

C.2 State Representations

For the proposed interconnected distribution network state transitions can be represented with schematic diagram highlighting both topological connections between different protection IEDs (nodes) and prevailing changes under various operation scenarios. In the following (Table C.2-1 to Table C.2-4) diagrams representing measurement data at each CB locations for different wind speeds (9m/s and 12.5 m/s) and different operation modes (Grid-Connected and Islanded mode) with 3 DFIG connected in distribution level have been illustrated.

Table C.2-1 Representations of the operation states at CB locations (IEDs) for state 1.

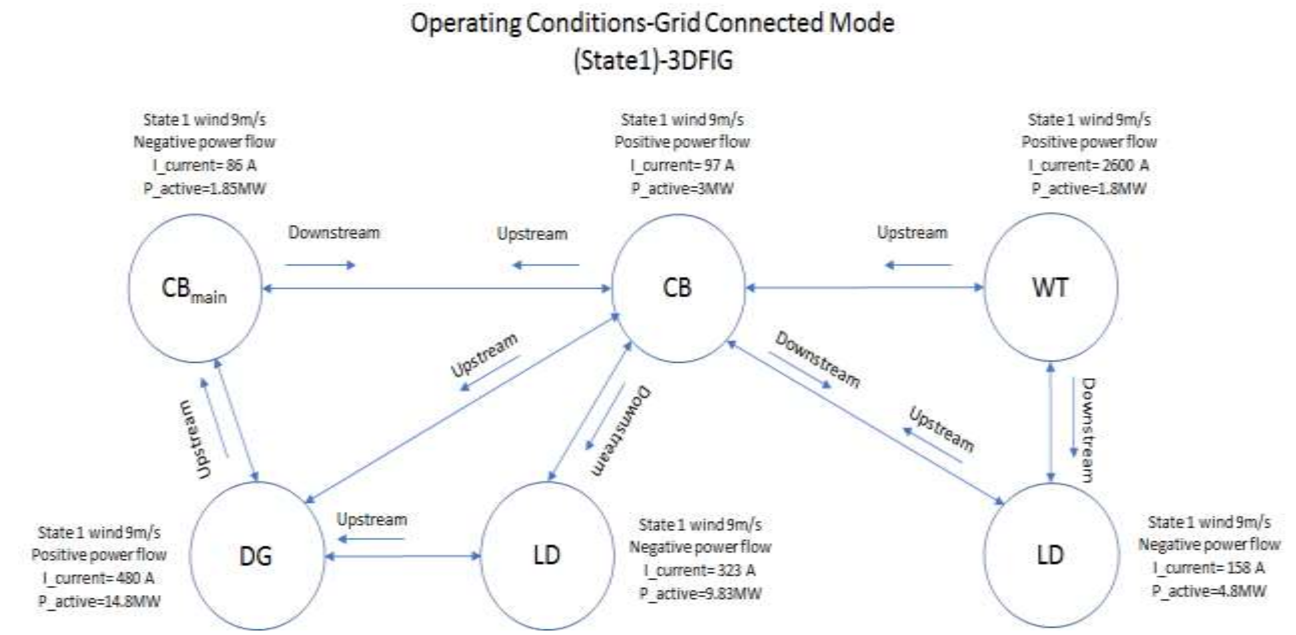


Table C.2-2 Representations of the operation states at CB locations (IEDs) for state 2.

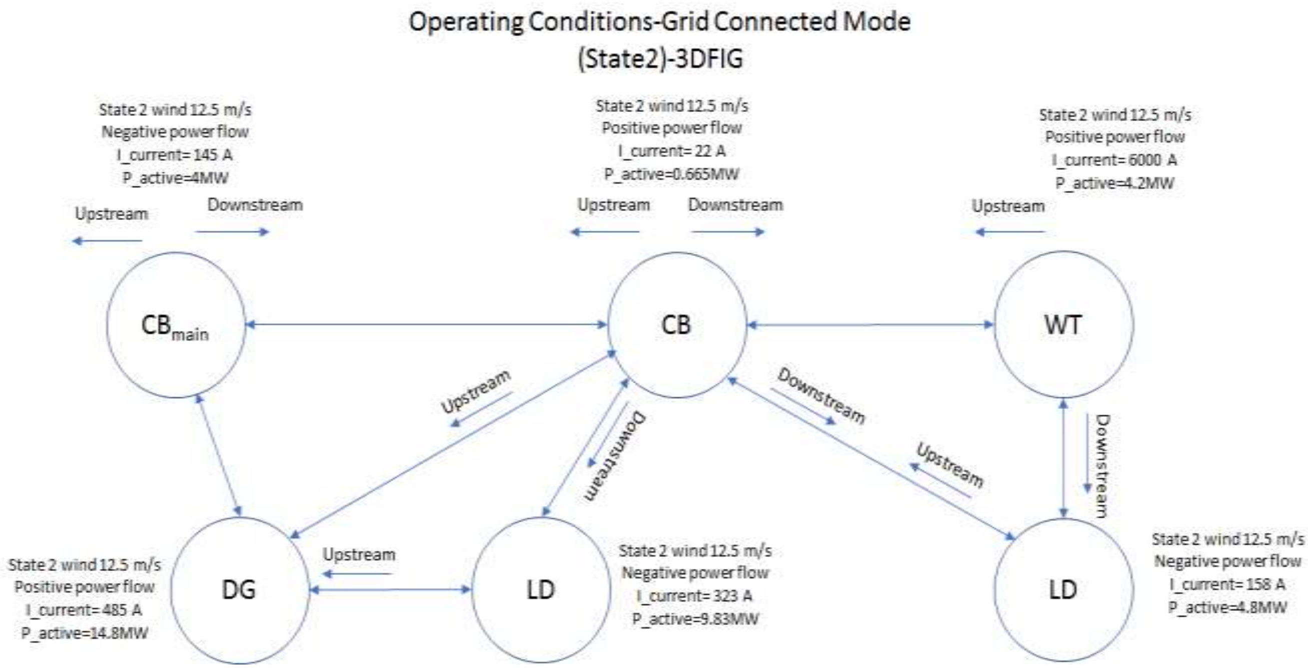


Table C.2-3 Representations of the operation states at CB locations (IEDs) for state 3.

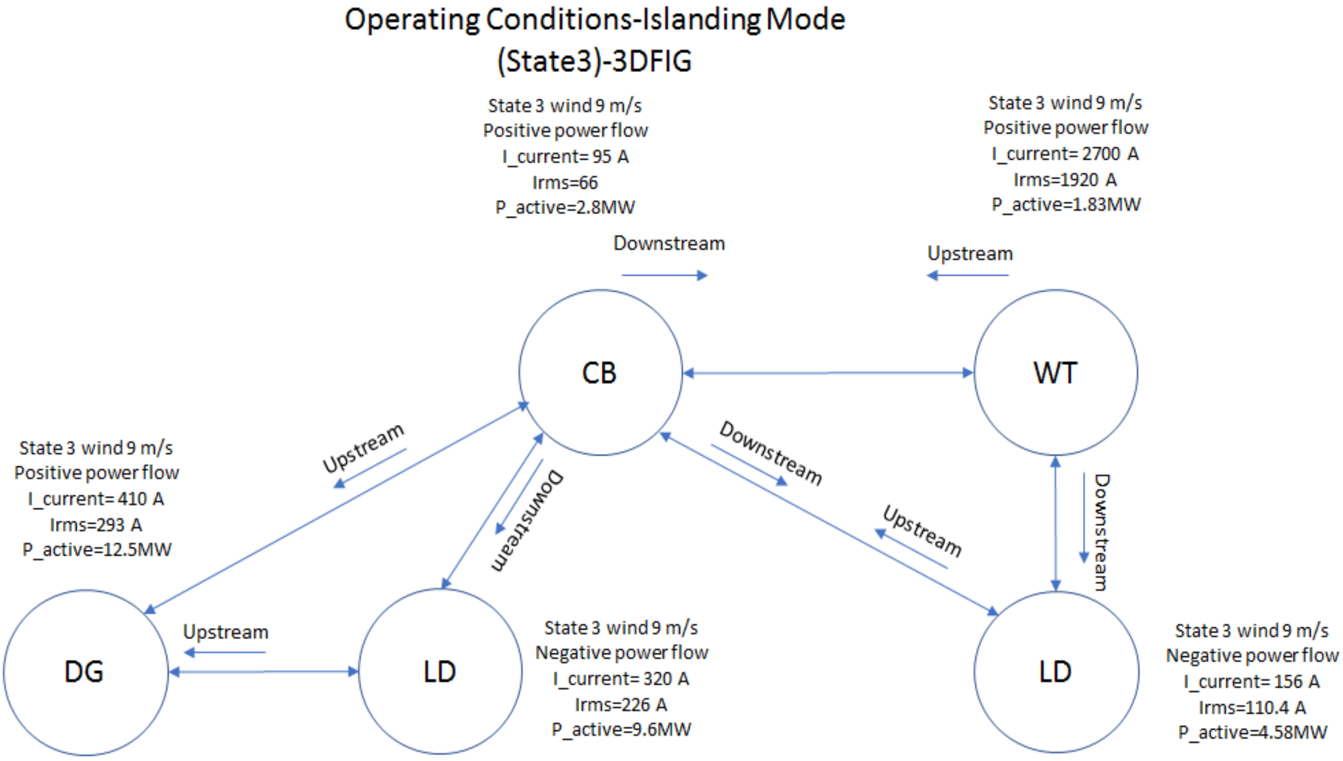
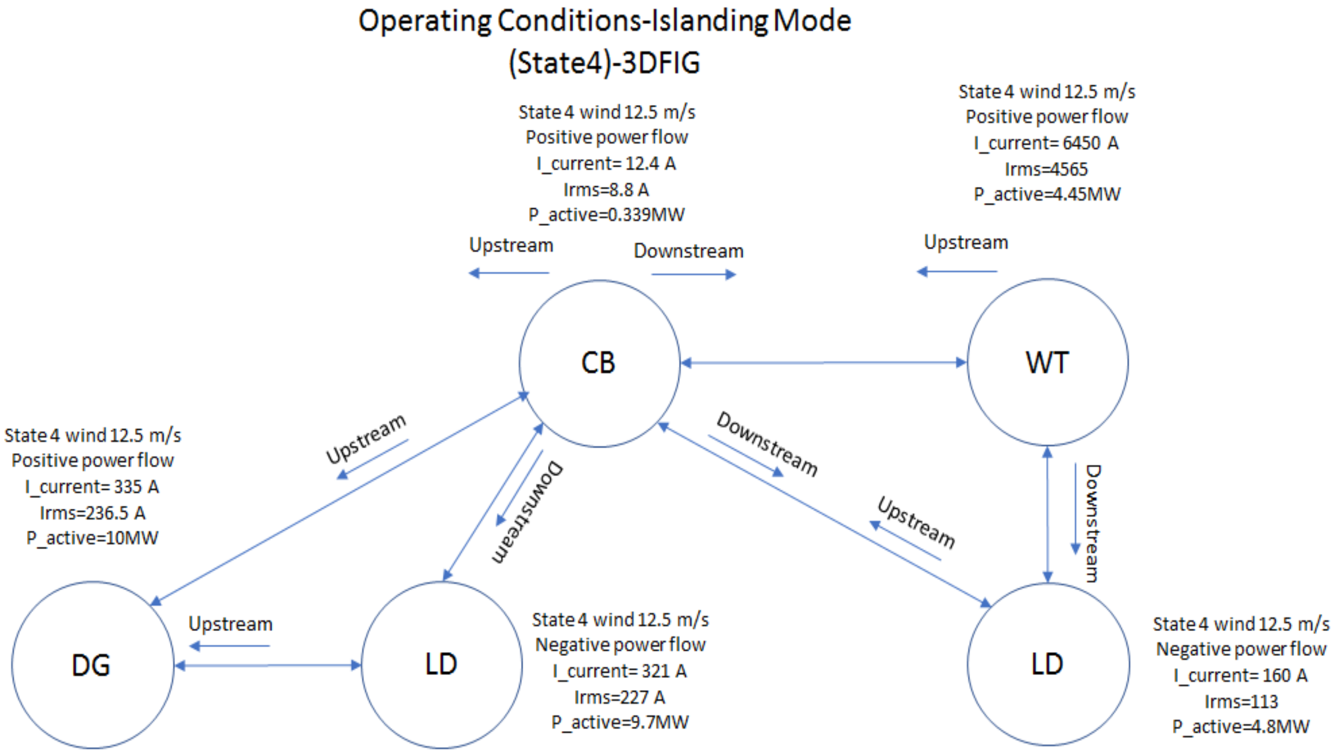


Table C.2-4 Representations of the operation states at CB locations (IEDs) for state 4.

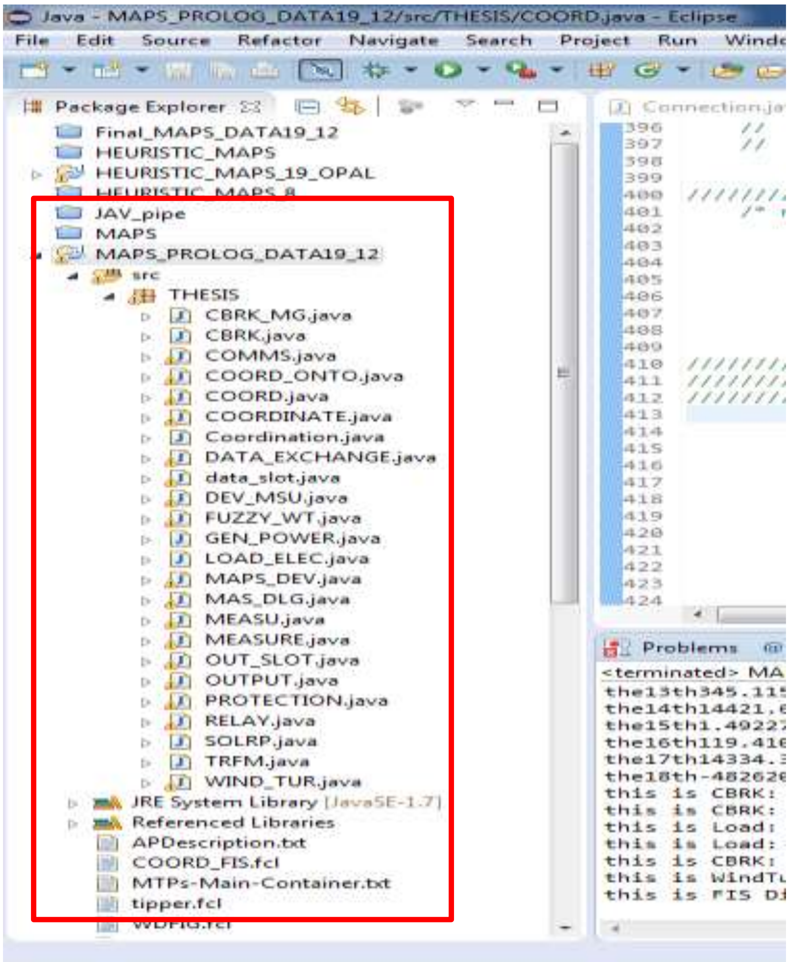


APPENDIX D

D.1 Software Files and Codes

The MAPS Software and source codes in JAVA/JADE have been shown in the screenshot (Table D.1-1) from JAVA eclipse development environment. As it is seen protection agents have been defined by different class types (MEASU, COMMS and COORD) and interfacing agents (SYNCH or DATA_EXCHANGE, OUTPUT) are listed in the red box which includes other classes related to object oriented approach for representing information associated to each power system component (WIND_TUR, CBRK, GEN_POWER and other classes).

Table D.1-1 Screenshot from software environment.



In the following (Table D.1-2) the MAPS development source code has been listed where the MAPS_DEV class constitutes the main method of the developed software.

Table D.1-2 Source codes for MAPS software.


```
package THESIS;


import jade.core.Profile;
import jade.core.ProfileImpl;
import jade.core.Runtime;
import jade.wrapper.AgentController;
import jade.wrapper.ContainerController;
import jade.wrapper.StaleProxyException;

import javax.swing.JDialog;
import javax.swing.JOptionPane;

import com.mathworks.engine.EngineException;
import com.mathworks.engine.MatlabEngine;

import THESIS.COMMS;
import THESIS.COORD;
import THESIS.DATA_EXCHANGE;
import THESIS.MAS_DLG;
import THESIS.MEASU;
import THESIS.OUTPUT;



public class MAPS_DEV {



public static void main(String[] args) throws StaleProxyException,
EngineException, InterruptedException {


                ///////////////////GETTING NUMBER OF IED NODES
(RELAYS) TO CONFIGURE JADE RUNTIME PLATFORM FOR
MAPS///////////////

                String
NUM__AGENTS=JOptionPane.showInputDialog("PLEASE ENTER NUMBER OF
IED NODES");

                /////////////////////CREATING RUNTIME PLATFORM
INSTANCE FOR
MAPS//////////////////////////////////////////////////
                Runtime rt=Runtime.instance();
                Profile p=new ProfileImpl();
                p.setParameter(Profile.MAIN_HOST, "pejman-PC");
                p.setParameter(Profile.MAIN_PORT, "1099");
                // Now JADE Runtime Platform  is up and running,
need to add the agents
                ////////////////////////END OF PREPARATION FOR
RUNTIME
PLATFORM///////////////////////////////////////////////////

//////////////////////////////////////////////////////////////////
////////////////////////////////////////////////
```

```
                //////////////////////////CREATING CONTAINER
CONTROLLER AND MANAGEMENT
AGENT////////////////////////////////////////

//////////////////////////////////////////////////////////////////
//////////////////////////////////////////////
                ContainerController cc=rt.createMainContainer(p);
                try {
                        AgentController
RMA_AGENT=cc.createNewAgent("MANAGEMENT_AGENT",
"jade.tools.rma.rma", null);
                        RMA_AGENT.start();
                } catch (StaleProxyException e) {
                        // TODO Auto-generated catch block
                        e.printStackTrace();
                }

//////////////////////////////////////////////////////////////////
//////////////////////////////////////////////////
                ////////////////////////////////////READING THE
NUMBER OF IED NODES AND
CREATING/////////////////////////////////////
                ////////////////////////////////////CORRESPONDING
AGENTS FOR MAS
ELEMENTS/////////////////////////////////////////////

                int NUM=0;
                AgentController
Agent1,Agent2,Agent3,Agent4,Agent5,Agent6;

                while(NUM<Integer.parseInt(NUM__AGENTS)) {

                ////////////////////////////////////CREATING THE MAPS
WIZARD TO COLLECT DATA/////////////////////////////////////////
                        MAS_DLG dialog = new MAS_DLG();

dialog.setDefaultCloseOperation(JDialog.DISPOSE_ON_CLOSE);
                        dialog.setVisible(true);

//////////////////////////////////////////////////////////////////
//////////////////////////////////////////////////////
                ///////////////////////////////////CREATING
CORRESPONDING AGENTS FOR EACH IED
NODE/////////////////////////////////////

                        String[]
AGENT_ARGUMENT=dialog.MAPS_DATA.toArray(new
String[dialog.MAPS_DATA.size()]);//converting list array to string
array


            /////////////////////////////////////////////STARTING OF
COMMUNICATION AGENT////////////////////////////////////////

Agent1=cc.createNewAgent(dialog.MAPS_DATA.get(0)+"_COMMS",COMMS.cl
```

```
ass.getName(), AGENT_ARGUMENT);
                        Agent1.start();

////////////////////////////////////////////STARTING OF
COORDINATION AGENT/////////////////////////////////////

Agent2=cc.createNewAgent(dialog.MAPS_DATA.get(0)+"_COORD",
COORD.class.getName(), AGENT_ARGUMENT);
                        Agent2.start();
            ///////////////////////////////////////////STARTING
MEASURMENT AGENT/////////////////////////////////////////

Agent3=cc.createNewAgent(dialog.MAPS_DATA.get(0)+"_MEASU",
MEASU.class.getName(), AGENT_ARGUMENT);
            Agent3.start();

////////////////////////////////////////////CLEARING MAPS_DATA
ARRAYLIST FOR NEXT IED NODE////////////////////
                        dialog.MAPS_DATA.clear();

                        NUM++;

                } // End of While LOOP

///////////////////////////////////////////STARTING THE
DATA_EXCHANGE AGENT////////////////////////////////////////////
Agent4=cc.createNewAgent("SYNCH_AGENT",DATA_EXCHANGE.class.getName
(), null);
Agent4.start();
////////////////////////////////////////STARTING THE OUTPUT
AGENT/////////////////////////////////////////////////////
Agent5=cc.createNewAgent("OUTPUT_AGENT", OUTPUT.class.getName(),
null);
Agent5.start();
///////////////////////////////////////////////////////////////////
/////////////////////////////////////////////////
/////////////////////////////////////END OF DEPLOYING
MAPS//////////////////////////////////////////////////////////////

        } // END of Main() Method


} // END of Class MAPS_DEV
```

MAS_DLG code (representing graphical form for entering data inputs and slots for exchanging real-time measurement data between MAPS and real-time digital simulator- OP5600).

MAS_DLG

```
package THESIS;


import java.awt.BorderLayout;
import java.awt.FlowLayout;

import javax.swing.JButton;
import javax.swing.JDialog;
import javax.swing.JPanel;
import javax.swing.border.EmptyBorder;
import javax.swing.JLabel;

import java.awt.Font;

import javax.swing.JTextField;

import java.awt.Color;
import java.awt.Dialog.ModalityType;
import java.awt.event.ActionListener;
import java.awt.event.ActionEvent;
import java.util.ArrayList;

public class MAS_DLG extends JDialog {

        private final JPanel contentPanel = new JPanel();
        private JTextField textField;
        private JTextField textField_1;
        private JTextField textField_2;
        private JTextField textField_3;
        private JTextField textField_4;
        private JTextField textField_5;
    public ArrayList<String> MAPS_DATA=new ArrayList();
    private JTextField textField_6;
    private JTextField textField_7;
        /**
         * Launch the application.
         */


    /*
        public static void main(String[] args) {
                try {
                        MAS_DLG dialog = new MAS_DLG();

dialog.setDefaultCloseOperation(JDialog.DISPOSE_ON_CLOSE);
                        dialog.setVisible(true);
                } catch (Exception e) {
                        e.printStackTrace();
                }
        }

        /**
         * Create the dialog.
         */
```

Page1

```
	public MAS_DLG() {
		setModalityType(ModalityType.APPLICATION_MODAL);
		setForeground(Color.GREEN);
		setTitle("MAPS (Multi Agent Protection System)
Wizard");
		setBounds(100, 100, 704, 389);
		getContentPane().setLayout(new BorderLayout());
		contentPanel.setBorder(new EmptyBorder(5, 5, 5,
5));
		getContentPane().add(contentPanel,
BorderLayout.CENTER);
		contentPanel.setLayout(null);
		{
			JLabel lblIedNodename = new JLabel("IED
NODE ");
			lblIedNodename.setFont(new Font("Tahoma",
Font.BOLD | Font.ITALIC, 11));
			lblIedNodename.setBounds(10, 11, 177, 24);
			contentPanel.add(lblIedNodename);
		}

		textField = new JTextField();
		textField.setBounds(99, 54, 129, 24);
		contentPanel.add(textField);
		textField.setColumns(10);

		JLabel lblMeasurementMessageSlot = new
JLabel("MEASUREMENT MESSAGE SLOT ");
		lblMeasurementMessageSlot.setFont(new
Font("Tahoma", Font.BOLD | Font.ITALIC, 11));
		lblMeasurementMessageSlot.setBounds(10, 107, 177,
24);
		contentPanel.add(lblMeasurementMessageSlot);

		textField_1 = new JTextField();
		textField_1.setBounds(66, 150, 43, 20);
		contentPanel.add(textField_1);
		textField_1.setColumns(10);

		JLabel lblStart = new JLabel("Start :");
		lblStart.setFont(new Font("Tahoma", Font.ITALIC,
14));
		lblStart.setBounds(10, 151, 46, 14);
		contentPanel.add(lblStart);

		JLabel lblLength = new JLabel("Length :");
		lblLength.setFont(new Font("Tahoma", Font.ITALIC,
14));
		lblLength.setBounds(176, 146, 69, 24);
		contentPanel.add(lblLength);

		textField_2 = new JTextField();
		textField_2.setBounds(255, 150, 43, 20);
		contentPanel.add(textField_2);
		textField_2.setColumns(10);
```

```
                JLabel lblCoordination = new JLabel("COORDINATION
");
                lblCoordination.setFont(new Font("Tahoma",
Font.BOLD | Font.ITALIC, 11));
                lblCoordination.setBounds(10, 187, 177, 24);
                contentPanel.add(lblCoordination);

                JLabel lblUpstream = new JLabel("UpStream :");
                lblUpstream.setFont(new Font("Tahoma",
Font.ITALIC, 14));
                lblUpstream.setBounds(10, 238, 79, 19);
                contentPanel.add(lblUpstream);

                textField_3 = new JTextField();
                textField_3.setBounds(99, 237, 116, 20);
                contentPanel.add(textField_3);
                textField_3.setColumns(10);

                JLabel lblDownstream = new JLabel("DownStream:");
                lblDownstream.setFont(new Font("Tahoma",
Font.ITALIC, 14));
                lblDownstream.setBounds(249, 240, 96, 15);
                contentPanel.add(lblDownstream);

                textField_4 = new JTextField();
                textField_4.setBounds(355, 235, 129, 24);
                contentPanel.add(textField_4);
                textField_4.setColumns(10);

                JLabel lblName = new JLabel("Name:");
                lblName.setFont(new Font("Tahoma", Font.ITALIC,
14));
                lblName.setBounds(10, 57, 52, 14);
                contentPanel.add(lblName);

                JLabel lblType = new JLabel("Type :");
                lblType.setFont(new Font("Tahoma", Font.ITALIC,
14));
                lblType.setBounds(246, 54, 52, 20);
                contentPanel.add(lblType);

                textField_5 = new JTextField();
                textField_5.setBounds(355, 56, 86, 20);
                contentPanel.add(textField_5);
                textField_5.setColumns(10);

                JLabel lblOut = new JLabel("OUT:");
                lblOut.setBounds(355, 153, 46, 14);
                contentPanel.add(lblOut);

                textField_6 = new JTextField();
                textField_6.setBounds(396, 150, 46, 20);
                contentPanel.add(textField_6);
                textField_6.setColumns(10);

                JLabel lblOutLength = new JLabel("OUT LENGTH:");
```

```
		lblOutLength.setBounds(481, 153, 69, 14);
		contentPanel.add(lblOutLength);

		textField_7 = new JTextField();
		textField_7.setBounds(560, 150, 52, 20);
		contentPanel.add(textField_7);
		textField_7.setColumns(10);
		{
			JPanel buttonPane = new JPanel();
			buttonPane.setLayout(new
FlowLayout(FlowLayout.RIGHT));
			getContentPane().add(buttonPane,
BorderLayout.SOUTH);
			{
				JButton okButton = new
JButton("OK");
				okButton.addActionListener(new
ActionListener() {
					public void
actionPerformed(ActionEvent arg0) {

MAPS_DATA.add(textField.getText()); // Name of IED Node

MAPS_DATA.add(textField_1.getText()); //  Start

MAPS_DATA.add(textField_2.getText()); // Length

MAPS_DATA.add(textField_3.getText()); // Upstream

MAPS_DATA.add(textField_4.getText()); // Downstream

MAPS_DATA.add(textField_5.getText()); // IED Node Type

MAPS_DATA.add(textField_6.getText()); // Start for output message
(relay setting)

MAPS_DATA.add(textField_7.getText()); // Length for output message
						dispose();

					}
				});
				okButton.setActionCommand("OK");
				buttonPane.add(okButton);

getRootPane().setDefaultButton(okButton);
			}
			{
				JButton cancelButton = new
JButton("Cancel");

cancelButton.setActionCommand("Cancel");
				buttonPane.add(cancelButton);
			}
		}
	}
```

MEASU agent Code (measurement agent used for receiving real-time measurement data from real-time simulation of the power system to identify and share knowledge about operation states at the CB location (IED) with other agent types).


```
package THESIS;


import java.io.IOException;
import java.lang.*;
import java.util.concurrent.CancellationException;
import java.util.concurrent.ExecutionException;
import java.util.concurrent.Future;

import net.sourceforge.jFuzzyLogic.*;
import net.sourceforge.jFuzzyLogic.fcl.*;
import net.sourceforge.jFuzzyLogic.FIS;

import com.mathworks.engine.EngineException;
import com.mathworks.engine.MatlabEngine;
import com.mathworks.engine.MatlabExecutionException;
import com.mathworks.engine.MatlabSyntaxException;
import java.lang.Math;

import THESIS.DEV_MSU;
import THESIS.GEN_POWER;
import THESIS.LOAD_ELEC;
import THESIS.SOLRP;
import THESIS.TRFM;
import THESIS.WIND_TUR;
import jade.content.ContentElement;
import jade.content.lang.Codec;
import jade.content.lang.Codec.CodecException;
import jade.content.lang.sl.SLCodec;
import jade.content.onto.Ontology;
import jade.content.onto.OntologyException;
import jade.content.onto.UngroundedException;
import jade.content.onto.basic.Action;
import jade.core.*;
import jade.core.behaviours.TickerBehaviour;
import jade.domain.DFService;
import jade.domain.FIPAException;
import jade.domain.FIPAAgentManagement.DFAgentDescription;
import jade.domain.FIPAAgentManagement.ServiceDescription;
import jade.lang.acl.ACLMessage;
import jade.lang.acl.MessageTemplate;
import jade.lang.acl.UnreadableException;

public class MEASU<FUZZY_WT> extends Agent  {


        private String[]
MEASU_DATA={"0","0","0","0","0","0","0","0","0","0","0","0","0","0
","0","0","0","0","0"}; // Array of 13 float data type read from
RTDS
        private String[]
MEASU_DATA0={"0","0","0","0","0","0","0","0","0","0","0","0","0","
0","0","0","0","0","0"};
        private String[] DATA2COORD=new String[19];
        private String
```

```
_Start,_Length,OUT_START,OUT_LENGTH,_DEV_NAME,_DEV_TYPE;
//      private data_slot OUT_DATA=new data_slot();
        private OUT_SLOT OUT_DATA=new OUT_SLOT();
        private OUT_SLOT OUT_DATA0=new OUT_SLOT();
        ///////////////////////////////////////////
        private String[] SETTING_OUT0=new String[3];
        private String[] SETTING_OUT1=new String[3];
        private String[] SETTING_OUT=new String[3];
        private String[] SETTING_OUT2=new String[3];
        public  String[] SET_REL={"0","0","0"};
        public  String[] SET_REL0={"0","0","0"};
        private Codec codec=new SLCodec();
        private Ontology ontology=COORD_ONTO.getInstance();
        private DEV_MSU COMP=null;
        private double
Current,Voltage,S,Power,_Current_,_Voltage_,_Power_;

        //////////////////////////////////////////////////STARTING
SETUP METHOD//////////////////////////////////////////
        private double CHK=1;


        protected void setup() {


/////////////////////////////////////////////////SERVICE
DESCRIPTION FOR MEASUREMENT AGENT//////////////////////
                DFAgentDescription dfd=new DFAgentDescription();
                dfd.setName(getAID());
                ServiceDescription sd=new ServiceDescription();
                sd.setName("Measurement");
                sd.setType("Measurement Agent");
                dfd.addServices(sd);
        /////////////////////////////////////////////REGISTERING
MEASUREMENT AGENT (MEASU) SERVICE/////////////////////
                try {
                        DFService.register(this, dfd);
                } catch (FIPAException e) {
                        // TODO Auto-generated catch block
                        e.printStackTrace();
                }

////////////////////////////////////////////////AGENTS
ARGUMENT//////////////////////////////////////////////////

                Object[] args=getArguments();

                _DEV_NAME=String.valueOf(args[0]);
                _DEV_TYPE=String.valueOf(args[5]);
                _Start=String.valueOf(args[1]);
                _Length=String.valueOf(args[2]);
                // args[3] and args[4] are for upstream and
downstream
                OUT_START=String.valueOf(args[6]);
                OUT_LENGTH=String.valueOf(args[7]);
```

```
        //   final Double[] XMU=new
Double[Integer.parseInt(_Length)];
             final float [] XMU=new
float[Integer.parseInt(_Length)];
            /////////////////////////////SPECIFING DATA MODEL FOR
THE ELECTRICAL COMPONENT///////////////////////////////////


             switch (_DEV_TYPE) {

             case "WT":

                COMP=new WIND_TUR();
            //   WIND_TUR COMP=new WIND_TUR();
                 break;

                        case "LD":

                         COMP=new LOAD_ELEC();

                                break;

                        case "SP":

                         COMP=new SOLRP();

                                 break;

                        case "DG":

                        COMP=new GEN_POWER();
                                break;

                        case "MG":

                                COMP=new CBRK_MG();
                                        break;

                        default :

                        COMP=new CBRK();

                        }


//////////////////////////////////////////////////Registering
Ontology and Content Language/////////////////////////

                getContentManager().registerLanguage(codec);
                getContentManager().registerOntology(ontology);


///////////////////////////////////////////////MESSAGE TEMPLATES
AND OUTPUT MESSAGE TO RTDS///////////////////////////
```

```
                final MessageTemplate
mt=MessageTemplate.MatchSender(new
AID("SYNCH_AGENT",AID.ISLOCALNAME));

                ///////////////////////////////////////////ACLMessage
REQUEST FOR COORDINATION/////////////////////////////////////////////
                final ACLMessage MSG=new
ACLMessage(ACLMessage.REQUEST);
                final ACLMessage MSG1=new
ACLMessage(ACLMessage.INFORM);
                final ACLMessage MSG2=new
ACLMessage(ACLMessage.INFORM);  // Message preparation for
Islanding mode notification
                MSG.addReceiver(new
AID(_DEV_NAME+"_COMMS",AID.ISLOCALNAME));
                MSG1.addReceiver(new
AID(_DEV_NAME+"_COORD",AID.ISLOCALNAME));
        //      MSG2.addReceiver(new
AID("OUTPUT",AID.ISLOCALNAME));

MSG1.setConversationId("measurement_coordination");
//(Coordination request)
                MSG.setLanguage(codec.getName());
                MSG.setOntology(ontology.getName());

        //      MSG1.setLanguage(codec.getName());
        //      MSG1.setOntology(ontology.getName());

////////////////////////////////////////VOCABULARY////////////////
////////////////////////////////////////////////////

                final PROTECTION PRO=new PROTECTION();
        //      final PROTECTION PRO1=new PROTECTION();
                final MEASURE MX=new MEASURE();




        ////////////////////////////////////TICKER
BEHAVIOUR////////////////////////////////////////////
    /////////////////////////////////////////Which receives data
from RTDS and Check for/////////////////////////
        ////////////////////////////////////changes in operating
condition correspondingly////////////////////////////
        ///////////////////////////////////will sending
coordination message to COORD agent/////////////////////////

//////////////////////////////////////////////////////////////////
///////////////////////////////////////////////
                addBehaviour(new TickerBehaviour(this,500) {

                        protected void onTick() {

                                int COUNT=0;
```

```
                              MEASU

                                ACLMessage ac=myAgent.receive(mt);
                //              ac.getUserDefinedParameter(key)


if (ac!=null) {



                                         try {
                                                 String[]
MEASU_DATA= (String[]) ac.getContentObject();


                               for (int k1=0;k1<19;k1++) {
                                   DATA2COORD[k1]=MEASU_DATA[k1];
                                //    System.out.println("this is
data2coord things : "+DATA2COORD[k1]);
                               }

                                                 for (int
k=Integer.parseInt(_Start);k<(Integer.parseInt(_Length)+Integer.pa
rseInt(_Start));k++) {


XMU[COUNT]=Float.parseFloat(MEASU_DATA[k].toString());

COUNT++;
                                                 } // End of for
loop
                                         } catch
(UnreadableException e) {
                                                 // TODO
Auto-generated catch block

e.printStackTrace();
                                         }

//////////////////////////////////////////////////////////////////
/////////////////////////////////////////////////////////
////////////////////////////////DEFINING DATA MODEL FOR THE
ELECTRICAL COMPONENT/////////////////////////////////////////
//////////////////////////////////////////////////////////////////
/////////////////////////////////////////////////////////

//////////////////////////////READING THE DATA SLOT FOR THE
CURRENT POWER COMPONENT/////////////////////////////

                                         if(COMP instanceof
WIND_TUR) {

                                 COMP.SET_CT(XMU[0]);
                                 COMP.SET_P(XMU[2]);
                                 COMP.SET_VT(XMU[1]);
                                 ((WIND_TUR)
COMP).SET_Slip(XMU[3]);
```

```
                              //    System.out.println("Slip0 is: "+
XMU[3]);

/////////////////////////////////////////////////////////////////

                                  /////////////////FUZZY
SYSTEM///////////////////////////////////////

///////////////////////////////////////////////////////////////
                                  String fileName = "WDFIG.fcl";
                                        //  FIS fis=new FIS();
                                       FIS
fis=FIS.load(fileName,true);
                                       fis.setVariable("slip",
XMU[3]);
                                       fis.setVariable("power",
Math.signum(XMU[2])*(XMU[2]/1000000));
                                  //     fis.setVariable("volt",
XMU[1]/320);
                                           fis.evaluate();

System.out.println("this is WindTurbine:
"+fis.getVariable("Trig").getValue());

//////////////////////////////////////////////////////////////////
/////////

                            //      FUZZY_WT fuzz=new
FUZZY_WT(_DEV_TYPE);


////////////////////////////////////////////////////
                                   if ((XMU[1]/320)<1.2 &&
0.8<(XMU[1]/320) ) {    //// start 0

                                           System.out.println("the
voltage ratio for WindTurbine is : "+ XMU[1]/320);

System.out.println("this is FIS outpu value for DFIG out: "+
fis.getVariable("Trig").getValue()/CHK);
                                           System.out.println("the
WindTurbine slip is : "+ XMU[3]);
                                           System.out.println("the
WindTurbine Current is : "+ XMU[0]);

                                           if
(fis.getVariable("Trig").getValue()>=1 &&
((fis.getVariable("Trig").getValue())/CHK)>1.1) {

                                 //   if (XMU[3]>1.1) {


System.out.println("this is FIS outpu value for DFIG:
"+fis.getVariable("Trig").getValue());
```

MEASU

```
try {

PRO.setCOMMAND("measurement");

getContentManager().fillContent(MSG, PRO);
} catch
(CodecException | OntologyException e) {
//
TODO Auto-generated catch block
e.printStackTrace();
}
send(MSG);


try {
MSG1.setContentObject(DATA2COORD);
myAgent.send(MSG1);

}
catch (IOException e) {
// TODO Auto-generated catch block
e.printStackTrace();
}



CHK=fis.getVariable("Trig").getValue();


}else{


System.out.println("this is FIS outpu value for DFIG else:
"+fis.getVariable("Trig").getValue());
}
}else{
System.out.println("this is FIS Did nothing");
}
} else if  (COMP instanceof GEN_POWER) {
```

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```
                                COMP.SET_CT(XMU[0]);
                        COMP.SET_P(XMU[2]);

/////////////////////////////////////////////////////////////////

/////////////////FUZZY SYSTEM/////////////////////////////////////
///////////////////////////////////////////////////////////////

String fileName = "XCB.fcl";
//  FIS fis=new FIS();
FIS fis=FIS.load(fileName,true);
//fis.setVariable("volt", XMU[1]/14000);
fis.setVariable("power", Math.signum(XMU[2])*1);
fis.evaluate();
System.out.println("this is DGs:
"+fis.getVariable("Trig").getValue());

/////////////////////////////////////////////////////////////////
/////////
if ((XMU[1]/14000)<1.05 && 0.8<(XMU[1]/14000) ) {    //// start 0


           if (fis.getVariable("Trig").getValue()>=1.8*CHK ||
(fis.getVariable("Trig").getValue())<CHK*1.8 ) {

                  try {

                      PRO.setCOMMAND("measurement");
                      getContentManager().fillContent(MSG, PRO);
                      send(MSG);

                //      PRO1.setCOMMAND("measurement");
                //      getContentManager().fillContent(MSG1,
PRO1);
               //       send(MSG1);
                      } catch (CodecException e) {
                      //TODO Auto-generated catch block
                      e.printStackTrace();
                      } catch (OntologyException e) {
                      //TODO Auto-generated catch block
                      e.printStackTrace();
                      }

                       }else{

                      //          System.out.println("No change in
GEN_POWER");
                          CHK=fis.getVariable("Trig").getValue();
                        //       _Current_=COMP.GET_CT();
                        //       _Power_=COMP.GET_P();
                      //        //  _Voltage_=COMP.GET_VT();
                           }
                  ////Whatever
}
              }else if (COMP instanceof CBRK ) {
```

```
                  COMP.SET_CT(XMU[0]);
                  COMP.SET_P(XMU[2]);

/////////////////////////////////////////////////////////////////

/////////////////FUZZY SYSTEM////////////////////////////////////
///////////////////////////////////////////////////////////////


String fileName = "XCB.fcl";
//FIS fis=new FIS();
FIS fis=FIS.load(fileName,true);
//fis.setVariable("volt", XMU[1]/14000);
fis.setVariable("power", Math.signum(XMU[2]));
fis.evaluate();
System.out.println("this is CBRK:
"+fis.getVariable("Trig").getValue());

//////////////////////////////////////////////////////////////////
/////////
if ((XMU[1]/1400)<1.05 && 0.8<(XMU[1]/14000) ) {    //// start 0

        //   if (fis.getVariable("Trig").getValue()>=1 &&
((fis.getVariable("Trig").getValue())/CHK)>1.1 ) {

        if  (fis.getVariable("Trig").getValue()>=1.8*CHK ||
(fis.getVariable("Trig").getValue())<CHK*1.8) {
                  try {

                      PRO.setCOMMAND("measurement");
                      getContentManager().fillContent(MSG, PRO);
                      send(MSG);

                 //     PRO1.setCOMMAND("measurement");
                 //     getContentManager().fillContent(MSG1,
PRO1);
                 //     send(MSG1);

                      } catch (CodecException e) {
                      //TODO Auto-generated catch block
                      e.printStackTrace();
                      } catch (OntologyException e) {
                      //TODO Auto-generated catch block
                      e.printStackTrace();
                      }
              }else{

                  CHK=fis.getVariable("Trig").getValue();
              }
       }
                  } else if (COMP instanceof TRFM) {

                  COMP.SET_CT(XMU[0]);
                  COMP.SET_P(XMU[2]);
```

```
////////////////////////////////////////////////////////////////////

/////////////////FUZZY SYSTEM///////////////////////////////////////
//////////////////////////////////////////////////////////////////


String fileName = "XCB.fcl";
//FIS fis=new FIS();
FIS fis=FIS.load(fileName,true);
//fis.setVariable("volt", XMU[1]/14000);
fis.setVariable("power", Math.signum(XMU[2]));
fis.evaluate();
System.out.println("this is Transformer:
"+fis.getVariable("Trig").getValue());

/////////////////////////////////////////////////////////////////////
/////////
if ((XMU[1]/14000)<1.05 && 0.8<(XMU[1]/14000) ) {    //// start 0

//         if (fis.getVariable("Trig").getValue()>=1 &&
((fis.getVariable("Trig").getValue())/CHK)>1.1 ) {

        if  (fis.getVariable("Trig").getValue()>=1.8*CHK ||
(fis.getVariable("Trig").getValue())<CHK*1.8) {
                  try {

                      PRO.setCOMMAND("measurement");
                      getContentManager().fillContent(MSG, PRO);
                      send(MSG);

                //      PRO1.setCOMMAND("measurement");
                //    getContentManager().fillContent(MSG1, PRO1);
                //     send(MSG1);

                      } catch (CodecException e) {
                      //TODO Auto-generated catch block
                      e.printStackTrace();
                      } catch (OntologyException e) {
                      //TODO Auto-generated catch block
                      e.printStackTrace();
                      }
      }else{
                           CHK=fis.getVariable("Trig").getValue();

                    }

 }

              } else if(COMP instanceof LOAD_ELEC) {

                  COMP.SET_CT(XMU[0]);
                  COMP.SET_P(XMU[2]);

////////////////////////////////////////////////////////////////////

////////////////FUZZY SYSTEM////////////////////////////////////
```

```
////////////////////////////////////////////////////////////////


String fileName = "XCB.fcl";
//FIS fis=new FIS();
FIS fis=FIS.load(fileName,true);
//fis.setVariable("volt", XMU[1]/14000);
fis.setVariable("power", Math.signum(XMU[2]));
fis.evaluate();
System.out.println("this is Load:
"+fis.getVariable("Trig").getValue());
///////////////////////////////////////////////////////////////////
/////////
if ((XMU[1]/14000)<1.05 && 0.8<(XMU[1]/14000) ) {    //// start 0

        //   if (fis.getVariable("Trig").getValue()>=1 &&
((fis.getVariable("Trig").getValue())/CHK)>1.1 ) {

        if  (fis.getVariable("Trig").getValue()>=1.8*CHK ||
(fis.getVariable("Trig").getValue())<CHK*1.8) {
                  try {

                      PRO.setCOMMAND("measurement");
                      getContentManager().fillContent(MSG, PRO);
                      send(MSG);

               //       PRO1.setCOMMAND("measurement");
               //     getContentManager().fillContent(MSG1, PRO1);
               //   send(MSG1);

                      } catch (CodecException e) {
                      //TODO Auto-generated catch block
                      e.printStackTrace();
                      } catch (OntologyException e) {
                      //TODO Auto-generated catch block
                      e.printStackTrace();
                      }

              }else{

                      CHK=fis.getVariable("Trig").getValue();
                }
     }else{

     }


              }else if(COMP instanceof CBRK_MG) {


                  COMP.SET_CT(XMU[0]);
                  COMP.SET_P(XMU[2]);

//////////////////////////////////////////////////////////////////

/////////////////FUZZY SYSTEM////////////////////////////////////
```

```
//////////////////////////////////////////////////////////////

String fileName = "XCB.fcl";
//FIS fis=new FIS();
FIS fis=FIS.load(fileName,true);
//fis.setVariable("volt", XMU[1]/14000);
fis.setVariable("power", Math.signum(XMU[2])*1);
fis.evaluate();
System.out.println("this is Load:
"+fis.getVariable("Trig").getValue());

                  if (XMU[0]>100 && (XMU[1]/14000)<0.8) {

                          System.out.println("MAIN CB should
Trip");
                //        send(MSG2);


              } else {
                  //////THIS IS FOR PCC CB
                  COMP.SET_CT(XMU[0]);
                  COMP.SET_VT(XMU[1]);
                  COMP.SET_P(XMU[2]);

              }



                        } else {

                                      block();

                                } // End of if


                        } //End of Tick method


                } // End of TickerBehavior



        }); // End of setup() method


    }  // End of class
}
```

COMMS agent Code (It includes the source code for communication agent types which has the role to identify and communicated with neighbouring IEDs to request information for their operation conditions and device they protect (CB types)).


```
package THESIS;


import java.lang.*;
import java.util.ArrayList;

import jade.content.abs.*;
import jade.util.leap.List;



import jade.content.ContentElement;
import jade.content.ContentManager;
import jade.content.abs.AbsContentElement;
import jade.content.lang.Codec;
import jade.content.lang.Codec.CodecException;
import jade.content.lang.sl.SLCodec;
import jade.content.onto.Ontology;
import jade.content.onto.OntologyException;
import jade.content.onto.UngroundedException;
import jade.content.onto.basic.Action;
import jade.core.*;
import jade.core.behaviours.OneShotBehaviour;
import jade.core.behaviours.TickerBehaviour;
import jade.domain.DFService;
import jade.domain.FIPAException;
import jade.domain.FIPAAgentManagement.DFAgentDescription;
import jade.domain.FIPAAgentManagement.ServiceDescription;
import jade.lang.acl.ACLMessage;
import jade.lang.acl.MessageTemplate;


public class COMMS extends Agent {



        private String
_Start,_Length,OUT_START,OUT_LENGTH,_DEV_NAME,_DEV_TYPE,_UP_STREAM
,_DOWN_STREAM;

        private ArrayList<String> UP_STREAM_LIST=new ArrayList();
        private ArrayList<String> DOWN_STREAM_LIST=new
ArrayList();
        private ArrayList<String> UP_DOWN_LIST=new ArrayList();

        private int UP_DOWN_NUM=0;
////////////////////////////////Ontology
Instances////////////////////////////////////////
private Codec codec=new SLCodec();
private Ontology ontology=COORD_ONTO.getInstance();

        ////////////////////////////////////////////SETUP() METHOD
FOR COMMS AGENT/////////////////////////////////////

private ContentManager manager=(ContentManager)
```

```
getContentManager();

        protected void setup() {

                DFAgentDescription dfd=new DFAgentDescription();
                dfd.setName(getAID());
                ServiceDescription sd=new ServiceDescription();
                sd.setName("Communication");
                sd.setType("COMM Agent");
                dfd.addServices(sd);
                ////////////////////////////////////////REGITERING
COMMUNICATION AGENT (COMMS) FOR SERVICE////////////////
                try {
                        DFService.register(this, dfd);
                } catch (FIPAException e) {
                        // TODO Auto-generated catch block
                        e.printStackTrace();
                }

                ////////////////////////////////////////ADDING
TICKER BEHAVIOUR FOR COMMS agent//////////////////////////////

Object[] args=getArguments();

                _DEV_NAME=String.valueOf(args[0]);
                _DEV_TYPE=String.valueOf(args[5]);
                _Start=String.valueOf(args[1]);
                _Length=String.valueOf(args[2]);
                _UP_STREAM=String.valueOf(args[3]);
                _DOWN_STREAM=String.valueOf(args[4]);
                // args[3] and args[4] are for upstream and
downstream
                OUT_START=String.valueOf(args[6]);
                OUT_LENGTH=String.valueOf(args[7]);

                UP_STREAM_LIST.add(_UP_STREAM);
                DOWN_STREAM_LIST.add(_DOWN_STREAM);

         /////////////////////////////////////////Ontology
Registration///////////////////////////////////////////////
         ////////////////////////////////////////Registering
Ontology and Content Language////////////////////////
        //      manager.registerLanguage(codec);
        //      manager.registerOntology(ontology);
        getContentManager().registerLanguage(codec);
        getContentManager().registerOntology(ontology);

        /////////////////////////////////////////MessageTemplate
for Receiving message From the neighbouring Nodes//////////////

        /////////////////////////////////////////SEARCHING FOR
COMMUNICATION AGENTS IN MAPS////////////////////

DFAgentDescription dfd_COMM=new DFAgentDescription();
ServiceDescription sd_COMM=new ServiceDescription();
sd_COMM.setType("COMM Agent");
```

```
dfd_COMM.addServices(sd_COMM);
//////////////////////////////////////////////////////////////////
doWait(1000); // this is to make sure that all the agents are
registered before searching for them
//////////////////////////////////////////////////////////////////

DFAgentDescription [] COMMUNICATION_AGENTS= null;
try {
COMMUNICATION_AGENTS=DFService.search(this, dfd_COMM); //searching
DF for agents with type of "Measurement"
} catch (FIPAException e) {
// TODO Auto-generated catch block
e.printStackTrace();
}


                addBehaviour(new OneShotBehaviour(){


                        public void action() {


                        }


                });    /// END OF BEHAVIOUR 1


//////////////////////////////////////////////////////////////////////
//////////////////////////////////////////////////////////////////////
/
/////////////////////////////////////////////////////////BEHAVIOUR
2/////////////////////////////////////////////////////////////////////
/
/////////////////////////////////RECEVING REQUEST for
Coordination From Measurement Agent ////////////////////////
//////////////////////////////////////and Sending request for
measurement data from neighboring
nodes/////////////////////////////////
///////////////////////////////////////MessageTemplate for
Receiving request from Measurement
agent//////////////////////////////////
//AID[]  id= {new AID(_DEV_NAME+"_MEASU",AID.ISLOCALNAME)};
 final MessageTemplate
mt=MessageTemplate.and(MessageTemplate.MatchSender(new
AID(_DEV_NAME+"_MEASU",AID.ISLOCALNAME)),MessageTemplate.MatchOnto
logy(ontology.getName()));
//////////////////////////////////////////////////////////////////////
/////////////////////////////////////////////////////////////////////

/////////////////////////////////////////Communication Predicate
to request measurement from Neighboring Nodes///////////////////
final PROTECTION PRO=new PROTECTION();
final ACLMessage MSG_COM=new ACLMessage(ACLMessage.REQUEST);
MSG_COM.setLanguage(codec.getName());
MSG_COM.setOntology(ontology.getName());
```

```
MSG_COM.setConversationId("measurement_request");

for (String K:UP_STREAM_LIST) {
        if (K!=null) {
MSG_COM.addReceiver(new AID(K+"_COMMS",AID.ISLOCALNAME));
        }
}

for (String M:DOWN_STREAM_LIST) {
        if(M!=null) {
        MSG_COM.addReceiver(new AID(M+"_COMMS",AID.ISLOCALNAME));
        }
}
/////////////////////////////////////////////////////////////////////
////////////////////////////////////////////////////////////////////
                addBehaviour(new TickerBehaviour(this,50){

                        protected void onTick() {

                                ACLMessage ac=myAgent.receive(mt);

                                if (ac!=null)  {

                                        try {

PRO.setCOMMAND("measurement");

getContentManager().fillContent(MSG_COM, PRO);

send(MSG_COM);

                                        } catch
(UngroundedException e) {
                                                // TODO
Auto-generated catch block

e.printStackTrace();
                                        } catch (CodecException e)
{
                                                // TODO
Auto-generated catch block

e.printStackTrace();
                                        } catch (OntologyException
e) {
                                                // TODO
Auto-generated catch block

e.printStackTrace();
                                        }

                                }else{

                                        block();
```

```
                          COMMS
                           }

                } // End of onTick() method


        }); /// End of Ticker Behavior 2



//////////////////////////////////////////////////////////////////////
//////////////////////////////////////////////////////////////////////
/
////////////////////////////////////////////////////////////BEHAVIOUR
3/////////////////////////////////////////////////////////////////////
/
///////////////////////////////////Replying Request message for
measurement data
////////////////////////////////////////////////////////
//////////////////////////////////////////////////////////////////////
//////////////////////////////////////////////////////////////////////
/
                  AID[]  id1= {new
AID(_DEV_NAME+"_COMMS",AID.ISLOCALNAME)};


                final MessageTemplate
mt1=MessageTemplate.and(MessageTemplate.MatchReceiver(id1),Message
Template.MatchConversationId("measurement_request"));
                final   ACLMessage MEASURE_reply=new
ACLMessage(ACLMessage.INFORM);
                final PROTECTION XXM=new PROTECTION();
                final MEASURE XXM_MU=new MEASURE();
                MEASURE_reply.setLanguage(codec.getName());

MEASURE_reply.setOntology(ontology.getName());


                addBehaviour(new TickerBehaviour(this,100) {


                        protected void onTick() {


                                ACLMessage
ac1=myAgent.receive(mt1);
                                if (ac1!=null) {


MEASURE_reply.addReceiver(ac1.getSender());
```

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```
XXM.setCOMMAND("measurement");

XXM_MU.setNAME_ID(_DEV_NAME);
XXM_MU.setTYPE_ID(_DEV_TYPE);
XXM_MU.setSTART_MU(_Start);
XXM_MU.setLENGTH_MU(_Length);
                                        XXM.setXMU(XXM_MU);

                                        try {
getContentManager().fillContent(MEASURE_reply, XXM);
myAgent.send(MEASURE_reply);
MEASURE_reply.clearAllReceiver();
                                        } catch (CodecException e)
{
                                                // TODO
Auto-generated catch block
e.printStackTrace();
                                        } catch (OntologyException
e) {
                                                // TODO
Auto-generated catch block
e.printStackTrace();
                                        }
                                }else{
                                        block();
                                }

                        }

                });
//////////////////////////////////////////////////////////////////////////////////////////////////////////////////////////////////////////////////////////////
/
///////////////////////////////////////////////////////////////////////////////////BEHAVIOUR
4///////////////////////////////////////////////////////////////////////////
/
/////////////////////////////////////////Collecting Measurements From
downstream and upstream nodes and send it to coordination
```

```
                                    COMMS
agent////////////////

////////////////////////////////////////MessageTemplate for
Receiving  Measurement data////////////////////////////////////



AID[]  id0= {new AID(_DEV_NAME+"_COMMS",AID.ISLOCALNAME)};
final MessageTemplate
mt0=MessageTemplate.and(MessageTemplate.MatchReceiver(id0),Message
Template.MatchPerformative(ACLMessage.INFORM));
//////////////////////////////////////////////////////////////////
/////////////////////////////////////////////////////////////////

final ACLMessage COORD_MSG=new ACLMessage(ACLMessage.REQUEST);
COORD_MSG.setLanguage(codec.getName());
COORD_MSG.setOntology(ontology.getName());
COORD_MSG.addReceiver(new
AID(_DEV_NAME+"_COORD",AID.ISLOCALNAME));

    final List XM = new jade.util.leap.ArrayList();
        final PROTECTION PRO=new PROTECTION();
        final MEASURE XMM=new MEASURE();
        final COORDINATE XMUD=new COORDINATE();
        final Action a=new Action();
                addBehaviour(new TickerBehaviour(this,500){

                        protected void onTick() {

                                ACLMessage
ac0=myAgent.receive(mt0);

                                if (ac0!=null) {


                                        //
System.out.println("this is the part of COMMS");

                                                ContentElement ce;
                                                try {
                                                        ce =
getContentManager().extractContent(ac0);

                                                        if (ce
instanceof PROTECTION) {



for (int j=0;j<UP_STREAM_LIST.size();j++) {
```

```
if (UP_STREAM_LIST.get(j)!=((PROTECTION)
ce).getXMU().getNAME_ID()) {



        XMM.setNAME_ID(((PROTECTION) ce).getXMU().getNAME_ID());

        XMM.setTYPE_ID(((PROTECTION) ce).getXMU().getTYPE_ID());

        XMM.setSTART_MU(((PROTECTION) ce).getXMU().getSTART_MU());

        XMM.setLENGTH_MU(((PROTECTION)
ce).getXMU().getLENGTH_MU());

        XM.add(XMM);



        UP_DOWN_NUM++;


        System.out.println("upstream checked");

}else{


        System.out.println("Do nothing upstream");

}

                                                              }

                                         for (int
j=0;j<DOWN_STREAM_LIST.size();j++) {



if (DOWN_STREAM_LIST.get(j)!=((PROTECTION)
ce).getXMU().getNAME_ID()) {



        XMM.setNAME_ID(((PROTECTION) ce).getXMU().getNAME_ID());
```

```
        XMM.setTYPE_ID(((PROTECTION) ce).getXMU().getTYPE_ID());

        XMM.setSTART_MU(((PROTECTION) ce).getXMU().getSTART_MU());

        XMM.setLENGTH_MU(((PROTECTION)
ce).getXMU().getLENGTH_MU());

        XM.add(XMM);



        UP_DOWN_NUM++;



        System.out.println("downstream checked");


}else{


        System.out.println("Do nothing downstream");

}

                                                            }

////////////////////////////////////////////////////////////////////
///////////////////

////////////////////////////////////////////////////////////////////
//////////////////

System.out.print(UP_STREAM_LIST.size()+DOWN_STREAM_LIST.size());

System.out.println("up/down num"+UP_DOWN_NUM);


                                        if
(UP_DOWN_NUM==UP_STREAM_LIST.size()+DOWN_STREAM_LIST.size()) {


XMUD.setXMU_DATA(XM);


                                            a.setActor(getAID());

a.setAction(XMUD);
```

```
                                                                        //
 XM.add(a);
getContentManager().fillContent(COORD_MSG, a);
send(COORD_MSG);
System.out.print(UP_DOWN_NUM);
UP_DOWN_LIST.clear();
                                                   UP_DOWN_NUM=0;
XMUD.ClearAllXMU_DATA();
                                                   XM.clear();
                                             }else{
System.out.println("Not completed for coordination");
                                             }
                                                         }
                                                   } catch
(UngroundedException e) {
                                                         // TODO
Auto-generated catch block
e.printStackTrace();
                                                   } catch
(CodecException e) {
                                                         // TODO
Auto-generated catch block
e.printStackTrace();
                                                   } catch
(OntologyException e) {
                                                         // TODO
Auto-generated catch block
e.printStackTrace();
                                                   }

                                       }else{
                                             block();
                                       }

                              } // end of onTick() method
                    });
```

```
    } // End of setup() method
} // End of class
```

COORD Agents code (The Coordination agent is the java class with has the capabilities to request for knowledge/information from its neighbouring node and perform the decision making to select protection setting utilizing API to consult with knowledge database in PROLOG).

COORD

```
package THESIS;


import java.io.IOException;
import java.lang.*;
import java.util.*;
import java.util.ArrayList;
import java.util.HashMap;

import net.sourceforge.jFuzzyLogic.FIS;
import jade.util.leap.*;
import jade.util.leap.Iterator;
import jade.util.leap.List;
import THESIS.OUT_SLOT;
import jade.content.ContentElement;
import jade.content.lang.Codec;
import jade.content.lang.Codec.CodecException;
import jade.content.lang.sl.SLCodec;
import jade.content.onto.Ontology;
import jade.content.onto.OntologyException;
import jade.content.onto.UngroundedException;
import jade.content.onto.basic.Action;
import jade.core.*;
import jade.core.behaviours.TickerBehaviour;
import jade.domain.DFService;
import jade.domain.FIPAException;
import jade.domain.FIPAAgentManagement.DFAgentDescription;
import jade.domain.FIPAAgentManagement.ServiceDescription;
import jade.lang.acl.ACLMessage;
import jade.lang.acl.MessageTemplate;
import jade.lang.acl.UnreadableException;


public class COORD extends Agent{

        private String
_DEV_NAME,_DEV_TYPE,_Start,_Length,UPSTREAM,DOWNSTREAM,OUT_START,O
UT_LENGTH;

/////////////////////////////////////////////////////////////////
///////////
        /////////////////////////Member Variables to Send
Settings To Outputs /////
        private OUT_SLOT OUT_DATA=new OUT_SLOT();
        private OUT_SLOT OUT_DATA0=new OUT_SLOT();

        private String[] SETTING_OUT0=new String[3];
        private String[] SETTING_OUT1=new String[3];
        private String[] SETTING_OUT=new String[3];
        private String[] SETTING_OUT2=new String[3];
        public  String[] SET_REL={"0","0","0"};
        public  String[] SET_REL0={"0","0","0"};
        public  String[] A={"0","0","0"};
        public  String[] B={"1","0","0"};
        public  String[] C={"0","1","0"};
        public  String[] D={"0","0","1"};
```

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```
        private String[]
MEASU_DATA={"0","0","0","0","0","0","0","0","0","0","0","0","0
","0","0","0","0","0"};
        //private String[] MEASUREMENT_DATA=new String[19];

///////////////////////////////////////////////////////////////////
////////////
        private ArrayList<String> UP_STREAM_COORD=new ArrayList();
        private ArrayList<String> DOWN_STREAM_COORD=new
ArrayList();

        private ArrayList<MEASURE> UP_STREAM_INFO=new ArrayList();
        private ArrayList<MEASURE> DOWN_STREAM_INFO=new
ArrayList();

///////////////////////////////////////////////////////////////////
/////////////
        private HashMap<String,MEASURE> map_info=new
HashMap<String,MEASURE>();

///////////////////////////////////////////////////////////////////
///////////
        private Codec codec=new SLCodec();
        private Ontology ontology=COORD_ONTO.getInstance();
        private int ps=0;
        private double power_up,power_down;
        private double current_up,current_down;
        int pow=0;

        /////////////////////////////////////////////////SETUP
METHOD() FOR COORD AGENT/////////////////////////////////
        protected void setup() {

                ///////////////////////////////////////////SERVICE
DESCRIPTION FOR COORDINATION AGENT////////////////////////
                DFAgentDescription dfd=new DFAgentDescription();
                dfd.setName(getAID());
                ServiceDescription sd=new ServiceDescription();
                sd.setName("Coordination");
                sd.setType("Coordination Agent");
                dfd.addServices(sd);

/////////////////////////////////////////////////////REGISTERING
COORDINATION AGENT (COORD) FOR SERVICE //////////

                try {
                        DFService.register(this, dfd);
                } catch (FIPAException e) {
                        // TODO Auto-generated catch block
                        e.printStackTrace();
                }


////////////////////////////////////////////////Registering
Ontology and Content Language////////////////////////
```

```
getContentManager().registerLanguage(codec);
getContentManager().registerOntology(ontology);


////////////////////////////////////////////////////AGENTS
ARGUMENT/////////////////////////////////////////////////////

Object[] args=getArguments();

_DEV_NAME=String.valueOf(args[0]);
_DEV_TYPE=String.valueOf(args[5]);
_Start=String.valueOf(args[1]);
_Length=String.valueOf(args[2]);
UPSTREAM=String.valueOf(args[3]);
DOWNSTREAM=String.valueOf(args[4]);
OUT_START=String.valueOf(args[6]);
OUT_LENGTH=String.valueOf(args[7]);



UP_STREAM_COORD.add(UPSTREAM);
DOWN_STREAM_COORD.add(DOWNSTREAM);

////////////////////////////////////////////////////////MEASUREMENT
DATA FROM RTDS//////////////////////////////////////////////////

//////////////////////////////////////////////////MESSAGE TEMPLATES
AND OUTPUT MESSAGE TO RTDS////////////////////////////

// final MessageTemplate mt=MessageTemplate.MatchSender(new
AID("SYNCH_AGENT",AID.ISLOCALNAME));

 //final MessageTemplate
mt=MessageTemplate.MatchConversationId("coordination
measurement");

 final MessageTemplate
mt=MessageTemplate.and(MessageTemplate.MatchSender(new
AID(_DEV_NAME+"_MEASU",AID.ISLOCALNAME)),MessageTemplate.MatchConv
ersationId("measurement_coordination"));
/////////////////////////////////////////ACLMessage REQUEST FOR
COORDINATION/////////////////////////////////////////////
final ACLMessage MSG=new ACLMessage(ACLMessage.REQUEST);
MSG.addReceiver(new AID(_DEV_NAME+"_COMMS",AID.ISLOCALNAME));
MSG.setLanguage(codec.getName());
MSG.setOntology(ontology.getName());

final float[] XMU=new float[19];
/////////////////////////////////////////VOCABULARY///////////////
/////////////////////////////////////////////////////

addBehaviour(new TickerBehaviour(this,100) {

        protected void onTick() {
```

```
                int COUNT=0;

                ACLMessage ac=myAgent.receive(mt);

if (ac!=null) {

        System.out.println("I GET MESSAGE ");

                        try {
                                String[] MEASU_DATA= (String[])
ac.getContentObject();

                        //      System.out.println("data in
Coord0: "+MEASU_DATA);

                                for (int k=0;k<19;k++) {

                                        System.out.println("data
in Coord1: "+MEASU_DATA[k]);
                                //
XMU[COUNT]=Float.parseFloat(MEASU_DATA[k].toString());

XMU[COUNT]=Float.valueOf(MEASU_DATA[k]);
                                //
System.out.println("data in Coord: "+XMU[COUNT]);
                                                        COUNT++;


                                } // End of for loop
                        } catch (UnreadableException e) {
                                // TODO Auto-generated catch block
                                e.printStackTrace();
                        }
}else {

        block();
}
        }

        });
////////////////////////////////////////////////////////////MessageT
emplate for sending settings to OUTPUT_AGENT////////////

final ACLMessage SETTING_MSG=new ACLMessage(ACLMessage.INFORM);
SETTING_MSG.addReceiver(new AID("OUTPUT_AGENT",AID.ISLOCALNAME));

/////////////////////////////////////////////////////////////Message
Template To Receive COORD action from MEASU
agent//////////////////////////////
      AID[]  id= {new AID(_DEV_NAME+"_COORD",AID.ISLOCALNAME)};
      final MessageTemplate
mt1=MessageTemplate.and(MessageTemplate.MatchReceiver(id),MessageT
emplate.MatchPerformative(ACLMessage.REQUEST));


//////////////////////////////////////////////////////////////////
```

```
/////////////////////////////////////////////////////////

//////////////////////////////////////////////////////////////ADDING
TICKER BEHAVIOUR///////////////////////////////////////////////////
     /////////////////////////////////////////////////////BEHAVIOUR 1
for COORDINATION in response to measurement agent///////////////

////////////////////////////////////////////////////////////////////
//////////////////////////////////////////////////////////////
      final jade.util.leap.List XM = new
jade.util.leap.ArrayList();
      final MEASURE XMM=new MEASURE();
          final COORDINATE XMUD=new COORDINATE();


      addBehaviour(new TickerBehaviour(this,500){


          protected void onTick() {


                  ACLMessage ac1=myAgent.receive(mt1);

                  if (ac1!=null) {


                          ContentElement ce = null;



                                                  try {
                                                                  ce
= getContentManager().extractContent(ac1);

                                                          Action a=
(Action) ce;




COORDINATE XMUD=(COORDINATE) a.getAction();


ps++;



for (int j=0;j<XMUD.getXMU_DATA().size();j++) {


        MEASURE XMM=(MEASURE) XMUD.getXMU_DATA().get(j);
```

```
        if (UP_STREAM_COORD.get(0)!=XMM.getNAME_ID()) {

                    UP_STREAM_INFO.add(XMM);
                    System.out.println("upstream coord");

            }else{

                    DOWN_STREAM_INFO.add(XMM);
                    System.out.println("Do nothing coord");
            }
}

System.out.println("connection
to"+getAID().getLocalName()+"from:"+XMM.getNAME_ID()+" and "+ps);
XMUD.ClearAllXMU_DATA();

ps=0;

                                                    } catch
(UngroundedException e1) {
                                                            // TODO
Auto-generated catch block
e1.printStackTrace();
                                                    } catch
(CodecException e1) {
                                                            // TODO
Auto-generated catch block
e1.printStackTrace();
                                                    } catch
(OntologyException e1) {
                                                            // TODO
Auto-generated catch block
e1.printStackTrace();
```

```
}

////GET the appropriate data from the message received and check it with the upstream or downstream data

/// and then provid the output message to OUTPUT_agent (no need to be in the ontology as it is making I/O service

if(Integer.parseInt(OUT_LENGTH)!=0){

int k=0;
for (MEASURE UP_MEASURE:UP_STREAM_INFO){

if(UP_STREAM_COORD.get(k)!=UP_MEASURE.getNAME_ID() && UP_MEASURE!=null) {

MEASURE val=UP_MEASURE;

System.out.println("this measure value in coor: "+ val.getSTART_MU());

//
power_up=XMU[Integer.parseInt(val.getSTART_MU())+1];

power_up=XMU[Integer.parseInt(val.getSTART_MU())+2];

current_up=XMU[Integer.parseInt(val.getSTART_MU())];

System.out.println("the power_up is : "+ power_up);

}

}

k=0;

for (MEASURE DOWN_MEASURE:DOWN_STREAM_INFO){
```

```
if(DOWN_STREAM_COORD.get(k)!=DOWN_MEASURE.getNAME_ID() &&
DOWN_MEASURE!=null) {


MEASURE val=DOWN_MEASURE;

power_down=XMU[Integer.parseInt(val.getSTART_MU())+2];

current_down=XMU[Integer.parseInt(val.getSTART_MU())];

System.out.println("the power_down is : "+ power_down);
                                                            }

                        }


////////////////////////////////////////////////////////////////

/////////////////FUZZY SYSTEM/////////////////////////////////////
//////////////////////////////////////////////////////////////
String fileName = "COORD_FIS.fcl";
//FIS fis=new FIS();
FIS fis=FIS.load(fileName,true);

fis.setVariable("power_up", power_up);
fis.setVariable("power_down", power_down);
fis.setVariable("volt", XMU[Integer.parseInt(_Start)]);
fis.evaluate();
System.out.println("this is pejman:
"+fis.getVariable("Trig").getValue());

/////////////////////////////////////////////////////////////////
/////////


                                        //      if
(fis.getVariable("Trig").getValue()>-2) {    //// start 0
                                                      if
(XMU[Integer.parseInt(_Start)]<-2) {    //// start 0


System.out.println("xmu is: "+ XMU[0]);
                                                      String []
SETTING_OUT0=B;  //{"1","0","0"}

                                                      for (int
j=0;j<3;j++) {


SET_REL0[j]=SETTING_OUT0[j];
                                                      }
```

```
OUT_DATA.Set_Start(Integer.parseInt(OUT_START));

OUT_DATA.Set_Length(Integer.parseInt(OUT_LENGTH));

OUT_DATA.Set_DATA(SET_REL0);
                                                  try {
SETTING_MSG.setContentObject(OUT_DATA);
send(SETTING_MSG);
                                                  } catch
(IOException e) {
                                                         //
TODO Auto-generated catch block
e.printStackTrace();
                                                  }

                              //              }else
if(0.5<fis.getVariable("Trig").getValue() &&
fis.getVariable("Trig").getValue()<=1.5){      //// start 3
                                                  }else
if(XMU[Integer.parseInt(_Start)]>=-2 &&
XMU[Integer.parseInt(_Start)]<0 ){      //// start 3
                                                  String[]
SETTING_OUT1=C;       //{"0","1","0"}
                                                  for (int
j=0;j<3;j++) {

SET_REL0[j]=SETTING_OUT1[j];
                                                  }

OUT_DATA.Set_Start(Integer.parseInt(OUT_START));

OUT_DATA.Set_Length(Integer.parseInt(OUT_LENGTH));

OUT_DATA.Set_DATA(SET_REL0);
                                                  try {
SETTING_MSG.setContentObject(OUT_DATA);
send(SETTING_MSG);
                                                  } catch
```

```
(IOException e) {
                                                                //
TODO Auto-generated catch block
e.printStackTrace();
                                                        }
                              //              }else if
(-0.5<fis.getVariable("Trig").getValue() &&
fis.getVariable("Trig").getValue()<=0.5) {    //// start 6

                                                        }else if
(XMU[Integer.parseInt(_Start)]>=0 &&
XMU[Integer.parseInt(_Start)]<1) {
                                                        String[]
SETTING_OUT=D;  //{"0","0","1"};
                                                        for (int
j=0;j<3;j++) {

SET_REL0[j]=SETTING_OUT[j];
                                                        }

OUT_DATA.Set_Start(Integer.parseInt(OUT_START));

OUT_DATA.Set_Length(Integer.parseInt(OUT_LENGTH));

OUT_DATA.Set_DATA(SET_REL0);
                                                        try {
SETTING_MSG.setContentObject(OUT_DATA);
send(SETTING_MSG);
                                                        } catch
(IOException e) {
                                                                //
TODO Auto-generated catch block
e.printStackTrace();
                                                        }

                                              }else {
//// start 9
                                                        String[]
SETTING_OUT2=A;  // {"0","0","0"};
                                                        for (int
```

```
                                COORD
j=0;j<3;j++) {

SET_REL0[j]=SETTING_OUT2[j];
                                                                  }

OUT_DATA.Set_Start(Integer.parseInt(OUT_START));

OUT_DATA.Set_Length(Integer.parseInt(OUT_LENGTH));

OUT_DATA.Set_DATA(SET_REL0);
                                                                  try {
SETTING_MSG.setContentObject(OUT_DATA);
send(SETTING_MSG);
                                                                  } catch
(IOException e) {
                                                                          //
TODO Auto-generated catch block
e.printStackTrace();
                                                                  }
                                                          }

                                                          }else{
System.out.println("nothing");
                                                          }

                  }else{
                          block();
                  }

          } //End of OnTick() method

      });  // End of Behaviour



        } // End of setup() method
} // End of class
                              Page11
```

DATA_EXCHANGE or SYNCH agent Code (It is an interfacing agent which synchronizes data exchange for co-simulation between MAPS agents and real-time power system simulation using OP5600 digital simulator).

```
                                DATA_EXCHANGE
package THESIS;

import java.io.BufferedReader;
import java.io.BufferedWriter;
import java.io.DataOutputStream;
import java.io.IOException;
import java.io.InputStream;
import java.io.InputStreamReader;
import java.io.OutputStreamWriter;
import java.io.Reader;
import java.io.Writer;
import java.lang.*;
import java.net.InetAddress;
import java.net.InetSocketAddress;
import java.net.ServerSocket;
import java.net.Socket;
import java.net.UnknownHostException;
import java.nio.ByteBuffer;
import java.nio.ByteOrder;
import java.nio.FloatBuffer;
import java.nio.channels.Selector;
import java.nio.channels.SocketChannel;
import java.util.Arrays;

import jade.core.*;
import jade.core.behaviours.Behaviour;
import jade.core.behaviours.ThreadedBehaviourFactory;
import jade.core.behaviours.TickerBehaviour;
import jade.domain.DFService;
import jade.domain.FIPAException;
import jade.domain.FIPAAgentManagement.DFAgentDescription;
import jade.domain.FIPAAgentManagement.ServiceDescription;
import jade.lang.acl.ACLMessage;
import jade.lang.acl.MessageTemplate;
import jade.lang.acl.UnreadableException;


public class DATA_EXCHANGE extends Agent {


        ////////////Member Variables////////////////
        private String[] DATA_FROM_OPAL=
{"0","0","0","0","0","0","0","0","0","0","0","0","0","0","0","0","
0","0","0"};   //A bucket to collect data read from the RTDS
        //private String[]
DATA_TO_RTDS={"0","0","0","0","0","0","0","0","0","0","0","0"}; //
default output for relay settings
        private String[]
DATA_TO_OPAL={"1","0","0","0","1","0","0","0","0","0","0","1"};
        private String[] DATA_TO_OPAL_UPDATE=new String[12]; //
relay settings updated

        //////////////////// JADE AGENT SETUP METHOD
//////////////////////////////////

                                    Page1
```

```
///////////////////////////////////////////////////////////////////
///////////////
        ////////////////////////////////REGISTERING AGENT
SERVICE////////////////////////

///////////////////////////////////////////////////////////////////
/////////////


//      private ThreadedBehaviourFactory tb=new
ThreadedBehaviourFactory();

        protected void setup() {

                DFAgentDescription dfd=new DFAgentDescription();
                dfd.setName(getAID());
                ServiceDescription sd=new ServiceDescription();
                sd.setName("SYNCH");
                sd.setType("Synchronization");
                dfd.addServices(sd);
                try {
                        DFService.register(this, dfd);
                } catch (FIPAException e) {
                        // TODO Auto-generated catch block
                        e.printStackTrace();
                }


////////////////////////////////END OF SERVICE
REGISTERATION////////////////////////////////
///////////////////////////////////////////////////////////////////
/////////////////////////
///////////////////////////////SEARCHING FOR MEASUREMENT AGENTS IN
MAPS////////////////////

DFAgentDescription dfd_MEASU=new DFAgentDescription();
ServiceDescription sd_MEASU=new ServiceDescription();
sd_MEASU.setType("Measurement Agent");
dfd_MEASU.addServices(sd_MEASU);
/////////////////////////////////////////////////////////////////
//doWait(1000); // this is to make sure that all the agents are
registered before searching for them
/////////////////////////////////////////////////////////////////

DFAgentDescription [] MEASUREMENT_AGENTS= null;
try {
        MEASUREMENT_AGENTS=DFService.search(this, dfd_MEASU);
//searching DF for agents with type of "Measurement"
} catch (FIPAException e) {
        // TODO Auto-generated catch block
        e.printStackTrace();
}

///////////////////////////END OF SEARCH FOR MEASUREMENT
AGENT//////////////////////////////
```

```
DFAgentDescription dfd_COORD=new DFAgentDescription();
ServiceDescription sd_COORD=new ServiceDescription();
sd_COORD.setType("Coordination Agent");
dfd_COORD.addServices(sd_COORD);

DFAgentDescription [] COORDINATION_AGENTS= null;
try {
        COORDINATION_AGENTS=DFService.search(this, dfd_COORD);
//searching DF for agents with type of "Measurement"
} catch (FIPAException e) {
        // TODO Auto-generated catch block
        e.printStackTrace();
}
/////////////////////////////////////////////////////////////////
/
final ACLMessage COORD_MSG=new ACLMessage(ACLMessage.INFORM);
COORD_MSG.setConversationId("coordination measurement");

for (int j=0;j<COORDINATION_AGENTS.length;j++) {

        COORD_MSG.addReceiver(COORDINATION_AGENTS[j].getName());
// adding receiver IDs to Measurement message "MEASU_MSG"

System.out.println(COORDINATION_AGENTS[j].getName().getLocalName()
);
}

/////////////////////////////////////////////////////////////////
//////////////////////////
//////////////////////////PREPARING MEASURMENT MESSAGE BY ADDING
RECIEVERS FROM DF SEARCH//////

final ACLMessage MEASU_MSG=new ACLMessage(ACLMessage.INFORM);

for (int j=0;j<MEASUREMENT_AGENTS.length;j++) {

        MEASU_MSG.addReceiver(MEASUREMENT_AGENTS[j].getName()); //
adding receiver IDs to Measurement message "MEASU_MSG"

System.out.println(MEASUREMENT_AGENTS[j].getName().getLocalName())
;
}



    ///////////////////////////////////////CHECKING FOR
AVAILABLE MESSAGE FROM MAPS TO UPDATE RELAY SETTINGS ///



final MessageTemplate mt=MessageTemplate.MatchSender(new
AID("OUTPUT_AGENT",AID.ISLOCALNAME));
```

```
        addBehaviour(new TickerBehaviour(this,50) {

                // I can use the Connection.java code in the
pj_opal_RT project to just read the data from Opal-RT no send
                // and if that worked I will build it up for next
step which is sending Output data to Opal-RT



                 float fval[] = null;
         int npoints = 19;
             int numOutPoints=12;
                 int size = numOutPoints * 4;


                 Socket s_client = null;

                 InputStream input_from_skt = null;  ///
SIMULINK_STREAM_READER

                 DataOutputStream out2skt = null;   ///
SYNCH_STREAM_WRITER

                 int num = -1;

                 int S=0;
                int H=0;

                protected void onTick() {

                         byte[] buff = new byte[(npoints) * 4];
                         byte[] buffer = new byte[size];
                        ByteBuffer outbuff =
ByteBuffer.wrap(buffer);


                         ACLMessage ac=myAgent.receive(mt); //
Only one type of message is received by DTA_EXCHANGE AGENT FROM
OUTPUT AGENT



                //        do  {





                         if(ac!=null){

                                 S++;
```

```
                              System.out.println("S counter is:
"+ S);

                              try {
                                      DATA_TO_OPAL = (String[])
ac.getContentObject();

DATA_TO_OPAL_UPDATE=DATA_TO_OPAL;
                                       System.out.println("DATA
TO OPAL***:"+ DATA_TO_OPAL_UPDATE[0]);
                              } catch (UnreadableException e1) {
                                      // TODO Auto-generated
catch block
//
e1.printStackTrace();
                              }


                              for (int i = 0;
i<numOutPoints;i++)
                              {

                              //byte[] src =
GTNET_SKT_UDP.convertToByteArray(Integer.valueOf((String)
GTNET_SKT_UDP.OPtable.getValueAt(i, 3)));
                              // Note: if input is sent as float
we can just round and the return will always be an INT so no
exception will be thrown as with above line of code
                      //      byte[] src =
convertToByteArray(Float.valueOf(DATA_TO_OPAL_UPDATE[i]));
                              byte[] src =
convertToByteArray(Float.valueOf(DATA_TO_OPAL[i].toString()));
                              outbuff.put(src, 0, 4);
                              }

                              while(true) {

                                                      try {

s_client = new Socket("140.159.122.73",7200);
                                                  //
s_client.setKeepAlive(true);
                                                      //
System.out.println("time out is: "+s_client.getSoTimeout());


input_from_skt =s_client.getInputStream();


out2skt =new DataOutputStream(s_client.getOutputStream());


                                                              //
 }else{
```

```
                                                                        //
         num1=num;

                                                                        //
 }
                                                                //
while( (num=input_from_skt.read(buff, 0, 4*npoints))>=0) {
                                         // Flush stream
num=input_from_skt.read(buff, 0, 4*npoints);
                                                if (num==(npoints)
* 4) {
                                                        try {
                                out2skt.write(buffer, 0, size);
                                out2skt.flush();
                        } catch (IOException e) {
                                // TODO Auto-generated catch block
                                e.printStackTrace();
                        }
                                                }
                                                        //num=-1;
                                               break;
                                                    }
                                                                        //
                 out2skt.write(buffer, 0, size);
                                                                        //
                 out2skt.flush();
                                                        //      }
                                                         catch
(IOException e2) {
                                                                        //
TODO Auto-generated catch block
e2.printStackTrace();
                                                        }
                                        //              while
(s_client.isConnected()==false) {
                                        //              }
                                                        //
if(s_client.isConnected()) {
                                                                        //
 try {
```

```
                                                                        //
        num=input_from_skt.read(buff, 0, 4*npoints);
                                                                        //
} catch (IOException e2) {

        // TODO Auto-generated catch block
                                                                        //
        e2.printStackTrace();
                                                                        //
}


                                                                        /*



        for (int i = 0; i<numOutPoints;i++)

        {


        //byte[] src =
GTNET_SKT_UDP.convertToByteArray(Integer.valueOf((String)
GTNET_SKT_UDP.OPtable.getValueAt(i, 3)));

        // Note: if input is sent as float we can just round and
the return will always be an INT so no exception will be thrown as
with above line of code

//      byte[] src =
convertToByteArray(Float.valueOf(DATA_TO_OPAL_UPDATE[i]));

        byte[] src =
convertToByteArray(Float.valueOf(DATA_TO_OPAL[i].toString()));

        outbuff.put(src, 0, 4);

        }

*/
                                                                /*

 try {

        out2skt.write(buffer, 0, size);

} catch (IOException e2) {

        // TODO Auto-generated catch block

        e2.printStackTrace();

}

 try {
```

```
        out2skt.flush();
} catch (IOException e2) {
        // TODO Auto-generated catch block
        e2.printStackTrace();
}

 */
                                }

                                        if (num==(npoints) * 4){
                                                        ByteBuffer
buf = ByteBuffer.wrap(buff);
buf.order(ByteOrder.LITTLE_ENDIAN);
FloatBuffer floatbuffer=buf.asFloatBuffer();
                                                  //
DoubleBuffer doublebuffer=buf.asDoubleBuffer();
                                                        float[]
fval=new float[floatbuffer.remaining()];
                                                        //
double[] doble=new double[doublebuffer.remaining()];

floatbuffer.get(fval);
                                          //
System.out.println("this is what I read 2");


                                                        for(int
j=0;j<npoints;j++) {
                                              //
DATA_FROM_OPAL[j]=Float.toString(fval[j]);
                                                  //
DATA_FROM_OPAL[j]=Float.toString(fval[j]);
DATA_FROM_OPAL[j]=String.valueOf(fval[j]);
System.out.println("the" + j+"th"+DATA_FROM_OPAL[j]);

                                                         }
```

DATA_EXCHANGE

```
}

// BufferedReader
input_data=new BufferedReader(input_from_skt); ///
SIMULINK_BUFF_READER_

try {
input_from_skt.close();
out2skt.close();
//
s_client.close();

} catch
(IOException e) {
// TODO
Auto-generated catch block
e.printStackTrace();
}

try {
MEASU_MSG.setContentObject(DATA_FROM_OPAL);
} catch
(IOException e) {
//
TODO Auto-generated catch block
e.printStackTrace();
}
myAgent.send(MEASU_MSG);
/*
try {
COORD_MSG.setContentObject(DATA_FROM_OPAL);
} catch
(IOException e) {
//
TODO Auto-generated catch block
e.printStackTrace();
}
myAgent.send(COORD_MSG);
```

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DATA_EXCHANGE

```
                                                   */
                }else{
                        block();
                        /*
                        try {
                                while(true) {
                                        s_client = new
Socket("140.159.122.73",7200);
                                        input_from_skt
=s_client.getInputStream();
                                        out2skt =new
DataOutputStream(s_client.getOutputStream());

                                        //      }else{
                                        //
num1=num;
                                        //      }
                        //                      while(
(num=input_from_skt.read(buff, 0, 4*npoints))>=0) {
                        // Flush stream
num=input_from_skt.read(buff, 0, 4*npoints);
                        if (num==(npoints) * 4) {
                                try {
        out2skt.write(buffer, 0, size);
        out2skt.flush();
} catch (IOException e) {
        // TODO Auto-generated catch block
        e.printStackTrace();
}

                        //      num=-1;
                                break;

                                  }
                                        //
```

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```
                                                        } catch
(IOException e2) {
                                                             //
TODO Auto-generated catch block
e2.printStackTrace();
                                                        }

               if (num==(npoints) * 4){
                                        ByteBuffer buf =
ByteBuffer.wrap(buff);
buf.order(ByteOrder.LITTLE_ENDIAN);
                                        FloatBuffer
floatbuffer=buf.asFloatBuffer();
                         //             DoubleBuffer
doublebuffer=buf.asDoubleBuffer();
                                        float[] fval=new
float[floatbuffer.remaining()];
                                        //              double[]
doble=new double[doublebuffer.remaining()];
                                        floatbuffer.get(fval);
               //                        System.out.println("this
is what I read 2");

                         //             doublebuffer.get(doble);
                         //             ByteBuffer buf0 =
ByteBuffer.wrap(buff, 4, 32);
                                        for(int j=0;j<npoints;j++)
{
                      //
DATA_FROM_OPAL[j]=Float.toString(fval[j]);
                         //
DATA_FROM_OPAL[j]=Float.toString(fval[j]);
DATA_FROM_OPAL[j]=String.valueOf(fval[j]);
                         //              System.out.println("the"
+ j+"th"+DATA_FROM_OPAL[j]);

                                         }
               }

     //             BufferedReader input_data=new
BufferedReader(input_from_skt);  /// SIMULINK_BUFF_READER_
```

```
                try {
                        input_from_skt.close();
                        out2skt.close();
               //       s_client.close();


               } catch (IOException e) {
                        // TODO Auto-generated
catch block
                        e.printStackTrace();
               }


                try {
MEASU_MSG.setContentObject(DATA_FROM_OPAL);
                        } catch (IOException e) {
                                // TODO
Auto-generated catch block
e.printStackTrace();
                        }
                         myAgent.send(MEASU_MSG);


                         try {
COORD_MSG.setContentObject(DATA_FROM_OPAL);
                        } catch (IOException e) {
                                // TODO
Auto-generated catch block
e.printStackTrace();
                        }
                         myAgent.send(COORD_MSG);

                */


        }

    }  // End of onTick() method


///////////////////////////////////////// Reading Measurements from
//////////////////////////////

//////////////////////////////////////////////////////////////////////
////////////////////////////////
```

```
////////////////////////////////SENDING MEASUREMENT DATA TO ALL
MEASUREMENT AGENTS (Broadcasting) ///////////
///////////////////////////////////////////////////////////////////
/////////////////////////////////////////////

/////////////////////////////////////END OF BROADCASTING
MEASUREMENT MESSAGE/////////////////////////////////////
///////////////////////////////////////////////////////////////////
/////////////////////////////////////////////

                });

//////////////////////////////////////////END OF OUTPUT
STREAM//////////////////////////////////////////////////////
//////////////////////////////////////////END OF SENDING RELAY
SETTING TO RTDS/////////////////////////////////

}   // END OF SETUP() METHOD

        public static  byte[] convertToByteArray(float value) {
        byte[] bytes = new byte[4];
        ByteBuffer buffer = ByteBuffer.allocate(bytes.length);
        buffer.order(ByteOrder.LITTLE_ENDIAN);
        //  buffer.putFloat(value);
       buffer.putFloat(value);
      return buffer.array();
                                }

        }  // END OF Class
```

OUTPUT agent Code (It is an interfacing agent which receives group settings from all coordination agents and deliver it to DATA_EXCHANGE agent to be published as GOOSE message to adjust protection settings within HIL IEDs).

```
                              OUTPUT
package THESIS;


import java.io.IOException;
import java.lang.*;
import java.util.*;

import THESIS.OUT_SLOT;
import jade.core.*;
import jade.core.behaviours.TickerBehaviour;
import jade.core.messaging.TopicManagementHelper;
import jade.domain.DFService;
import jade.domain.FIPAException;
import jade.domain.FIPAAgentManagement.DFAgentDescription;
import jade.domain.FIPAAgentManagement.ServiceDescription;
import jade.lang.acl.ACLMessage;
import jade.lang.acl.MessageTemplate;
import jade.lang.acl.UnreadableException;

public class OUTPUT extends Agent {


        private String[] UPDATE_SET={"0","0","0"};

        private String[] UPDATE_SET_F={"0","0","0"};
        private String[] UPDATE_SET_S={"0","0","0"};
        private String[]
UPDATE_SET1={"0","0","0","0","0","0","0","0","0","0","0","0"};//ch
anged
        private ArrayList<String> UPDATE_SET0=new
ArrayList<String>(Collections.nCopies(12, "1"));
//      private String[]
UPDATE_SET1={"0","0","0","0","0","0","0","0","0","0","0","0"};//ch
anged
//      private String[] UPDATE_SET0=new String[12];
//      private String[] UPDATE_SET1=new String[12];
//      private OUT_SLOT SETTINGS_OUT=new OUT_SLOT();

        private OUT_SLOT SETTINGS_OUT=new OUT_SLOT();

        ///////////////////////////////////SETUP METHOD FOR JADE
AGENT///////////////////////////
        ///////////////////////////////////SERVICE DESCRIPTION FOR
OUTPUT AGENT//////////////////////////////

        protected void setup() {


                DFAgentDescription dfd=new DFAgentDescription();
                dfd.setName(getAID());
                ServiceDescription sd=new ServiceDescription();
                sd.setName("OUTPUT");
                sd.setType("SYS_OUTPUT");
                dfd.addServices(sd);

/////////////////////////////////////////////////////////////////
                               Page1
```

```
/////////////////////////////////
/////////////////////////////////REGISTERING OUTPUT AGENT SERVICE
FOR MAPS///////////////////
                try {
                        DFService.register(this, dfd);
                } catch (FIPAException e) {
                        // TODO Auto-generated catch block
                        e.printStackTrace();
                }


//////////////////////////////////END OF SERVICE
REGISTERATION////////////////////////////////


                //////////////////////INTRODUCING MESSAGE TEMPLATE
FOR OUTPUT AGENT////////////////////////////////
//////////////////////////////////////////////////////////////////
//////////////////////////////
///////////////////////////////////////////STARTING SERVER SOCKET
TO RECEIVE DATA FROM RTDS///////
AID[]  id= {new AID("OUTPUT_AGENT",AID.ISLOCALNAME)};

final MessageTemplate mt=MessageTemplate.MatchReceiver(id);


//////////////////////INTRODUCING MESSAGE TEMPLATE FOR OUTPUT
AGENT////////////////////////////////

final ACLMessage OUT_MSG=new ACLMessage(ACLMessage.INFORM);
OUT_MSG.addReceiver(new AID("SYNCH_AGENT",AID.ISLOCALNAME));

                ///////////////////////////////////ADD A TICKER
BEHAVIOUR/////////////////////////////////////////
                        addBehaviour(new TickerBehaviour(this,500)
{

                                protected void onTick() {


                                        ACLMessage
ac=myAgent.receive(mt);


                                        if (ac!=null) {

                                                try {

OUT_SLOT SETTINGS_OUT= (OUT_SLOT) ac.getContentObject();

UPDATE_SET=SETTINGS_OUT.Get_DATA();
        //////////////////////////////////////{
```

```
//UPDATE_SET_F=UPDATE_SET;

                                             for (int
k=SETTINGS_OUT.Get_Start();k<(SETTINGS_OUT.Get_Start()+SETTINGS_OU
T.Get_Length());k++) {

UPDATE_SET1[k]=UPDATE_SET[k-SETTINGS_OUT.Get_Start()];
                                             }

                                                     } catch
(UnreadableException e) {
                                                             //
TODO Auto-generated catch block

e.printStackTrace();
                                                     }

                                     //              try {
                                     //
OUT_MSG.setContentObject(UPDATE_SET1); //changed
                                     //
myAgent.send(OUT_MSG);
                                     //              } catch
(IOException e) {
                                                             //
TODO Auto-generated catch block
                                     //
e.printStackTrace();
                                     //              }


                                             } else{

                                             block();
                                     }  // End of If
                             } // End of onTick() method
                     })      ; //End of TickerBehaviour

//////////////////////////////////////////////////////////////////
///////////////////////////
addBehaviour(new TickerBehaviour(this,3000){


                             protected void onTick() {
                                     final ACLMessage
OUT_MSG=new ACLMessage(ACLMessage.INFORM);
                                     OUT_MSG.addReceiver(new
```

```
                               OUTPUT
AID("SYNCH_AGENT",AID.ISLOCALNAME));

OUT_MSG.setConversationId("Out2RTDS");


System.out.println("Output agent Inside second Behaviour
:"+Arrays.toString(UPDATE_SET1));

                        //                for (int m=0;m<12;m++) {
                        //
UPDATE_SET2[m]=UPDATE_SET1[m];
                        //                }
                                        try {

OUT_MSG.setContentObject(UPDATE_SET1); //changed

myAgent.send(OUT_MSG);
                                        } catch (IOException e) {
                                                // TODO
Auto-generated catch block

e.printStackTrace();
                                        }

                                }



                        });

        } //End of setup() method

} //End of class
```

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Device Measurement object (It identifies a general representation for power system components where measurement data from real-time simulation environment are modelled as power system component data structure).

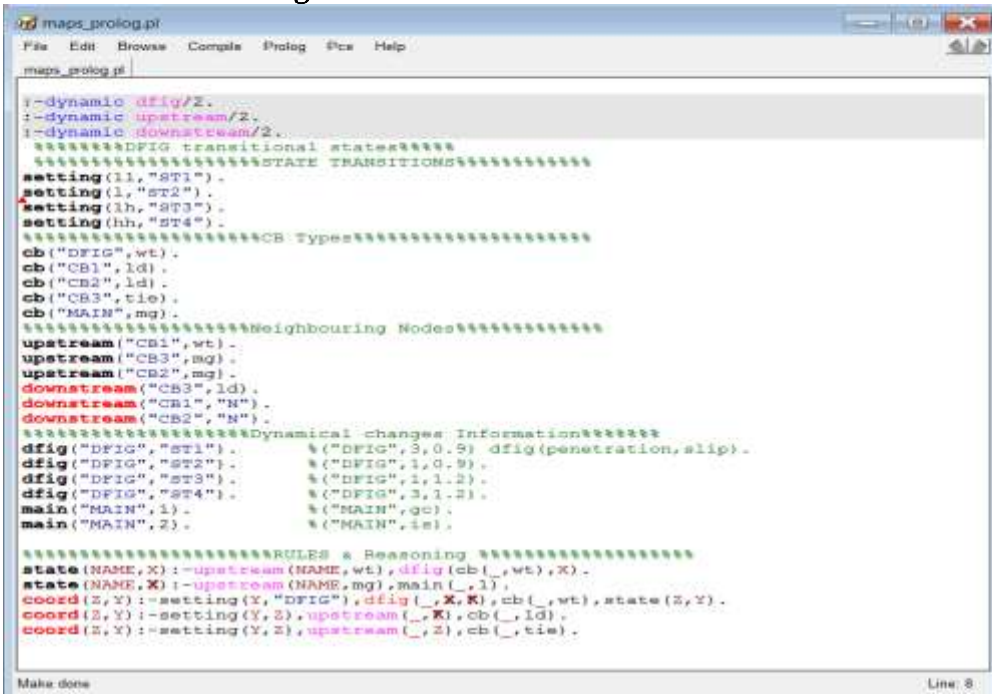
```
                              DEV_MSU
package THESIS;

public class DEV_MSU {


        // Abstract class for storing measurements from the
simulink for GENERAL TYPE o f COMPONENTS
                private double _VT;
                private double _CT;
                private float  _Phi;  // lead or lag
                private float  _Alpha; // power angel

                // These are calculated in _MEASU agent

                private int _DIR;
                private double _P;
                private double _R;

                // GET & SET  _VT

                public double GET_VT(){

                        return _VT;
                }

        public void  SET_VT(double a){

                        double _VT=a;
                }

        // GET & SET    _CT

                public double GET_CT(){

                        return this._CT;

                }

        public void SET_CT(double a){

                        double _CT=a;

                }

                // GET & SET    _Phi

                public float GET_Phi(){

                        return _Phi;

                }

        public void SET_Phi(float a){

                              Page1
```

```
                float _Phi=a;

        }

//GET & SET    _Alpha

        public float GET_Alpha(){

                return _Alpha;
        }

public void SET_Alpha(float a){

                float _Alpha=a;
        }

        // GET & SET    _Phi

        public int GET_DIR(){

                return _DIR;
        }

public void  SET_DIR(int a){

                int _DIR=a;
        }

        // GET & SET    _P  (Active power)

        public double GET_P(){

                return _P;
        }

        public void SET_P(double a){

                double _P=a;
        }

        // GET & SET _R (Reactive power)

        public double GET_R(){

                return _R;
        }

        public void SET_R(double a) {

                double _R=a;
        }
```

D.2 MAPS knowledge Database

For the MAPS system knowledge database PROLOG has been embedded to automate decision making based on descriptive logic reasoning provided by power system protection knowledge inferred base on knowledge sharing between different protection IEDs (nodes). Table D.2-1 represents the knowledge database embedded in the Coordination agent for Tie CB types.

Table D.2-1 Knowledge database in PROLOG




```
:-dynamic dfig/2.
:-dynamic upstream/2.
:-dynamic downstream/2.
 %%%%%%%%DFIG transitional states%%%%%
 %%%%%%%%%%%%%%%%%%%%%%%%%STATE TRANSITIONS%%%%%%%%%%%%%
setting(ll,"ST1").
setting(l,"ST2").
setting(lh,"ST3").
setting(hh,"ST4").
%%%%%%%%%%%%%%%%%%%%%%%%%CB Types%%%%%%%%%%%%%%%%%%%%%%%%
cb("DFIG",wt).
cb("CB1",ld).
cb("CB2",ld).
cb("CB3",tie).
cb("MAIN",mg).
%%%%%%%%%%%%%%%%%%%%%%%%Neighbouring Nodes%%%%%%%%%%%%%%
upstream("CB1",wt).
upstream("CB3",mg).
upstream("CB2",mg).
downstream("CB3",ld).
downstream("CB1","N").
downstream("CB2","N").
%%%%%%%%%%%%%%%%%%%%%%Dynamical changes Information%%%%%%%
dfig("DFIG","ST1").        %("DFIG",3,0.9) dfig(penetration,slip).
dfig("DFIG","ST2").        %("DFIG",1,0.9).
dfig("DFIG","ST3").        %("DFIG",1,1.2).
dfig("DFIG","ST4").        %("DFIG",3,1.2).
main("MAIN",1).            %("MAIN",gc).
main("MAIN",2).            %("MAIN",is).

%%%%%%%%%%%%%%%%%%%%%%%%%%%RULES & Reasoning %%%%%%%%%%%%%%%%%%%%%
state(NAME,X):-upstream(NAME,wt),dfig(cb(_,wt),X).
state(NAME,X):-upstream(NAME,mg),main(_,1).
coord(Z,Y):-setting(Y,"DFIG"),dfig(_,X,K),cb(_,wt),state(Z,Y).
coord(Z,Y):-setting(Y,Z),upstream(_,K),cb(_,ld).
coord(Z,Y):-setting(Y,Z),upstream(_,Z),cb(_,tie).
```

Rule-bases for CBs of Tie types as follows:

Rule1(descriptive logic reasoning):

HH ≡ (∀ CBs) ∩ (∃ is Grid-Connected.⊥) ∩ (∃ has_Downstream.Load)

IF state is GC & has Downstream Type Load Then HH

Rule 2:

HL ≡ (∀ CBs) ∩ (∃ is Grid-Connected.⊥) ∩ (∃ has_Downstream.Load)

IF state is GC & has Downstream Type Load Then HL

Rule3:

L ≡ (∀ CBs) ∩ (∃ is Islanded.⊥) ∩ (∃ has_Downstream.Load)

IF state is Islanded & has Downstream Type Load Then L

Rule 4:

LL ≡ (∀ CBs) ∩ (∃ is Islanded.⊥) ∩ (∃ has_Downstream.Load)

IF state is Islanded & has Upstream Type Load Then LL