Design and Development of a Communication-Assisted Microgrid Protection System

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Abstract

Climate change concerns due to the rising amounts of the carbon gas in the atmosphere have in the last decade or so initiated a fast pace of technological advances in the renewable energy industry. Such developments in technology and the move towards cleaner sources of energy have made renewable resources based Distributed Generators (DGs) more desirable. However, it is a known fact that rising penetrations of DGs have adverse impacts on the grid structure and its operation. The microgrid concept is a solution proposed to control the impact of DGs and make conventional grids more suitable for large scale deployments of DGs.

Unlike conventional utility grids, microgrids comprise generators, storage devices and loads at all levels of the system. Therefore, power generation, distribution and consumption levels are not discrete in microgrids and power flows may occur in any direction. Microgrids may be disconnected from the utility grid and continue its operation under islanding conditions. Furthermore, some microgrids may have changing structures with alternative paths and the coupling point for a device or a part of the microgrid may change due to the altering conditions. Due to their unprecedented structure, these smaller grids experience very significant protection issues. Conventional fault current protection schemes cannot be used and should be modified due to the existence of generators at all levels of the distribution system. It is a challenge to include different types of DG in protection considerations and estimate their fault current contributions. Some DGs, such as Inverter Interfaced DGs (IIDGs), do not provide high fault currents which makes the fault detection more difficult. On the other hand, the operating point of relays cannot be lowered boundlessly as this will trigger erroneous trippings when there is no fault.

In order to sustain a safe operation in such a versatile and dynamic structure, which has numerous parameters and variables, a new communication-assisted protection strategy is required. The need of extensive communication between the microgrid components is widely accepted in the Power Engineering field. In this research, a novel microgrid protection system has been developed, which utilizes extensive communication to monitor the microgrid and update relay fault currents according to the variations in the microgrid. This system is designed to respond to dynamic changes in the microgrid such as connection/disconnection of DGs. The operating points and connections of microgrid components are analyzed by the Microgrid Central Protection Unit (MCPU). MCPU implements the protection parameter calculation and assignment method developed in this work. After performing necessary calculations, MCPU determines the operating points and updates them into relay settings to ensure safe and reliable operation.

In this research, the communication infrastructure has been based on international standard IEC 61850 and its recent extension for DGs, IEC 61850-7-420. New extensions have also been proposed for these standards where there is a need for a new component such as fault current limiters or electric vehicles. Since standard logical nodes and communication procedures are utilized, the developed protection system can easily be installed in new microgrid, integrated with existing infrastructures and adjusted to new deployments. Given that the components follow standard communication modeling set by logical nodes defined in

IEC 61850 and IEC 61850-7-420, the realization of plug-and-play concept would be easier. However, it is worthy to highlight that the proposed protection system does not depend on any particular communication standard or modeling. Should there be the need to use other standards such as DNP3; this microgrid protection system can be implemented with them as well.

In order to minimize human input and realize automated process, the microgrid has been modeled according to the graph theory where the components are represented as nodes. Dijkstra’s algorithm, which is famous for shortest-path calculation purposes, is run over the microgrid to determine the relay hierarchy at any point in time. In this manner, regardless of the dynamic changes occurring in the microgrid, the hierarchy of network components can be extracted. The implemented algorithm not only ensures proper selective operation under fault conditions but also facilitates the introduction of new connections and new devices to the system. Since the microgrid hierarchy can be detected automatically, even with new connections, the developed algorithm serves for plug-and-play concepts in electrical networks.

The main contribution to knowledge presented in this thesis is the development of a new communication-assisted protection scheme for the protection of microgrids. The developed protection system is very versatile and can be implemented as the primary protection scheme in a microgrid, or it can be utilized simultaneously with other protection schemes, or it can be installed as a roll-back strategy for other protection schemes when they cannot operate due to a malfunction, e.g. in case of communication or synchronization failures in differential protection systems.

Declaration of Originality

“I, Taha Selim USTUN, declare that the PhD thesis entitled “**Design and Development of a Communication-Assisted Microgrid Protection System**” is no more than 100,000 words in length including quotes and exclusive of tables, figures, appendices, bibliography, references and footnotes. This thesis contains no material that has been submitted previously, in whole or in part, for the award of any other academic degree or diploma. Except where otherwise indicated, this thesis is my own work”.

Signature | Date:
03/07/2013

Acknowledgements

In the name of Allah, the Beneficent, the Merciful.

Read in the name of your Lord Who created. He created man from a clot. Who taught (to write) with the pen, Taught man what he knew not.

(The Clot – 96th Surah – Verses 1 to 5)

They said: Glory be to Thee! We have no knowledge but that which Thou hast taught us; surely Thou art the Knowing, the Wise.

(The Cow – 2nd Surah – 32nd Verse)

...and say: O my Lord! Increase me in knowledge.

(Ta Ha – 20th Surah – 114th Verse)

English translations from the original Arabic script, by M.H. SHAKIR.

List of Publications

Peer-Reviewed Journal Papers

[1] Taha Selim Ustun, Cagil Ozansoy, Aladin Zayegh, "Recent developments in microgrids and example cases around the world--A review," in Renewable and Sustainable Energy Reviews, Elsevier, vol. 15, pp. 4030-4041, 2011

[2] Taha Selim Ustun, Cagil Ozansoy, Aladin Zayegh, "Modeling of a Centralized Microgrid Protection System and Distributed Energy Resources According to IEC 61850-7-420," in *IEEE Transactions on Power Systems,* vol. PP, pp. 1-8, 2012.

[3] Taha Selim Ustun, Cagil Ozansoy, Aladin Zayegh, "Fault Current Coefficient and Time Delay Assignment for Microgrid Protection System with Central Protection Unit," in *IEEE Transactions on Power Systems*, vol. PP, pp. 2012 .

[4] Taha Selim Ustun, Cagil Ozansoy, Aladin Zayegh, "Implementing Vehicle-to-Grid (V2G) Technology with IEC 61850-7-420," *IEEE Transactions on Smartgrids*, vol. PP, pp. 2012 (accepted).

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[1] Taha Selim Ustun, Cagil Ozansoy, Aladin Zayegh, "A central microgrid protection system for networks with fault current limiters," in *Proceedings of Environment and Electrical Engineering (EEEIC), 2011 10th International Conference on* , vol., no., pp.1-4, 8-11 May 2011, Rome, Italy, ISBN 978-1-4244-8781-3.

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Under Review:

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[2] Taha Selim Ustun, Cagil Ozansoy, Aladin Zayegh, "Investigation of Electric Vehicle Potential of Australian Households and Its Impact on Smartgrids," IEEE Industrial Electronics Magazine, Special Issue on Microgrids

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List of Abbreviations

AC	Alternating Current
ACSI	Abstract Communication Service Interface
ASG	Analogue Setting
CB	Circuit Breaker
CCM	Communication and Control Module
CDC	Common Data Class
CERTS	Consortium for Electric Reliability Technology Solutions
CORBA	Common Object Request Broker Architecture
CT	Current Transformer
DC	Direct Current
DCOM	Distributed Component Object Model
DCP	Controllable Double Point
DER	Distributed Energy Resource
DG	Distributed Generator
DMS	Distribution Management System
DNO	Distribution Network Operator
ECP	Electrical Connection Point
EE	Electrical Engineering
ENN	Electrical Network Node
EV	Electric Vehicle
FACTS	Flexible AC Transmission System
FCL	Fault Current Limiter
FQB	Frequency-Reactive Power Boost

G2V	Grid-to-Vehicle
GOOSE	Generic Object Oriented Substation Event
GTO	Gate Turn Off
HEV	Hybrid Electric Vehicle
ICS	Internal Combustion Engine
IEC	International Electrotechnical Committee
IED	Intelligent Electronic Device
IGBT	Insulated Gate Bipolar Transistor
IIDG	Inverter Interfaced Distributed Generator
ING	Integer Status Setting
IR	Individual Relay
LC	Local Controller
LD	Logical Device
LN	Logical Node
LV	Low Voltage
MCPU	Microgrid Central Protection Unit
MEMS	Microgrid Energy Management System
MGCC	Microgrid Central Controller
MHEPP	Micro Hydroelectric Power Plant
MMS	Manufacturing Message Specification
MMS	Microgrid Management System
MO	Market Operator
MPPT	Maximum Power Point Tracking
MV	Measured Value
MV	Medium Voltage

NS	Node Settings
OO	Object-Oriented
PE	Power Electronics
PHEV	Plug-in Hybrid Electric Vehicle
PLC	Power Line Carrier
PV	Photovoltaic
R&D	Research and Development
RBD	Reliability Block Diagram
RE	Renewable Energy
RoCoF	Rate-of-Change-of-Frequency
SAS	Substation Automation System
SCADA	Supervisory Control and Data Acquisition
SCC21	IEEE Standard Coordinating Committee 21
SCFCL	Superconducting Fault Current Limiter
SPS	Single Point Status
T&D	Transmission and Distribution
TCP/IP	Transmission Control Protocol/Internet Protocol
UML	Unified Model Language
V2G	Vehicle-to-Grid
VPD	Voltage-Power Droop
VPP	Virtual Power Plant
VSI	Voltage Source Inverter

Chapter 1

Thesis Overview

1.1. Introduction

The search for cleaner and more efficient power systems drew engineers' attention to Distributed Generators (DGs). As a result of recent developments in technology and concerns for global warming, the new tendency in the Power Engineering field is to generate electricity from cleaner energy sources and closer to the consumption areas [1]. This implies that the share of DG in the power generation shall increase substantially. These generators may be Renewable Energy (RE) based such as wind turbines and solar systems.

However, existing transmission and distribution networks are not suitable for large scale DG connections since they were traditionally designed with the assumption of a passive network. The DG interconnection to such networks changes their fundamental characteristics and create unprecedented technical problems [2]. Moreover, in the case of a fault, DG systems contribute to the fault currents and the transient characteristics of the network become completely different [3]. Since the Inverter Interfaced DGs (IIDGs) have highly variable characteristics, they alter the grid structure and jeopardize safe and reliable operation[4]. These are only a few of the issues caused by the connection of DGs to grids. In order to overcome these problems a new concept called "microgrid" is proposed by the power engineers.

A microgrid is a collection of loads and micro-generators along with some local storage and behaves like a model-citizen [5] from grid side thanks to intelligent control [6]. Although a microgrid has many generators and loads, it appears as a net load or a net generator to the broader grid with well-behaved characteristics [7], i.e. with stable voltage and frequency.

Through microgrids, the gigantic conventional utility network can be divided into smaller networks which manage distributed generators, loads, storage and protection devices in their own grid [8]. In microgrids, these generators are handled in smaller quantities and, thus, DGs can be connected to the grid and side-effects on the grid operation can be eliminated.

Despite their advantages, microgrids bring along some technical challenges in control, management and protection fields [9, 10]. Since the very basics of conventional network operation do not hold any more (such as grid's being radial and passive) revolutionary changes are required for safe operation. Protection systems, in particular, are affected heavily by the current contribution of DGs and the bidirectional power flow. Therefore, a new approach is required for power grid protection purposes.

1.2. Aim of This Research

The research presented in this thesis aimed to investigate the impact of Distributed Generators (DGs) on the operation of electrical networks and design a novel protection system with extensive communication. In order to accommodate new deployments and follow the dynamic changes occurring in a microgrid, the proposed protection system has been designed to be flexible and versatile. In line with the smartgrid evolution, the proposed protection system uses communication lines to gather information and send data. This communication infrastructure has been based on and modeled according to the international substation communication standard IEC 61850 [11] and its extension for DGs, IEC 61850-7-420[12].

The specific aims of this research can be summarized as follows:

- Research on evolving concepts of microgrids and smartgrids

Extensive literature review has been performed to closely follow the recent developments in microgrid and smartgrid research areas. Being relatively new in power engineering field, these areas constantly develop at a high speed. It is imperative to monitor the research work and the associated findings almost on a day-to-day basis to stay up to date with these areas. The literature review was performed in a wide perspective, so as to include the evolution power networks are experiencing nowadays. Old, interconnected, passive and massive power networks are being transformed into smaller and isolated smaller entities which may be both active and passive. The motivations behind this evolution, its impact on power networks, practical aspects which relate to the end-users, novel technologies and possible research areas have been investigated in detail. Accordingly, this research has touched upon various concepts in the power engineering field such as network protection, fault currents, relay programming, communication standards, communication infrastructure and new technologies such as Fault Current Limiters (FCLs) and Electric Vehicles (EVs). The literature review provided in this research provides a good reference for these different concepts, their places in microgrids and possible future research work in the field.

- Investigation of the impact of DGs on microgrids

It is not a secret that recent years have experienced a sharp increase in the network penetration of DG systems . This can be traced back to benefits of DGs such as lower carbon emissions, more environment friendly generation, less dependence on oil and its products for electricity generation as well as local generation and grid-support at peak hours. However, electricity networks were designed several decades ago. There was no local generation in those days and the power flow was unidirectional from generation points to consumption points. The addition of DGs to power networks at various levels such as transmission and distribution renders these earlier assumptions invalid. The consequences of DG usage have been investigated thoroughly in this research, especially from fault levels and fault current protection perspectives. The work carried out was not limited conventional DGs such as diesel generators or PV panels but novel technologies such as Electric Vehicles (EVs) have also been studied.

- Investigation of the potential and impact of Electric Vehicles (EVs) and Vehicle-to-Grid (V2G) operation on microgrids

Due to rising oil prices and environmental concerns, EVs have become very popular and car manufacturers increased their focus on EV technology. Also, governments started giving incentives for wide spread EV usage. Therefore, this research focused on investigating the potential of EVs from social and financial perspectives. Some test cases have been set up and simulated in order to investigate the impacts of EVs on microgrids under Vehicle-to-Grid (V2G) and Grid-to-Vehicle (G2V) operating conditions when they are supplying power to the grid and drawing power from the grid, respectively.

- Design of a novel communication-assisted protection system

Following the investigations and findings above, a novel protection system which uses extensive communication has been designed. Communication lines are deemed necessary for the fact that microgrids are not only differ from conventional electrical grids in terms of their size, hence micro-grid, but also in terms of intelligence, hence the term smartgrid is used. These new generation grids require the components and the management system to be smarter, to monitor even the slightest of changes, to communicate with different parts of the grid and make decisions on the fly. Therefore, the protection system proposed in this thesis incorporates communication between the components and the central management unit. The novelty of this research is its special focus on the fault protection in microgrids. In the literature, there have been several works done in the management, load sharing and marketing fields but little has been contributed towards the design of a protection system for the unprecedented conditions occurring in microgrids.

- Assignment of protection parameters on the fly

One of the key contributions of this research is the developed ability to calculate the fault current parameters required to coordinate the protection devices in the protection system. In conventional power networks, the passive mode of operation and the unidirectional power flow eased the protection calculations massively. Power Engineers had the luxury to calculate fault conditions beforehand and program protection devices accordingly. However, the dynamic nature of microgrids, bidirectional power flows, presence of generation at every level of power networks require that the protection systems shall follow all these changes and calculate operating points for any modification, when it occurs. It is almost impossible to calculate and tabulate all of the possible conditions in a microgrid beforehand. Even if it is accomplished, a new deployment or a new connection of a generator would require all of the calculations and possible cases to be updated. Therefore, a calculation method has been developed where the fault levels and fault current contributions are calculated by the protection system automatically. In this fashion, human input is lowered to a minimum and automated operation can be realized.

- Modeling communication infrastructure with international substation communication standard IEC 61850 and its extension for DGs, IEC 61850-7-420

In addition to designing a new protection system for microgrids, this research contributes to the knowledge by modeling the whole system along with its components in compliance with international substation communication standard IEC 61850 and its recent extension IEC 61850-7-420. This is a solid step towards standardizing the communication required for the microgrids. It is constantly repeated in the literature that communication is an indispensible factor in microgrids. However, there is no specific step towards modeling microgrids management systems with standard models. By designing the whole protection system according to the IEC standard, this research paves the way for standardization both for manufacturers and operators.

- Extending IEC 61850 standard to accommodate new equipment definitions

IEC 61850 standard does not cover every single equipment present in power grids. In order to address this short coming, the International Electrotechnical Committee (IEC) published an extension for DGs which is titled IEC 61850-7-420. Nevertheless, through the course of this research, it has been determined that there are some crucial components that are not included in these standards. In an effort to model the entire microgrid and the newly designed protection system, new extensions have been proposed to include devices such as FCLs and EVs. The Logical Nodes (LNs) derived for these devices follow the strict rules of IEC standards and, hence, they are fully compatible. With these extensions, some missing links in the standard have been bridged and the application of the IEC 61850 standard to Microgrids has been made more feasible.

- Automatic relay hierarchy extraction after a microgrid structure change or a new deployment

As expressed earlier, one of the biggest challenges power engineers face in microgrids is their ever-changing nature. This requires the protection systems to be flexible, dynamic and compatible with the changes occurring therein. For instance, an operating condition which is correct for a certain structure of microgrid might become absolutely unacceptable after several modifications made in the microgrid structure. Therefore, it is required to monitor these changes as well as new deployments to adapt the installed protection system accordingly. For this purpose, a groundbreaking approach has been implemented in this research where Dijkstra’s algorithm, an algorithm which is used to find the shortest path between two points, has been used to extract the relay hierarchy in a microgrid without the need for prior knowledge of the microgrid structure. Regardless of the modifications and new deployments occurring in the microgrid, this algorithm enables protection systems to extract new microgrid structure and hence, the relay hierarchy. This is invaluable for plug-and-play purposes in power networks.

- Supporting other protection systems with the proposed system

This research also explains how the proposed protection system can be used to support other protection systems used in power networks. Some power networks have established their protective devices for a particular protection scheme and it is not realistic to propose the complete removal of these devices. In these places, the proposed system can be used to support to the protection systems as a roll-back strategy. For instance, this has been implemented for communication failure cases in differential protection which requires continuous communication over a dedicated line. Furthermore, being very versatile and flexible, the developed protection system can be adapted or realized to support other protection schemes wherever necessary.

1.3. Research Methodologies and Techniques

In order to achieve the above-mentioned aims of this research, a step by step approach has been implemented in this research. These steps can be summarized with the following research methodologies and techniques:

- Literature review for new concepts such as microgrids and smartgrids

A thorough literature review has been performed to get the full grasp of these newly introduced concepts. Since these concepts have emerged recently, they are evolving very fast and special attention shall be paid to stay up-to-date. Moreover, the interpretation and implementation of these new concepts may differ in different parts of the world. Therefore, various microgrid test cases from different countries have been examined. In addition to management and stability issues, special attention has been paid to protection considerations due to relatively less research work done in this particular field.

- Investigation of the effects of DGs and other equipment such as FCLs

Following the wide-scoped literature review explained above, research work has been dedicated to investigate the effects of DG deployments and use of other devices such as FCLs on microgrids. This step was particularly important to analyze the behavior and effects of such equipment on the microgrid operation since the protection system modeling has to account for them. The design of the new protection scheme was heavily based on these findings.

- Investigation of the impact of EVs and V2G technology

Although this item is very close to the one above, some differences ask for a separate analysis. Firstly, most of the devices considered in the above item are large establishments such as diesel generators or wind farms. It is not likely that every household would have a diesel generator or a wind turbine on its own. However, the vehicle predictions show that almost all households could own an EV in the future. Furthermore, most of these devices have single operating mode, either generator or load, whereas EVs can freely alter between charging (G2V) and generating (V2G) modes of operation. Due to these major differences, EVs and their modes of operation have been investigated as a separate item in this research.

- Design of a novel protection system based on extensive communication

Once the necessary investigations were done and the knowledge gap regarding the microgrid protection systems were identified and understood, a novel protection system has been designed. This new protection system considers the smartgrid vision where extensive communication lines will be utilized between the grid components. Therefore, the proposed protection system does not require new communication line installation for protection purposes, rather it uses the lines which will be present in future smartgrids. Although the use of communication in protection lines might seem a tedious task, it makes it possible to monitor the changes occurring in the microgrid and take necessary actions immediately. These changes might be short-term changes such as disconnection of a relay or long-term changes such as a new DG deployment.

- Modeling of the proposed protection system with IEC 61850 Standard and its recent extension IEC 61850-7-420

In order to make the developed protection system universal, the research focused on modeling of this conceptual design using the international substation communication standard IEC 61850 and its recent extension for DGs, IEC 6180-7-420. This step is very crucial to have a universal protection system which can be implemented in different microgrids. When the standard modeling stipulated by IEC standards has been implemented, the developed protection system can be used in all microgrids regardless of the manufacturer or the model of the grid components. Instead of having a localized, custom-made protection system for a particular microgrid, this approach ensures that the proposed protection system can be utilized as a generic system.

- Extending IEC 61850-7-420 for new equipment

Although a recent extension of IEC 61850 was recently published for DGs, i.e. IEC 61850-7-420, there are still some devices which are not defined in this standard. These include FCLs and EVs. Since they are bound to be used very often in future power networks, they need to be incorporated to IEC communication standards. In this research, these missing links have been connected by proposing IEC models for these devices.

- Automated microgrid structure detection for plug-and-play purposes

After designing a new protection scheme and modeling it within the IEC communication framework, it was required to automate the microgrid structure detection. This has particular importance in microgrids, since several connections/disconnections may happen in a very short period of time and some new deployments are always bound to occur. These deployments need not be very high cost projects. For instance, whenever a new EV is purchased by a household, this will appear as a new deployment from network operator's point of view. Therefore, a new approach has been taken to enable the microgrid protection system monitor the changes and extract the resulting structure. Thanks to this automated approach, network structure is not required to be known by the protection system beforehand.

- Adaptation of the proposed system for other protection systems

Finally, the developed protection system was implemented with other protection schemes seen in microgrids. This adaptation was designed in two aspects. The first one envisages that the proposed protection system would support others wherever they are insufficient. For instance, multi-terminal protection with long distance between the terminals in a differential protection set-up would be very meticulous and tedious task. Furthermore, any new deployment would require the multi-terminal connections to be updated. The proposed protection system is utilized to support differential protection in this aspect. Secondly, some protection schemes such as differential protection require the communication link to be active continuously. Should there be a communication failure the protection scheme becomes ineffective. Thanks to the local decision making of the proposed scheme, it is implemented as a roll-back strategy in case of a failure. This is also important to depict the interaction between different protection schemes.

1.4. Originality of the Thesis

This thesis presents a microgrid protection system which is equipped with various capabilities to address the changing nature of power networks. While striving to realize a reliable and secure power network, the proposed protection system takes individual components into account. In this manner, the protection system is implemented in a holistic sense where micro-management is also performed. The following points can be listed as the key contributions of this research work to the scientific knowledge:

- Details the design of a Microgrid Central Protection Unit (MCPU)

This thesis provides the design details of an MCPU which is required for the coordination of the developed protection system. The conceptual design explains how the individual fault contributions of different generators shall be taken into account, how new fault levels and operating conditions shall be updated in protective devices and how different operating modes, i.e. grid-connected or islanded mode, shall be accounted for. This MCPU is designed to be versatile so that it can be adapted to different microgrids with different set of components. Furthermore, the design is intended to be flexible so as to accommodate various components such as FCLs, EVs with V2G operation as well as operation with other protection schemes such as differential protection.

- Implementation of communication with IEC standards for universality

This research has modeled a complete protection system according to the IEC international communication standards. This is very important to show how different equipment is included in the protection scheme, regardless of their manufacturers or serial numbers. This standard way of modeling is crucial to include all kinds of equipment and, thus, make the proposed protection scheme universal.

In this research, modeling of the data and information exchange for the newly designed protection system has been carried out according to the various components of the IEC 61850 standards. This is significant to ensure a standard means of data communication between the microgrid components and protection elements. The work carried out has therefore made contributions to the realization of the plug-and-play concept in microgrid protection systems.

- Wherever applicable, it extends IEC standard, thus contributes to betterment of it

In order to model every device present in the power grids, some extensions have been made to the IEC 61850 standard. This includes extensions for FCLs and EVs which are bound to be very often utilized in future grids. This thesis stands out for the fact that as part of the work carried out, new LNs have been devised and proposed for the devices which are not currently included in these standards. In this fashion, the applicability of IEC 61850 standard and its scope has also been extended.

- It automates the protection system adjustments with Dijsktra’s algorithm on graph theory. This serves for plug and play purposes in power networks.

Unlike previous protection systems, the proposed protection scheme has a unique feature which enables it to monitor the changes occurring in the microgrid and extract the resultant structure thereof. This is achieved by representing microgrids with graph theory where devices are represented as nodes. Then, Dijkstra's algorithm, which is traditionally used to find shortest path on a graph, is run over this representation to extract the paths connecting these nodes. These paths represent the connections present between grid components and shall be used in protection scheme coordination. Representation of power networks with graph theory and extraction of microgrid structure with Dijkstra's algorithm is unprecedented and unique to this research. In this fashion, the dynamic connections/disconnections in a microgrid can be monitored while new deployments can be easily included in the protection system

- The proposed scheme can be used to support various protection schemes

The proposed protection scheme can be used as a standalone system to ensure protection of the microgrids. Additionally, a unique feature of the proposed system enables it to be used to support other protection systems whenever necessary. Alternatively, the proposed system can be installed as a roll-back strategy in case of a failure which renders the primary protection system invalid such as a communication failure in differential protection systems.

1.5. Organization of the Thesis

This thesis consists of nine chapters in total and it is organized as follows:

Chapter1 gives an overview of the thesis, its aims of the research and its contribution to the knowledge. It also sheds some light on the research techniques and methodologies used in the research. Chapter 2 provides a comprehensive literature review for new concepts in the power engineering field such as DGs, microgrids, their implementations, interactions with one another and the larger power network. These concepts have been introduced recently and their implementations might differ in different parts of the world. This literature review is intended to provide the required background information, especially from microgrid protection perspective. Although relatively much work is done in other aspects of microgrids such as stability and islanding detection, not much effort has been reserved for fault levels and fault current calculations.

Following this review and the detection of the research field, Chapter 3 depicts the details of a conceptual microgrid protection system which is proposed to fill the knowledge gap outlined in the previous chapter. It reveals the connection of grid components with MCPU over communication lines, the process for collecting grid data and its analysis, the calculation of operating points and updating them in relevant grid components. It is also mentioned in this section, how this conceptual design is kept flexible and how several generators with different grid connection interfaces such as rotating machines, IIDGs or DGs with FCL can all be handled in single design.

The hallmark of microgrids is their dynamic structure which is bound to change very often. Therefore, Chapter 4 explains how the developed protection scheme is designed to automatically monitor changes happening in the microgrid and adapt the operating points accordingly. This is achieved by representing electrical networks as a graph with Object-Oriented (OO) models. Then, the steps of automatic operation through Dijkstra’s algorithm are examined where, in an unprecedented manner, this shortest-path-finding algorithm is utilized to extract the microgrid structure. This automatic operation is also applicable for new deployments and this serves as a solid step towards plug-and-play purposes.

Chapter 5 analyzes the mathematical approach to fault levels and protective devices coordination calculations. This approach is formed to match with the flexible conceptual design and automated operation explained above. In a unique manner in microgrid research, Chapter 6 gives the full communication framework of the developed microgrid protection system according to IEC 61850 communication standard. This type of standardized communication ensures that any grid component will be compatible with the proposed microgrid protection system for communication purposes, regardless of its manufacturer or model. Also in this chapter, several extensions to this standard have been proposed for some crucial devices which are bound to be indispensible in microgrids in the near future.

Chapter 7 gives the details of implementation of the protection system with several simulation works performed and presents the results. Chapter 8 gives an insight about how the developed protection scheme can be used as a roll-back strategy or an additional support for other protection schemes in case of a failure. This chapter also provides valuable information about the interaction between the developed protection system and others, should they exist in the same microgrid. Finally, Chapter 9 summarizes the whole research work, highlights the contributions made and draws the conclusions.

Chapter 2

Literature Review on Microgrid Concept and Its Implementation

Publications pertaining to this chapter:

1) ***Taha Selim Ustun, Cagil Ozansoy, Aladin Zayegh, "Recent developments in microgrids and example cases around the world--A review," Renewable and Sustainable Energy Reviews, Elsevier, vol. 15, pp. 4030-4041, 2011***

2.1. Introduction

The prominence of generating electric power in very large steam-powered central power stations seems to have ended. The increased concerns for the environmental impacts of centralized coal-fired generation, most importantly those that relate to high CO_2 emissions, are the main factors driving the transition towards small-scale decentralized generation of power. Decentralized (distributed) generation of electricity most favorably occurs from renewable sources that are located on the distribution system close to the point of consumption. Governments and industries all around the world are increasingly looking for ways to reduce the greenhouse emissions from their operations with a major focus on the use and installation of sustainable distributed energy systems [1].

The need for far more efficient electricity management systems has given rise to the development of innovative technologies and groundbreaking ideas in power generation and transmission. The trend is to increase the share of Distributed Generator (DG) in the electricity supply. DG may also comprise Renewable Energy (RE) systems such as solar, wind, fuel cells and wave, which are promising cleaner technologies leading to reductions in greenhouse gas emissions and in effect aiding in the remedy of the global warming problem [13]. Consequently, governments and energy regulation authorities worldwide are encouraging more deployments of RE based DGs. However, higher penetration of micro-sources, i.e. small scale PV panels, wind turbines, and diesel generators into the grid changes the traditional "radial" structure of the grid. This revolutionary change in the structure triggers many problems which were previously unknown to the grid operators and power engineers [2]. There are now various micro-sources at different penetration levels in the grid and this new structure invalidates the traditional power flow control methods. Moreover, DGs also make contributions to the fault currents around the network. Hence, in case of a fault, the transient characteristics of the network become completely different [3]. These are only a few of the issues that have arisen in relation with the revolutionary changes occurring in the grids and the way they are operated.

There are still many technical challenges that must be overcome so that DGs can be cost-effectively, efficiently and reliably integrated into existing electric power systems. Existing distribution systems are not designed for significant penetration of DG. Distribution systems were traditionally designed with the assumption of a passive network. The interconnection of decentralized renewable energy generation systems to such networks inevitably changes the characteristics of the system and presents key technical challenges such as circuit protection coordination, power quality, reliability, and stability issues that must be overcome. Controlling a huge number of geographically dispersed DGs in a large network is a daunting challenge for the safe, reliable, and effective operation of the network.

The search for alternative energy sources and more efficient utilization of the energy as a means of tackling the global warming concerns will require fundamental changes in the Electrical Engineering (EE) field explicitly in relation to the matters associated with the Transmission and Distribution (T&D) of this renewable electricity. Although T&D grids have been around for many decades, DG and RE concepts have recently become irreversibly popular. As a result, many research and development needs have evolved as a necessity to enable the scaling up of the implementation and uptake of renewable energy systems giving them recognition and equal status in energy sector investment processes.

Microgrids, which are small entities in a power system network, are capable of coordinating and managing DGs in a more decentralized way thus reducing the need for the centralized coordination and management of such systems [5, 9]. This is highly recommended in [9], where it is claimed that such a scheme would permit DGs to provide their full benefits. Yet, there are still many research and development needs associated with the microgrids [10].

Microgrid is a very exciting research field in the power engineering field and it has many different aspects which are complete research fields in their own. Furthermore, microgrids resemble an intersection zone of several concepts such as network operations, protection, power electronics, distributed generation, renewable energy etc. [14]. Consequently, it is not a surprise to see more researchers focusing on microgrids and more publications appearing in the literature.

This chapter presents a detailed review of the literature with regard to microgrids by outlining the existing knowledge as well as the problems and challenges being encountered. It also provides an overview of the current research and development work being carried out all over the world. It gives an insight into some real-life implementations of microgrids. Finally, it focuses on knowledge gaps yet to be addressed and possible future work in this field of Power/Electrical Engineering. Quite naturally, special attention has been paid to microgrid protection, recently proposed schemes and knowledge gaps since the work presented in thesis pertain to the same research field.

2.2. The Microgrid Concept

A microgrid is a new concept which refers to a small-scale power system with a cluster of loads and distributed generators operating together with energy management, control and protection devices and associated software. Such devices include the Flexible AC Transmission System (FACTS) control devices such as power flow controllers and voltage regulators as well as protective relays and circuit breakers [15]. In other words, a microgrid is a collection of loads and micro-generators along with some local storage and behaves similar to a model-citizen [5] from grid side thanks to intelligent control [6]. This means, although a microgrid is itself composed of many generators and loads, it appears as a net load or a net generator to the broader grid with well-behaved characteristics [7].

A sample microgrid architecture is shown in Figure 2.1. As shown, the microgrid is a very versatile concept as it can accommodate various types of the micro generators (wind turbine, Photovoltaic (PV) array, diesel generator, and wave generator), local storage elements (capacitors, flywheel) and loads. A distributed generator might be a diesel generator (DG4) which can be coupled to the grid directly, or a PV array which needs Direct Current (DC)/Alternating Current (AC) inverter interface (DG2, DG3) or an asynchronous wind turbine (DG1) which requires AC-DC-AC inversion for proper grid connection. Similarly, the storage devices used in the system may or may not require an inverter interface as in the case of capacitor banks and flywheel, respectively.

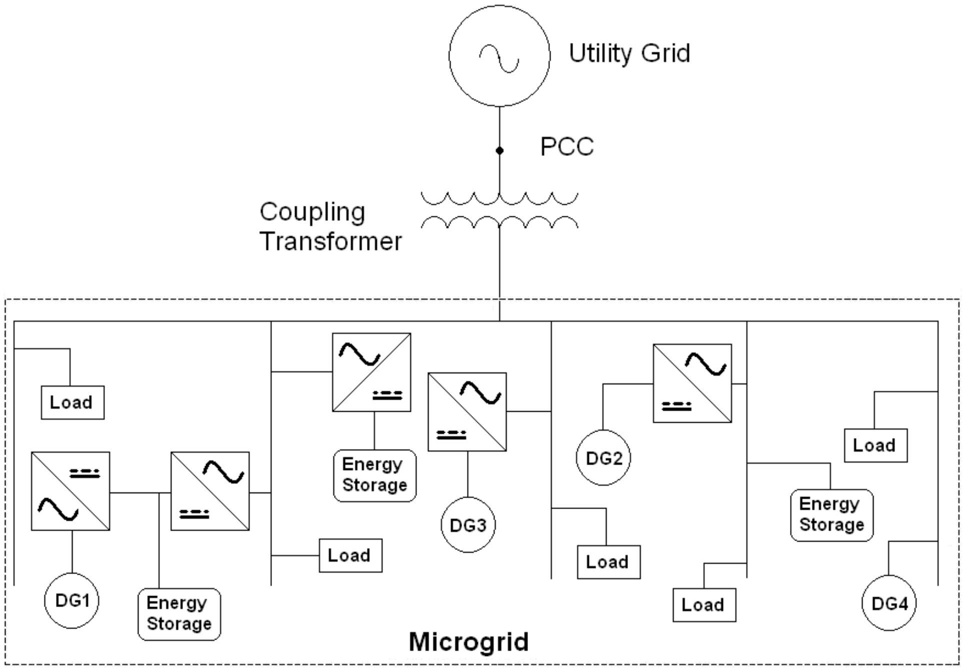

Figure 2.1. A Sample Microgrid Architecture

A microgrid can be a DC [16], AC or even a high frequency AC grid [17]. It can be a single or a three phase system or it may be connected to low voltage or medium power distribution networks [15]. Furthermore, a microgrid could be operating in either grid connected or islanded operation mode. For each operating mode operational requirements are different and distinct control schemes are required.

The groundbreaking feature of a microgrid is its ability to operate “autonomously” when there is a power outage in the main grid. This operation mode is called islanded operation since the microgrid disconnects from the grid and becomes an island with local generators and loads. In this way, the consumers may receive continuous service even when there is power outage in the grid due to a fault or maintenance. Moreover, if there are voltage sags, frequency drops, or faults in the main grid then the microgrid can be easily disconnected, i.e. islanded from the rest of the grid and the users can be isolated from those problems. In this way, microgrids not only help in providing uninterrupted service but also contribute to the maintaining service quality.

The motivation behind using microgrids is to divide the enormous conventional utility network into smaller and more easily operable grids. These smaller electrical networks will manage distributed generators, loads, storage and protection devices in their own grid. Provided that each microgrid is operating as a model citizen, i.e. either as a load receiving power with acceptable electrical characteristics or as a power supply supplying power with acceptable electrical characteristics, then the overall utility grid can be operated properly. It is a well-known fact that higher penetration levels of distributed generators, especially those that require Power Electronics (PE) interface, alter the grid structure and jeopardize safe and reliable operation. The microgrid concept is introduced to manage these generators in smaller quantities rather than trying to tackle the whole network in a holistic manner. In this way, more distributed generators can be employed in the grid and side-effects on the grid operation can be eliminated.

2.3. Current Status of Literature and Ongoing Research

Distributed generators and storage devices almost always require a PE interface for a proper connection to the grid. Accordingly, all research on PE devices such as inverter control and storage can therefore be linked to the microgrid research field. For better operation and control, PE devices such as Insulated Gate Bipolar Transistors (IGBTs) or thyristors with higher current/voltage ratings are required. References [18, 19] discuss the research projects that are being carried out to accomplish these objectives. Energy storage is an indispensable part of microgrids for storing excess energy, supplying power in case of shortages, and for preventing voltage sags. For a better operation; energy storage devices with higher efficiencies, longer lifetimes along with faster charging and slower discharging characteristics are desired. Projects with a focus on energy storage matters are outlined in [20, 21].

The most promising one of the new generation batteries is the NAS (sodium-sulfur) battery. Although it needs to be maintained at high temperatures, it has advantages when compared with other types of batteries. Table 2.1 [22] shows that a NAS battery, when compared with other battery types, has substantially a higher energy density, a fair efficiency and no self-discharge. These characteristics of NAS make it very appealing and hence it is being deployed by companies operating in the RE sector in Japan[23] and in the United States (U.S.) [24].

TABLE 2.1. BATTERIES USED FOR DISTRIBUTED ENERGY STORAGE

	Unit	NAS	Redox Flow	Lead	ZincBr
Voltage	V	2.08	1.4	2	1.8
Ideal Energy	Wh/kg	780	100	110	430
Density	Wh/l	1000	120	220	600
Efficiency	% DC	85	80	85	80
Temperature	^{o}C	280-350	40-80	5-50	20-50
Auxiliaries	-	Heater	Pump	Water	Pump
Self Discharge	-	No	Yes	Yes	Yes

Another innovative energy storage system is being developed by the RAPS Pty Ltd which is based on high purity graphite blocks. These blocks are heated up with energy received from solar panels, wind generators or the grid for later use. This energy may then be used to produce steam through embedded heat exchangers and converted back to electricity with steam turbine generators [25]. According to the inventor company, the storage capacity of high purity graphite ranges from around 300kWh (thermal) per ton at a storage temperature of 750°C to around 1000kWh (thermal) per ton at 1800°C [26]. There are pilot deployments in Silverwater and King Island, Australia.

The Research and Development (R&D) work being undertaken at the device level is very comprehensive and the literature can be referred to. The main focus of this article will be three main sub-topics of microgrid research: control, protection and microgrid management systems.

2.3.1. Control

The controller capabilities of a microgrid are one of the most crucial elements in determining the introduction of this new concept to the utility and its wide acceptance. Depending on the type and depth of the penetration of Distributed Energy Resource (DER) units, load characteristics and power quality constraints of a microgrid can be significantly and even conceptually different than those of the conventional power systems [8]. Market participation strategies, the required control and operational strategies can also be added to this list. This is due to the fact that the characteristics of DGs are much different than conventional synchronized motors. They rely on intermittent resources in the system which cannot be controlled or estimated. Hence, a microgrid is a dynamic entity and DGs might connect/disconnect while the microgrid is in operation.

The main objective of control systems in microgrids is to continuously supply power to the loads despite the changes in the system. A microgrid may be operating in grid-connected mode and gets islanded due to a fault. One or more DG units may connect to/disconnect from the grid, or there might even be significant changes in the amount of power demanded by the loads. Under all these circumstances, the microgrid control shall ensure that power is supplied to the loads with acceptable voltage and frequency characteristics. Since there are two distinct operation modes of a microgrid, control schemes are designed for two distinct phases. Table 2.2 [8] shows the control strategies of DG in a microgrid. When there is grid connection, grid-following controls are employed. On the other hand, in islanded operation, when a grid needs to be formed, grid-forming controls are used.

TABLE 2.2. CONTROL STRATEGIES FOR DG COUPLING INVERTERS IN MG

	Grid-Following	**Grid-Forming**
Non-interactive Control Methods	Power export (may be with MPPT)	V-f control
Interactive Control Methods	P and Q support	Load Sharing

In the grid-following mode, the frequency and voltage values are dictated by the utility grid and DG units are operated to follow these set values. The non-interactive control method strives to harvest the maximum power available through Maximum Power Point Tracking (MPPT), or a predetermined amount of power whereas the interactive control method is used for real and reactive power support depending on the system and the loads. The former method is suitable for solar panels and wind generators where the energy resources are inconsistent and unreliable. The latter method is implemented in DGs such as diesel generators or distributed storage devices which can supply energy continuously. A microgrid may incorporate both of these control methods for different types of DGs.

When microgrid operates in islanded mode, a similar two-way approach is used. Some large DGs are operated with Voltage and Frequency (V-f) control to keep these values constant in the islanded microgrid. If this is achieved with a number of DGs, then the rest of them will be operated in the load sharing mode to share the loads in the system. In this fashion, the microgrid operates within acceptable voltage/frequency limits and the loads are supplied with the required power.

The most popular control scheme employed for load sharing is droop control since it realizes automatic load sharing in a microgrid without any central control mechanism or communication between DGs [27-31]. This feature shines when the microgrid is working in islanded mode where droop control solves the control problem [32]. In fact, it has been demonstrated that by imitating the generator-turbine-governor units, drooping characteristics can be successfully applied to inverters working in an isolated AC system. [33]. Of the two possible generation modes, V-f and, Real and Reactive Power (P-Q) droops, the latter is more preferable by producers whereas the former is needed to form a grid, especially in islanded microgrids [34]. This is yet another challenge for microgrid operation where there is poor market organization. To better understand the theory behind it, please consider the power flow equations given in (2.1) and (2.2):

$$U_{rec} * \sin \delta = (X * P - R * Q) / U_{sen} \qquad (2.1)$$

$$U_{sen} - U_{rec} * \cos \delta = (R * P + X * Q) / U_{sen} \qquad (2.2)$$

where X: line reactance

R: line resistance

P: real power

Q: reactive power

U_{sen}: sending end voltage magnitude

U_{rec}: receiving end voltage magnitude

and

δ: phase difference between sending and receiving ends

For high voltage lines X >> R, R may be neglected, and δ is very small. So assumptions can be made that sin δ = δ and cos δ = 1. The equations can then be rewritten as follows:

$$\delta = X * P / (U_{sen} * U_{rec}) \qquad (2.3)$$

$$U_{sen} - U_{rec} = X * Q / U_{sen} \qquad (2.4)$$

It can be seen from (2.3) and (2.4) that the power angle mostly depends on the real power whereas the voltage difference mostly depends on reactive power. In other words, by controlling P&Q, the frequency and the voltage of the grid can be set.

The infamous droop regulation equations (2.5) and (2.6) are obtained by associating a permissible error on the voltage and frequency values with real and reactive power values. When there is a variation in the frequency or the voltage value, the DGs adjust their real and reactive output values accordingly. The adjustment should be done and the power mismatch should be recovered immediately to maintain the system frequency. Consequently, storage devices are needed for a successful droop control implementation [32, 35].

$$f - f_0 = -k_p(P - P_0) \tag{2.5}$$

$$U_{sen} - U_0 = -k_q(Q - Q_0) \tag{2.6}$$

where f: frequency and f_0: rated frequency

U_0: rated grid voltage

P_0, Q_0: set real and reactive power of the inverter

The power sharing of the generators are mostly indirectly proportional to their capacities. The load sharing coefficient m_{Pi} is based on an equitable load share in the form:

$$m_{P1} * P_1 = m_{P2} * P_2 = m_{Pi} * P_i = \text{constant (k)} \tag{2.7}$$

where P_i is the rated output power of i_{th} DG [36]. It is worthy to note that this scheduling scheme does not take technical or financial aspects into account. That is to say, DG's ability to provide sufficient level of reserves or the economical outcome is not considered in determining new droop operating points. In tackling this issue, [37] acknowledges the economic importance of selective sharing among DGs and proposes using four different droop coefficients based on production cost or available reserves. Although this improves the droop performance, it has stability concerns since the increase of droop coefficients beyond certain limit triggers instability [38, 39].

Another shortcoming of droop control presents itself when implemented in low voltage networks. For low voltage wires, X >> R assumption does not hold [40] and classical droop equations are insufficient. The control system proposed in [41] considers the effect of R and uses improved droop equations. Another improvement presented in [37] is controlling not only the fundamental component of the voltage but also its harmonics. Systems proposed in [36, 41-44] have droop control for harmonic components and thus can feed non-linear loads. In order to address the versatile nature of microgrids, the central controller in [45] calculates droop lines for every different condition, shown in Figure 2.2, and updates them. This gives the controller the flexibility it needs to respond varying operation modes.

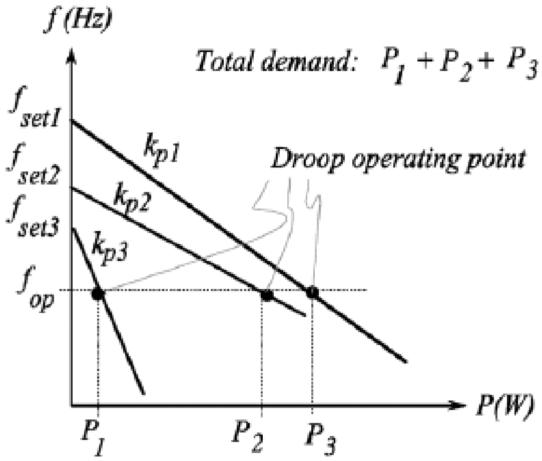

Figure 2.2. Different droop lines and operating points in [45]

The conventional droop method employs low-pass filters to calculate average P & Q values, hence it has a slow dynamic response [46]. A wireless controller was proposed in [47] to enhance the dynamic response with integral-derivative term addition. Furthermore, the power sharing is degraded when the sum of output and line impedances are not balanced [48]. This might be solved with interface inductors or with control loops that emulate lossless resistors and reactors as in [49].

There are alternative drooping schemes available in the literature. For example, [50] proposes a control scheme that droops microgrid output voltage with real power (P) and system frequency (f) with reactive power (Q). This is in stark contrast with conventional load sharing schemes [29, 51]. However, this system can only be used for only one voltage source inverter (VSI) and another scheme called voltage-power droop/frequency-reactive power boost (VPD/FQB) control is proposed in [43]. This scheme also droops the voltage reference against real power output and boosts the frequency with reactive power output. In addition to that, it can be run in parallel with other VSIs and the utility grid itself.

Other controls include controlling resistive output impedance of the inverters and realizing load-sharing with wireless load-sharing controllers [48, 52] or running all inverters in grid-following mode even if the microgrid is islanded [53]. The system in [35] has two level control design which implements droop control for system level multiple DG coordination controllers and L1 control theory for device-level inverter controllers. This realizes a more reliable, robust and stable microgrid control.

2.3.2. Protection

The protection of microgrids has been examined in two aspects; islanding detection and fault current protection. Although these two concepts are intertwined the research work has been carried out separately. The following two sub-headings describe them in detail. It shall suffice to mention here that both of these concepts are very important for safe and reliable microgrid operation [54]. Islanding detection is important for several microgrid management purposes as well as protection. The fault current contribution of the interconnected power grid and other adjacent microgrids play a major role in the programming of protective devices. Therefore, the detection of islanded or grid-connected operation is vital from microgrid protection point of view [55].

2.3.2.1. Islanding Detection

Islanding is a situation that occurs when part of a network is disconnected from the utility grid but is still energized by one or more DGs [56]. In conventional distribution networks, in the case of a fault in the transmission system, the distribution network does not receive any power. However, with the introduction of DGs, this presumption is not valid any more [57]. This phenomenon of unintentional islanding may cause some of the following issues[58]:

- Safety issues since a portion of the system remains energized when it is not expected;
- Loss of control over system frequency and voltage levels;
- Insufficient grounding of the islanded network over DG interconnection
- Out of phase re-closure problems which may damage the equipment [59]

Because of these issues, a DG unit should pass either one of the two anti-islanding standard tests, UL 1741[60] or IEEE 1547 [61] before it can be installed. Moreover, almost all utilities require DG units to be disconnected from the grid as soon as possible in case of islanding [62]. IEEE 929-1988 standard [63] requires the disconnection of DG units once the microgrid is islanded. The IEEE 1547-2003 standard on the other hand requires all DGs to be shut down after a maximum delay of 2 seconds once islanding is detected. In order to achieve this, there must be a fast and reliable islanding detection method. There are various kinds of islanding detection methods in the literature which are studied under two sub-headings; remote and local techniques. The local techniques include three types which are: passive, active and hybrid detection methods.

Passive detection methods measure some local parameters such as voltage, frequency, total harmonic distortion [57, 64], rate of change of power signal [65], rate of change of frequency over power. By comparing these values with pre-determined thresholds, islanding is detected. Passive detection methods detect islanding very fast and without disturbing the system. However, should the mismatch be small they become unreliable. The challenge of setting suitable thresholds and the large non-detection zone are the major drawbacks [16] of passive methods.

Active detection methods try to address the shortcomings of passive methods by intentionally introducing perturbations into the system and detecting islanding according to the response of the system [66, 67]. In this way, it is possible to detect islanding even if the power mismatch is very small hence a much smaller non-detection zone. The downside of active methods is that they are not as fast as passive methods and they degrade the power quality with the injected perturbations.

Hybrid detection methods are the combination of passive and active methods. The system is constantly monitored with passive methods and if islanding is suspected by the passive methods then the active methods are implemented. This combines smaller non-detection of active methods whereas unnecessary disturbance in the system is prevented by passive methods [57, 68]. The drawback is long detection time since both of the methods are implemented.

There are communication based approaches to islanding detection with an effort to overcome the problems posed by active and passive detection methods. These methods are based on a direct communication between the utility and DGs in a microgrid [69]. Islanding is caused by opening of a line circuit breaker so it is proposed to use this event to detect islanding and execute necessary protection schemes. Some of the methods that incorporate this principle are [70]: Power Line Carrier (PLC) Communications , Supervisory Control and Data Acquisition (SCADA), Intertripping/Disconnection signal. These methods do not suffer from non-detection zones and they do not affect the power quality by de-stabilizing the system. The only set back is the additional cost of communication systems and their reliability. According to [71], PLC communication is a practical, reliable and cost-effective method to realize islanding detection. In this method, a signal is injected to bus bars at substations and

DGs operate as long as they receive the signal. Should a tripping occur and the microgrid become islanded, the signal vanishes and DGs are shut down automatically [69].

2.3.2.2. Fault Current Protection

Integration of DGs to the grid and increasing penetration levels of DGs change the fault current levels and direction in networks [4, 72]. Traditional protection schemes shall be re-designed in order to meet these fundamental changes. Also microgrids have dynamic structures, i.e. several DGs and loads connect/disconnect at any instant, and various operating modes. Fault current levels may vary for all these situations and current protection designs are not sufficient to tackle these issues. Some of the prominent protections issues are: short circuit power, fault current level and direction, device discrimination, reduction in reach of over-current relays, nuisance tripping, protection blinding etc. [73-76].

Protection of microgrids against fault currents and design of new protection schemes are promising research fields. In conventional power networks, the power flows from higher voltage levels to lower voltage levels. In case of a fault, the short circuit current decreases as the distance from the source increases. However, DGs change these concepts as there may be power flow from the microgrid to the utility if the local generation exceeds local consumption. As Figure 2.3 shows the fault current may grow downstream with the contribution of fault currents from DGs. Fault contribution from a single DG may not be large; however the combined effect of several DGs can reach significant levels [77]. Estimating this contribution is not an easy task as it highly depends on the type of the DG. Another problem is that DGs with PE interface do not supply short circuit currents sufficient enough to trigger protective devices [78]. If the fault current settings of the relays are decreased so that they sense fault currents from inverter-interfaced DGs, then undesired trippings and nuisance trippings will occur due to transients in the system [79]. The position of a fault with respect to DG also affects the operation of protection system. It may be that the relay is only measuring some part of the actual fault current as there may be several fault current paths towards the fault [80]. Fault current challenges shall be discussed in detail, in the next chapter where the conceptual design of the proposed system is explained.

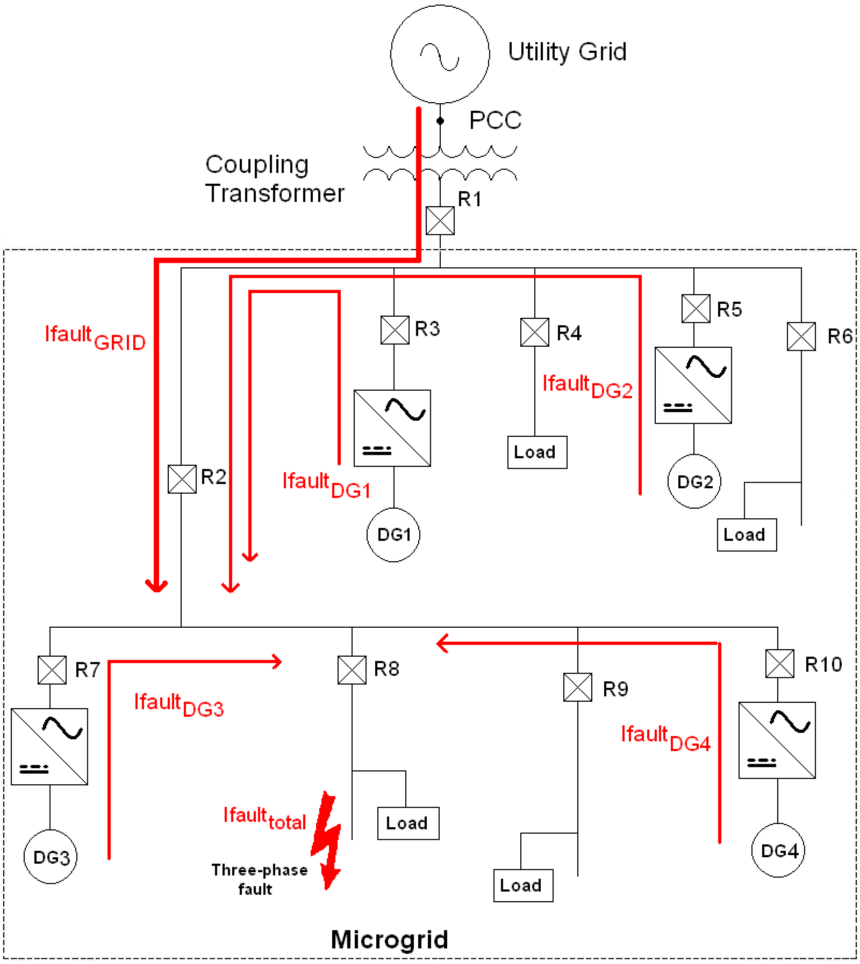

Figure 2.3. Grid and DG fault current contribution in MG

Moreover, fault currents are different for grid-connected and islanded modes of operation. In the former case, the utility grid contributes to the fault current whereas the latter only includes the fault currents from DGs. In an islanded grid, the storage devices, intermittency of DGs such as solar panels or wind turbines, load types and their power demand affect the fault levels. The new protection system should be dynamic and respond to those changes in the operation conditions [81, 82].

Furthermore, low voltage systems may have single phase loads which will alter the balanced system parameters [83]. DC microgrids which have simpler connection and more efficient PE interfaces need special attention [84, 85]. Protection of microgrids against over voltages [86] or utility voltage sags [87] are also amongst popular research fields. Fault current protection in microgrids and the related challenges are the main focus of this research. Therefore, more comprehensive discussions on fault current protection challenges, the impact of DGs and proposed solutions are discussed in other chapters such as Chapter 3 and Chapter 4.

There are different solutions proposed in the literature for the issues stated above. There are proposals to change the relay types used or update their operating currents regularly or to re-design the protection techniques from scratch. The use of anti-islanding frequency relays is proposed in [88]. It is argued that frequency relays can satisfy anti-islanding and frequency tripping requirements. It is pointed out in [89] Rate-of-Change-of-Frequency (RoCoF) relays are more reliable in islanding detection under small power imbalances but Vector Surge relays are yet more susceptible to faulty operation.

However, these solutions are not feasible as it is not realistic to assume that all relays can be replaced [74]. Alternatively, the method in [90] can be implemented where operating points of relays are calculated with modified particle swarm optimization. In another approach, instead of using relays and circuit breakers blindly, some smart algorithms are implemented to selectively operate relays and isolate the fault [91-93]. There are more ground-breaking systems which employ a developed communication system to follow the system parameters and carry out necessary calculations [73, 94]. These systems consider the fact that microgrids will have extensive communication feature and make use of it. Figure 2.4 shows a new generation microgrid protection system which relies on the use of communication lines. This generic structure is given in [82] as a general framework to be used as a template in future microgrid protection systems. It categorizes different grid components under separate headings and shows what kind of additional devices might be required to sustain the required communication infrastructure. This approach strives to design the communication hierarchy for protection and management purposes.

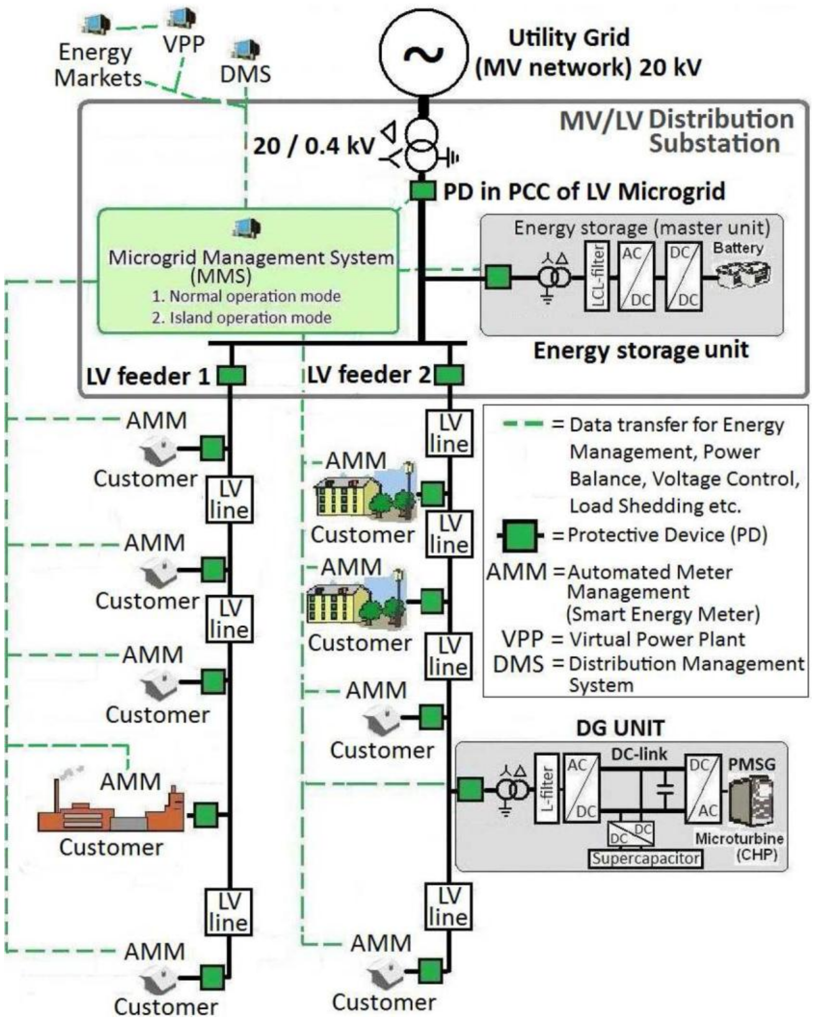

Figure 2.4 General Structure of New Generation Microgrid Protection Systems [82]

According to given design, microgrid management system (MMS) is an interface agent between individual grid components and distribution management system (DMS). This higher management entity, in turn, takes part in higher levels of cooperation in microgrids such as Virtual Power Plants (VPPs) or Energy Markets. This work is very comprehensive for providing a generic structure for microgrid protection systems, determining the placement of communication and measurement devices as well as the hierarchical structure for management purposes. However, specific details of a protection system such as devices, details of their coordination, operating algorithms have not been given. Therefore, this research work is, despite being an invaluable contribution, does not have practical features and feasibility.

An embodiment of the new generation microgrid protection system is shown in Figure 2.5 [73]. This research work actually focused on a real-life implementation of the conceptual design given above. The microgrid components are connected to Microgrid Central Controller (MGCC) through communication lines and the operating curves of the relays controlling circuit breakers (CBs) are adapted in accordance with the changes occurring in the microgrid structure, hence the name adaptive protection system.

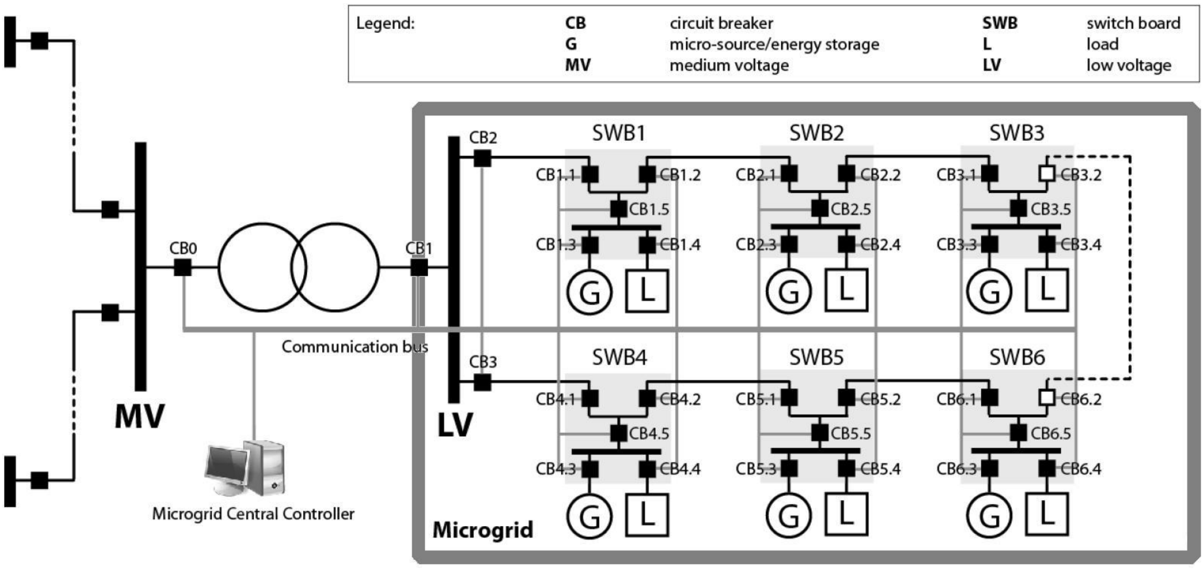

Figure 2.5 Adaptive Microgrid Protection System proposed in [73]

Depending on the loading of the microgrid, normal operating currents as well as fault currents may flow in both directions. This is a major challenge in microgrid protection and is discussed in the next chapter. Adaptive protection system given above assumes an interlock direction based solution for this issue. As shown in Figure 2.6, in addition to tripping characteristics, each relay is assigned with an interlock direction. When a fault occurs, relays compare the flowing fault current with the pre-assigned interlock direction and thus isolate the fault. This is achieved between the last relay in which fault current direction and interlock direction are the same, and the first relay in which the fault current direction is opposite of interlock direction.

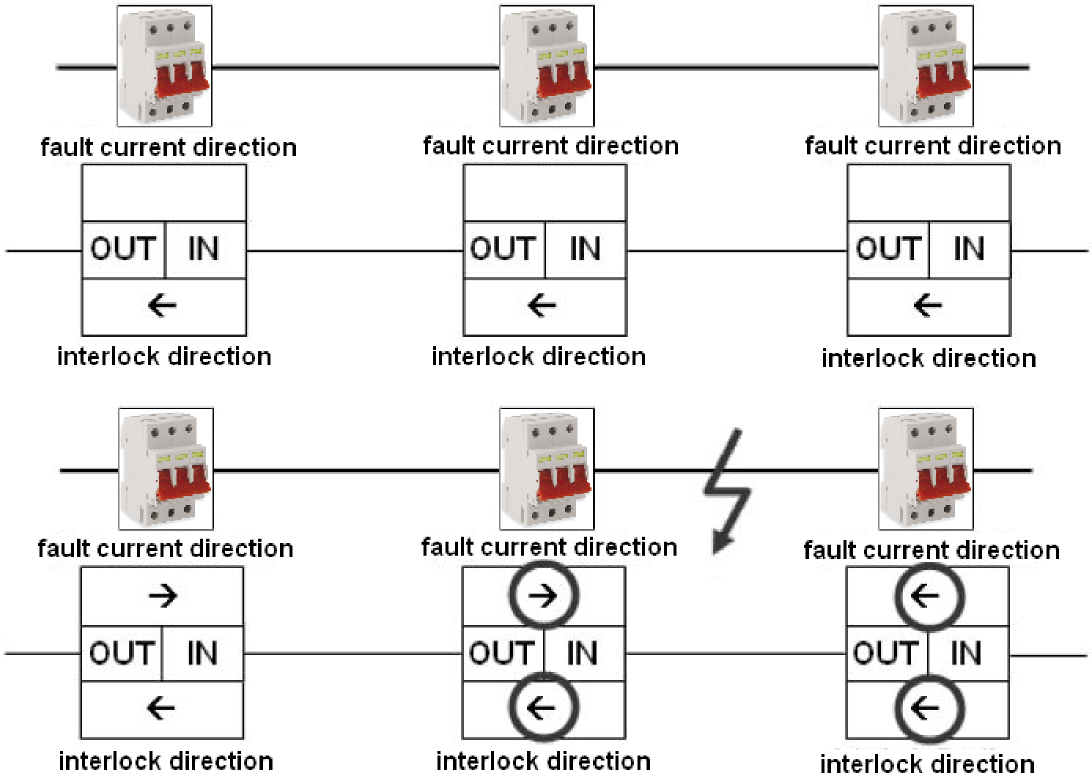

Figure 2.6 Implementation of Selectivity with interlock direction in [73]

However, the major drawback of this approach is the need to know possible microgrid structures beforehand. This is required to arrange tripping characteristics of the relays as well as to assign their interlock directions in accordance with the expected operating current flow. It is required to study the possible structures of this microgrid and tabulate the necessary parameters. Then, the protection system will update these parameters accordingly. This is a major drawback because a new structure or a connection in this microgrid as well as a new deployment will render the whole adaptive protection system useless. Each new deployment requires the parameter tables to be updated with a new entry.

Following from the example given above, current systems use some sort of database or event table to search the current status and take pre-determined precautions [73, 90]. However, since microgrids are designed to accommodate new generators and loads, their structure is bound to change very often. Therefore, these schemes are not practical. Some sort of algorithm which manages to adjust the protection scheme to the new state of microgrid is direly needed. Machine learning, artificial intelligence or fuzzy logic algorithms are the trivial candidates as a foundation for such adaptive-automatic microgrid protection schemes. All of these new approaches would necessitate the use of communication lines in microgrids.

Despite providing many advantages, use of extensive communication is not all good news for power networks. It is discussed in the literature that having extensive communication networks would make the microgrid more expensive and less reliable [95]. Moreover, in a distributed energy system, components may be located far away which makes communication difficult [38]. Another communication challenge is posed by the existence of different manufacturers and models for grid components. The communication between them shall be regulated by certain set of rules so that all grid devices use the same variables and parameters for coordination purposes. Simply put, a standardized communication framework is required to make sure that these grid components speak in the same language. In this manner equipments from different vendors and with different capabilities can be modeled in a standard manner. This phenomenon is explored in detail in Section (2.5) in this chapter and the relevant modeling is given in Chapter 6. To solve this issue, Standard communication protocols such as the IEC 61850 [11] might be used in these microgrid protection systems as in [96], however it is of concern that how the new fault currents and fault levels shall be calculated for any change occurring in the system.

It is important to define a set of data and information exchange models for the communication of data within power networks for protection and automation purposes. This has been partly achieved by the introduction of IEC 61850, which mainly focuses on the standardization of data to be communicated within substations for various purposes including protection. IEC 61850 focuses mainly on substation communications. But, the work presented in this thesis investigated the possible uses of this standard for the protection of microgrids.

There are conceptual designs or proposed opinions in the literature while it is hard to find a new protection design in a microgrid which responds to the needs of microgrid operation modes and components. The biggest challenge is to have a dynamic protection system which discovers new deployments and structure changes in the microgrid automatically, and update the operating parameters of protective devices. There is a strong need for plug-and-play concept in microgrids, at least from protection point of view. Furthermore, the possibility of having differing sets of microgrid components should also be taken into account during the design of a protection system. These points are yet to be addressed in the literature. Consequently, the author focused his research project on these points to come up with a generic yet practical, comprehensive yet standardized and universalized microgrid protection system.

2.3.3. Microgrid Energy Management System (MEMS)

In order to execute the duties described so far, a microgrid utilizes a microgrid management system. This system ensures that different components of the microgrid are managed to serve towards a certain objective [97]. It typically comprises of three hierarchical levels of control as shown in Figure 2.7.

Microgrid Central Controller (MGCC) acts as an interface between the microgrid and the outside world. It communicates with Distribution Network Operator (DNO) and Market Operator (MO) and optimizes microgrid operation through Local Controllers (LCs). It ensures that in a network where more than one microgrid exists, microgrids work in harmony to sustain a reliable and safe operation. LCs are responsible to control components of a microgrid such as distributed generators, storage devices, loads or protection equipment. MGCC manages LCs and updates their operation modes and points in parallel with the events occurring in the network and/or the microgrid. Once the updates are received, LCs mostly behave autonomously until a new instruction is received from MGCC [98]. Based on the decision making scheme, the control systems (also known as supervisory systems [8]) are categorized as centralized and decentralized microgrid control [99].

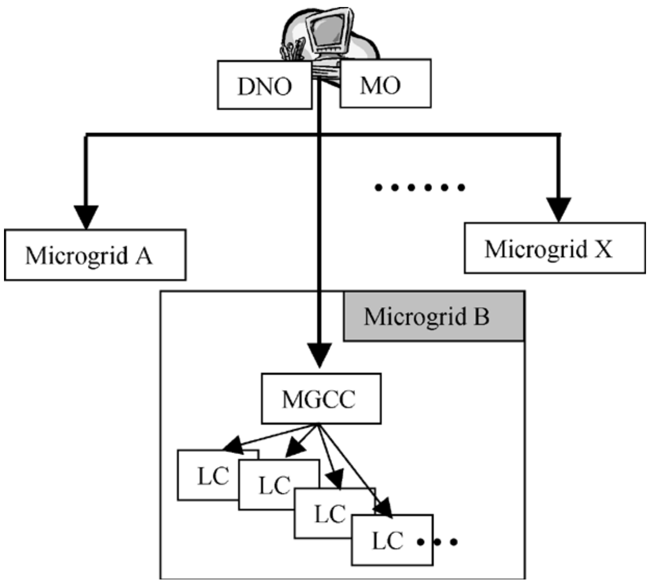

Figure 2.7. Control Levels of the Microgrid [100]

Centralized control strives to maximize the local production according to market prices. For this to occur, there is a two-way communication between the MGCC and each LC [8]. Starting from this point there is a new concept called Virtual Power Plants (VPPs) where distinct entities inside a microgrid are controlled by a central unit to act as a power plant [101].

Conversely, in decentralized control, the larger part of the decision making is in the hands of LCs. They act in a smart fashion and communicate with each other to increase the revenue and the performance of the microgrid. The most popular way to design this intelligent system, which is composed of smaller less intelligent components, is by using multi-agent systems [100]. Multi-agent systems are already proposed for the protection [102], stabilization [103], restoration [104]of large power systems.

There are on-going research projects being carried out to investigate alternative control systems. A control system based on ‘Game Theory’ is proposed in [105]. In this approach, power electronics based inverters are treated as variable impedance loads and every generator in the microgrid is taken as a player. The stabilization and the control of the system may be achieved through real-time or turn-based games. For different scenarios, different games such as “Maximum Power Game” or “Microgrid Stability Game” can be played. Depending on the level of communication, games might be cooperative and non-cooperative.

In an another study, the “Ant Colony Optimization” algorithm is proposed to solve constraint satisfaction problem for microgrids [106]. Ant colony optimization is a nature-inspired artificial intelligence technique where several ant colonies cooperate to solve a problem [107]. In microgrid applications, distributed generators, storage devices and loads are represented by a variable. The domain of each variable represents the quantized operating points at which the generator or load could be commanded to operate [106]. By stipulating constrains, ants walk on the construction graphs and each variable will be assigned an operating point. The touring of the colonies continue until the solution is attained for each and every variable.

By implementing a central control unit in microgrids, different objectives can be realized. Minimizing system disturbances, maximizing efficiency, meeting power demands from local resources, stabilizing the system are to name a few. This formulation outlines the difficulty of the control task. With competing objectives and highly variable parameters, a real-time power management system which is both robust and flexible is needed.

Microgrid Energy Management Systems (MEMS) which are aimed at controlling the microgrid in a holistic sense are fairly new in the literature. Although the very concept of MEMS is proposed some time ago [5], real design and implementation of MEMS are crucial to get more knowledge and experience in the field. Conceptual designs look appealing but implementations or simulations on models shall be carried out to see the real side of the picture[14].

Microgrids have dynamic structures which change more often than the conventional large networks. This dynamic behavior of microgrids is a major protection challenge since the conventional selectivity methods assume a fixed network structure and a predetermined relay hierarchy [108]. Whenever restructuring occurs, the selective levels assigned prior to that become erroneous. For a proper operation, the selective levels of relays should follow the changing conditions of the network. Whenever a structure variation takes place in a microgrid, new relay hierarchy should be extracted and corresponding settings including time delays should be determined before updating these settings within the relays via communication lines [109, 110]. It is essential that this process is performed automatically so that the processing time is minimal and there is no interruption in power delivery. This requires an algorithm which will determine the current structure of the system and yield the relay hierarchy at all branches of the network.

In order to ensure protection under these conditions, a centralized management is required to monitor and communicate with the microgrid components and assign suitable operation parameters. It is almost impossible to know the parameters of a microgrid beforehand. Therefore, a centralized microgrid management system is required for monitoring the grid components, their operating points, new deployments and connection changes occurring in the microgrid. Then, necessary adjustments can be made by the MEMS and through communication lines related protective devices can be programmed accordingly.

2.4. Examples around the World

There are various microgrid implementations or active experiments worldwide to understand the operation of microgrids in a better sense. Different technologies and topologies have been studied for different purposes. Some of the experiments are run for purely R&D purposes whereas others are deployed on islands or isolated/distant grids. Since the microgrid concept is very versatile, the experiment conditions and the objectives have a very wide span.

2.4.1. European Union (EU)

The level of climate change awareness in the EU is very high and there are certain targets that need to be achieved by the member states by 2020. There are various directives passed by the European Parliament such as 2001/77/EC, 2003/30/EC and 2006/32/EC. These directives stipulate that the carbon emissions shall be reduced by certain amounts, the share of renewable energies in the energy market shall be increased and the energy consumption shall be reduced by increasing energy efficiency [111]. Accordingly, there are incentives from the EU and several on-going projects in member states.

The first project funded by the EU was the “Microgrids Project” and it was undertaken by a consortium led by National Technical University of Athens (NTUA). The objective was to investigate the dynamics of DGs in microgrids and develop strategies for a number of issues such as control algorithms, protection schemes, black start strategies as well as definition of DG interface response and intelligence requirements [9]. A pilot installation was realized on the Kythnos Island, Greece. A comprehensive study on microgrid control methods was performed in ISET microgrid, Germany [112]. The continuation of the project was "More Microgrids Project" again undertaken by a consortium led by NTUA. This project was executed to study alternative methods, strategies along with universalization and plug-and-play concepts. The demonstration site is an ecological estate in Mannheim-Wallstadt, Germany [113].

Other implementations with smaller scales include the Labein Microgrid in Spain, Frielas Feeder in Portugal, CESI Microgrid in Italy, Continuon Holiday Camp Microgrid in the Netherlands, Am Steinwag Settlement in Germany [6, 9, 113].

2.4.2. Japan

Japan is committed to utilize RE systems, however this puts the country's well-earned high power quality reputation in jeopardy. The RE systems used in Japan are mostly wind turbines and PV systems, intermittent nature of which is an additional set-back. Microgrid's ability to address these problems motivated the projects in Japan and hence the country has the most microgrid implementation projects worldwide [114]. Most of the projects are funded by the New Energy and Industrial Technology Development Organization (NEDO). Three demonstrations sites were installed in 2003 under NEDO's Power grid with renewable Energy Resources Project.

The first project started operation in 2005 World Exposition in Aichi although it is removed to Tokoname City near Nagoya in 2006. This system uses fuel cells, PV panels and NaS battery storage system. This microgrid is used to feed some major pavilions and it was put to test twice for independent operation in 2005 and 2007. Although the first test revealed some deficiencies in controlling the voltage and frequency, the second experiment was more successful [114]. The second demonstration site is in Kyotango where a biogas plant is connected to two PV systems and a small wind turbine. This network operates as a VPP and interestingly instead of the latest technology the communication is realized over conventional information networks such as ISDN and ADSL [6, 9]. The third project in Hachinohe is being undertaken by the Mitsubishi Research Institute and Mitsubishi Electric [115]. This system has its private distribution line and consists of PV systems, wind turbines, gas engines and storage. The management scheme developed here ensures stability and meets building demands. An additional project has been started by NEDO in Sendai city where four levels of customer power will be studied. The system will have power quality backup system in order to reduce interruptions and voltage drops. This project is aimed at studying the possibility of supplying different service levels to customers in the same area. The system has enhanced the power quality since it was put into action in 2007 [10].

There are several private microgrid research projects. For example, the Shimizsu Microgrid is being developed by the Shimuzu Corporation with the cooperation of the University of Tokyo to develop an optimum operation and control system. Tokyo Gas on the other hand, again partnering with the University of Tokyo, is trying to develop an integrated DG control through simulations and experiments at its facility in Yokohama [10]. Crossing boundaries, Mitsubishi Corporation has installed a small grid in Hsinchiang, China and it can be supplied by distribution network, PV systems, battery storage and genset operation [116].

2.4.3. Korea

Korea’s first and only pilot project is being developed by the Korean Energy Research

Institute (KERI). The test system is very comprehensive as it includes several types of DGs such as PV simulator, fuel cells, diesel generators, wind turbine simulator along with significant and non-significant loads. The network is equipped with storage and power quality devices. An energy management system is being implemented which even takes weather conditions into account and communicates with the components through a gateway. Being equipped with rich mixture of components, the KERI microgrid is aimed at testing and studying almost all aspects of microgrids. The whole project was implemented in two phases where in the first phase, the microgrid was kept as a 100 kW class plant and in the second phase it was extended for further studies [117].

Jeju Island is receiving increasing attention due to its immense potential for RE resources. The total wind power energy in Jeju was only 19 MW in 2006 and it has increased to 230 MW in 2009 whereas several fuel cell plants are either constructed or planned on the island [118]. Jeju Island and similar Korean islands are prime candidates for microgrid implementations in Korea in the future [119].

2.4.4. North America

CERTS (the Consortium for Electric Reliability Technology Solutions), shown in Figure 2.8 [6], is the most well-known of U.S. microgrids. It is a collaboration between AEP, TECOGEN, Northern Power Systems, S&C Electric Co, Sandia National Laboratories and the University of Wisconsin [6]. It consists of several DGs and a thyristor based switch to allow isolation from the grid. The main objective of this research was to facilitate easy connection of small distributed generators to the network. As a result, three advanced concepts, also referred to as the CERTS microgrid concept, have been developed and demonstrated to decrease the field engineering work on microgrids. These concepts can be listed as a method to ensure automatic and seamless transition between grid connected and islanded modes, a protection method inside the microgrids which does not depend on high fault currents and a microgrid control scheme to stabilize system frequency and voltage without utilizing high speed communication [120].

Also, two software tools, which are required for microgrid deployment, are being developed in relation with CERTS project. These are µgrid Analysis tool (µGrid) developed by the Georgia Institute of Technology and the Distributed Energy Resources Customer Adoption Model (DER-CAM) in use at the Berkeley Lab [9].

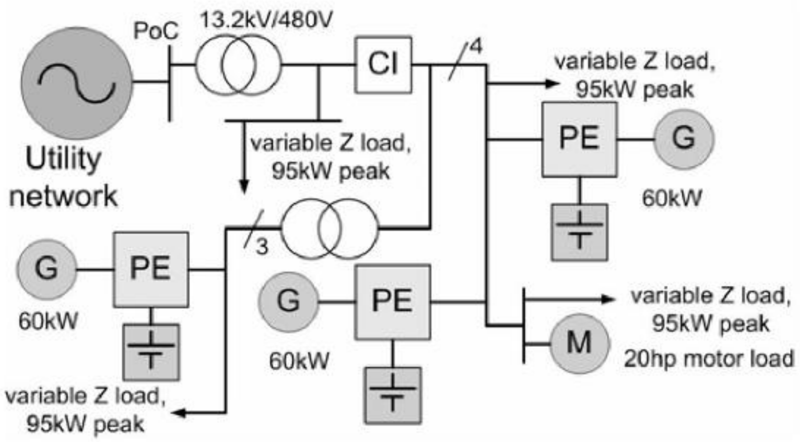

Figure 2.8. CERTS Microgrid [6]

There are other implementations going on in Mad River Waitsfield by Northern Power Systems [121] , British Colombia Institute of Technology Microgrid [122] and the General Electric Microgrid [6]. These systems are currently at R&D stage and the objective is to design control and protection strategies for different types of microgrids.

2.4.5. Australia

Currently, there are no microgrid pilot projects in Australia but there is a large potential, and with the Government's incentives, extensive research on distributed energy and microgrids has recently started [123]. Australia is a very vast continent-country which has many isolated communities. It is a new trend in the Australian Electricity Market to utilize RE resources for local power generation and local consumption. Some of these communities are not only far away but also lack access roads to the weather conditions. Utilization of DGs and implementation of microgrids for that purpose will ease the transmission and distribution burden on service providers. The ultimate goal is to realize the design and provision of power station infrastructure which will be optimized to suit the unmanned status of the power stations [124]. The Yungngora and Kalumburu communities in Western Australia [125], and the Windorah community in Queensland [126] are examples of such distant communities which are candidates for microgrid operations. In addition to this, some energy companies are trying to operate microgrids on islands such as Thursday Island in Queensland [126] and King Island in Tasmania [25].

2.5. Standards and Universalization

Proper integration of DGs to the electric power systems is needed since these systems are not designed to accommodate active generation and storage at the distribution level [127]. The evolution of DG was not pioneered by a single organization or a company rather every institution runs its own R&D project. As a result, there are many different types of DGs, interconnections, electronics interfaces. This makes it incredibly difficult to draft a set of rules/guidelines for DGs interconnection and utilization. In an effort to tackle this issue, there are several standardization and universalization works performed by several bodies. The ultimate objective is to standardize certain aspects of DGs and microgrids while there is no technology or design constraint stipulated to hinder the versatility of these concepts. Some of these standards, shown in Figure 2.9, are in force while others are still in drafting phase [128].

The first standard prepared was about the rules governing the connection of DGs to the electric power system. For a DG to be connected to the grid, it has to conform with requirements of IEEE Standard 1547.1 [61]. Only for this purpose, an alternative standard UL 1741 [60] can also be used. Both standards require that in the case of islanding, all DGs shall be disconnected from the islanded microgrid. This does not take full advantage of DGs nor is it possible to conform with this requirement if islanded operation is desired [99]. For this reason, another part to the IEEE standard 1547, namely 1547.4, is being drafted which focuses on integration of islanded systems with the utility.

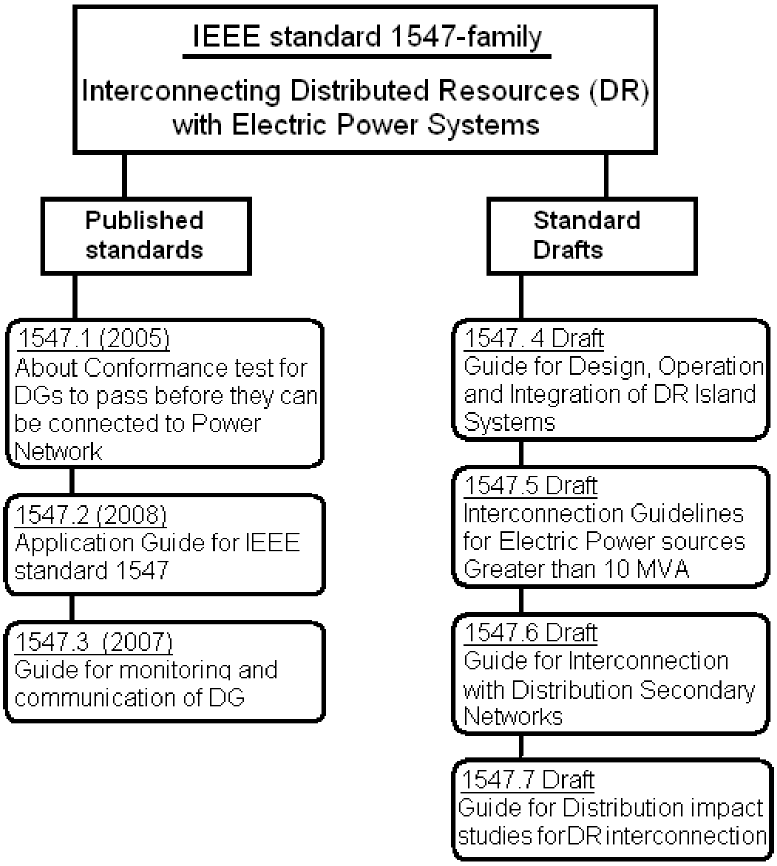

Figure 2.9. IEEE SCC21 1547 Series of Interconnection Standards [61]

The part 1547.4 is being treated as one of the fundamental standards to play a key role for microgrid standardization as it covers vital planning and operating aspects such as impacts of voltage, frequency, power quality, protection schemes and modifications, the characteristics of the DER, reserve margins, and load shedding [129]. The part 1547.3 is about monitoring and communication of DGs. Its purpose is to facilitate the interoperability of DGs in an interconnected system.

IEEE Standard Coordinating Committee 21 (SCC21) is well aware of the developments in the electricity sector and it constantly supports the development of new standard drafts. Initially, IEEE 1547 standard covered DGs with capacity less than 10 MVA [127]. However, with the recent developments in technology, there are systems with larger capacities. The draft standard 1547.5 is aimed at preparing guidelines for such systems which are not covered by the IEEE 1547.1. The draft standard 1547.6 considers interconnection of distribution secondary network system types of area electric power systems (Area EPS) with DG. 1547.7 is a very significant step towards standardization and universalization in microgrids and DGs. It covers the necessary methodology, testing steps and aspects to assess the impact of a DG on the system. This study will be helpful for network operators, contractors, and regulatory bodies to understand the impact of a particular DG on the network after connection.

In a larger scale than that of the 1547.7 draft, a "Microgrid Citizenship Tool" is proposed in [1] to evaluate how a microgrid will appear to the grid. This tool assesses a microgrid's good citizenship level based on the three key characteristics: generation capacity, installed storage and load. A microgrid is classified as a good citizen if it contributes to the performance of the grid with a consistent profile whereas a microgrid with high transient and unpredictable variations will represent a bad citizen. Such a method may be utilized in electricity market as a useful tool to estimate the impact of a microgrid on the network. If a standard methodology is developed, such a concept will be an indispensable part of standardized microgrid assessment and planning process.

National Renewable Energy Laboratory (NREL), in the USA, conducted research on interconnection, grid effects and tariff design for DERs and one of the areas was "Advanced Universal Interconnection Technology". It is believed that universalized interconnection DGs will facilitate the connection with EPS [97]. The objective is to design a modular interface device which will respond the power electronics requirements of any DG system and provide interconnection interface in a safe, reliable and cost effective manner [130]. A prototype was developed by the Northern Power Systems (NPS) which manages power management, conditioning and relaying functions with a DSP-based architecture. It was designed to be compatible with different circuit breakers, switching technologies, RE based DGs and conventional generators [131]. The research outcomes were promising and a new design with cost reduction as the primary objective is planned.

As outlined in the preceding sections, there is a growing interest in extensive communication for network management, control and protection purposes. However, there is no consensus in the literature about which communication protocol shall be used in these systems. It is known that communication devices and systems will add to the complexity of microgrids and this may constitute some problems. For this reason, worldwide collaboration is required in identifying a universal or standardized communication protocol that shall be used in microgrids for DGs, storage and protection devices to tackle the arising problems.

IEC 61850 is an international communication standard aimed at reaching a universal communication infrastructure in electrical systems [132]. It uses Object Oriented (OO) modeling for the equipment and their functionalities. IEC 61850 effectively reduces the burden of communication infrastructure modeling by virtual modeling of physical devices in a standard manner. Furthermore, it also defines necessary procedures for data transfer and client/server interactions between the equipment in an electrical network. IEC 61850 was released in 2003 for the first time for a communication within a substation automation system, yet it has been used for other purposes [133]. With a vision of controlling DGs, it has been extended. The first release, IEC 61400-25 was about the communication in wind power [96]. Two more extensions IEC 61850-7-410 on hydroelectric power plants and IEC 61850-7-420[12] on DERs logical nodes have also been published. These two extensions might be used in designing the communication system of DGs in detail. This standard and its utilization for microgrid protection systems have been examined in detail, in chapter 6 of this thesis.

For microgrids to be embraced rapidly and implemented easily, there is need for systematic standardization and universalization. This would not only help in bringing different organizations together but also encourage more people towards microgrid transition. If standard procedures are implemented and universalized components/interfaces are utilized instead of re-inventing the wheel for every single microgrid project, past experiences can easily be put into practice.

2.6. Impact of Electric Vehicles (EVs) on Future Microgrids

The internal combustion engines, which provide the traction for vehicles for the past century, can only give a maximum efficiency of 30 % [134]. Considering the increasing oil prices, an alternative to fuel is necessary for a sustainable transportation. This is also desirable for security policy of many countries since it decreases the dependency on foreign oil [135, 136]. These factors have increased the interest in EVs dramatically[137]. All the technology required for EV is readily available and the research focuses on improving performance or efficiency [134].

When coupled with the smart grid technology, an EV can act as a load as well as a distributed storage device[138]. Being connected to the grid when not in use, battery of the EV can supply power at peak load times and thus increase the power reliability of the grid. This technology is called V2G [139]. Considering the total number of vehicles in a locality, distributed storage capacity provided by V2G can have very large impact on the economical operation of smart grids[140]. In the light of this information, it can be expressed that EVs will become an indispensable part of future microgrids.

One major concern about wide EV acceptance is the immediate impact on electricity networks. Considering the cumulative generation capacity of the power systems and the estimated EV burden, it is concluded that at power generation and transmission levels, no major issue is anticipated in power systems [141]. The impact of EV is an issue at distribution level since it becomes comparable with the parameters therein [142]. It is discussed in the literature that introducing two EVs to a distribution system is equivalent to introducing one new house to the neighborhood [143]. If it is assumed that 60 % of the households have only two cars, a full EV migration will be equivalent to 30 % rise in the number of the houses in the neighborhood. This is a significant impact on distribution systems and it shall surely be taken into account by distribution companies.

Impact of EVs as a load is one aspect while the potential distributed storage provided is another. In summer for instance, following rush hour in the morning most of the vehicles are parked at parking lots (such as business hub or school/university parking lots). When they are coupled to the grid, they can support the grid until the rush-hour in the afternoon. EVs, mostly parked in garages of the owners, can provide energy to the grid throughout the evening and get recharged during the night [144].

Likewise during winter, EVs can support the grid in the evening when electricity is required for heating, illumination etc. It is apparent from Figure 2.21 that the peak hours are longer and more dominant than summer peak hours. The support of EVs during these shall be very beneficial. In similar fashion EVs can be programmed to recharge during night.

In short, the availability of the technologies required and the higher efficiency of electric-driven cars create a genuine interest for EVs in the car market. The dual role of EVs in the microgrids, i.e. load while charging and distributed storage through V2G, brings many opportunities as well as challenges. Power flow analyses, reliability, protection and fault current flow phenomena will change massively with the introduction of EVs. Therefore, network grid operators and power engineers need to consider the impact of EVs on networks for future plans.

2.7. Conclusion

The world we live in today is being troubled by the concerns on global warming, pollution and CO2 emissions. RE systems offer means of generating cleaner and sustainable energy. However, there are lots of challenges that must be tackled so that RE resources could be utilized to their full potential. RE resources are mostly dispersed and different generation approaches should be used to harvest the maximum potential out of those sources. This is contradictory to the traditional concept of central generation and distribution over large distances. For this reason, existing grids are not entirely compatible for excessive integration of DG units. On top of that, micro-scale implementation of known generation plants such as micro hydroelectric power plants, diesel generators and etc, have similar aspects since they are also distributed and their generation capacities are much smaller than their traditional giant counterparts.

In order to achieve a cleaner, reliable, and secure power generation, transmission and distribution system, the various challenges brought about by this new grid structure and management system shall be tackled with similar research projects. The outputs of studies on microgrids will aid in the development of secure, reliable, and stable real-life small-scale networks with greater penetration of RE sources. This will aid in achieving a more reliable, secure and cleaner energy without compromising from environment protection and similar concepts.

This chapter summarized the current status of the research on microgrids, their management and operation. As it is stated above, microgrid protection has received relatively less attention as compared to other research fields. There is a knowledge gap regarding;

i) monitoring the structural changes occurring in microgrids due to connection changes or new deployments,
ii) adjusting parameters of protective devices according to these changes to ensure proper and reliable operation,
iii) standardizing the much-needed communication between grid components in microgrids, and
iv) interaction between different protection schemes applied on microgrids.

Identifying this research opportunity, author has focused his research on these topics. Consequently, the research work presented in the coming chapters of this thesis is an effort to address these knowledge gaps pertaining to microgrid protection systems. In a nutshell throughout this research work, a versatile microgrid protection system with communication support [55] has been developed. The operating parameters are calculated in on-the-fly and no prior knowledge of the microgrid structure is required [145]. This system can be extended to accommodate various types of components such as fault current limiters [146] or EVs [147], accept new deployments and extract the new microgrid structure with adaptive computing [7] and can be implemented with international communication standards[148] such as IEC 61850 [8] and IEC 61850-7-420 [12]. In order to accommodate all types of grid components, necessary extensions have been developed for this standard, e.g. for FCLs [149] and EVs [147].

Chapter 3

Conceptual Design of Centralized Microgrid Protection System

Publications pertaining to this chapter:

1) Taha Selim Ustun, Cagil Ozansoy, Aladin Zayegh, "A microgrid protection system with central protection unit and extensive communication," in Proceedings of 10th International Conference on Environment and Electrical Engineering (EEEIC), 2011, vol., no., pp.1-4, 8-11 May 2011, Rome, Italy, ISBN 978-1-4244-8781-3.

2) Taha Selim Ustun, Cagil Ozansoy, Aladin Zayegh, "A central microgrid protection system for networks with fault current limiters," in Proceedings of 10th International Conference Environment and Electrical Engineering (EEEIC), 2011, vol., no., pp.1-4, 8-11 May 2011, Rome, Italy, ISBN 978-1-4244-8781-3.

3.1. Introduction

The first step of the methodology assumed in this research work is to devise a conceptual design for the developed microgrid protection system. This process is the foundation stone of the overall research work on which the other methodology steps shall build. Therefore, during this period, different possibilities in microgrid operation, equipment used in power grids and different operation cases have been investigated. This has been done with the aim of thoroughly understanding the operational situations that could occur in microgrids and designing the protection system in a comprehensive manner. Unlike most of the studies reported in the literature, instead of focusing on a particular microgrid topology or a particular case thereof [73, 90, 150-153], this research strives to achieve a flexible protection system. It is an aim of this research that the designed protection system can be used in microgrids with different topologies and set of components. It is also desired that the varying operating conditions, connection/disconnection of components and new deployments can be handled with this new microgrid protection system.

In order to serve this purpose, different DG types have been investigated. It is a known fact that rotating-machine type DGs such as wind turbines or diesel generators have different fault current contributions as compared to IIDGs such as PVs or Fuel Cells [14, 15, 153, 154]. Same type of DGs have different fault current contributions which depend on their operating capacity [155] and might be manipulated with auxiliary elements such as Fault Current Limiters (FCLs) [156]. There are devices which may provide power as well as demand it, such as EVs or storage devices [14]. All this information has been taken into account during the conceptual design process.

The overall conceptual design has been developed in a fashion to respond to the demands of new generation microgrids with their various operating conditions and dynamic set of grid components. Furthermore, this design has been tailor-made to enable the implementation of the underlying communication exchange using the IEC 61850 standard. This is essential for a protection system which is intended to be used on different topologies where same devices might have different manufacturers and models. This design is suitable for automated grid structure detection whereby the changes occurring in the microgrid topology can be monitored automatically and necessary actions could be taken. These above-mentioned two factors have been paid special attention since they are the building blocks of the plug-and-play concept in power networks. When these two features are used, this conceptual design can implement plug-and-play for new grid components connected to the microgrid.

The next section of this chapter explains the fault current challenges in microgrids. Different protection challenges have been explained along with their representations on microgrid topologies. Then, Section 3.3 reveals the details of the conceptual design of the developed microgrid protection system. Section 3.4 sheds light on a very important device, i.e. FCL, which is bound to be used frequently in microgrids, and its integration to the conceptual design. EVs and storage devices have the ability to operate as a load or a generator and they have been implicitly included in the conceptual design in terms of individual generators and loads. EVs and their implementation shall be discussed in detail in Chapter 6.

3.2. Fault Current Challenges in Microgrids

The recent developments in technology and the growing concerns for global warming motivated engineers to search for cleaner and more efficient systems. In order to decrease the impacts of fossil fuel based generation on the environment, the new vision is to generate electricity from cleaner energy sources and closer to the consumption areas. Consequently, the power industry is moving towards Distributed Generation (DG), which may be Renewable Energy (RE) based DG such as wind turbines, solar systems and etc. This also decreases the burden on transmission lines which already operate close to their limits.

Although DG has recently become irreversibly popular, there are some serious challenges for the large scale integration to the utility grids. Existing distribution systems are not designed for significant penetration of DG as they were traditionally designed with the assumption of a passive network. The interconnection of RE based DG systems to such networks inevitably changes the characteristics of the system and presents key technical challenges which were previously unknown to grid operators and power engineers [2]. Moreover, DG systems also make contributions to the fault currents around the network. Hence, in case of a fault, the transient characteristics of the network become completely different [3]. These are only a few of the issues that have arisen in relation with the revolutionary changes occurring in the grids and the way they are operated.

In an effort to tackle these problems, the microgrid concept has been introduced [5, 7, 9]. The motivation behind using microgrids is to divide the enormous conventional utility network into smaller and more easily operable grids. These smaller electrical networks will manage distributed generators, loads, storage and protection devices in their own grid. Provided that each microgrid is operating as a model citizen, i.e. either as a load receiving power or as a power supply supplying power with stable voltage and frequency, then the overall utility grid can be operated properly. It is a well-known fact that higher penetration levels of DGs, especially those that require Power Electronics (PE) interface, alter the grid structure and jeopardize safe and reliable operation. The microgrid concept is introduced to manage these generators in smaller quantities rather than trying to tackle the whole network in a holistic manner. In this way, more DGs can be employed in the grid and side-effects on the grid operation can be eliminated.

However, there are technical challenges regarding microgrids and their full integration into existing grids such as control, management and protection [9, 10]. Especially, the conventional protection schemes totally collapse since two fundamentals of traditional utility grids, which are the “radial” structure of the grid and passive transmission and distribution networks, do not hold anymore. Instead of making small amendments in these protection systems that are no longer applicable, revolutionary changes are required for safe operation.

The integration of DGs to the grid and the increasing levels of penetration change the fault current levels and their direction in networks [4, 72]. In conventional networks, transmission and distribution networks are passive and do not contribute to faults. In a microgrid, DGs will contribute to fault currents and the contribution level depends on the DG type. So the ratings of the protection equipment should be re-planned accordingly.

Consider the case shown in Figure 3.1, where a microgrid operates in grid connected mode and an internal fault occurs at the load just downstream from the relay R3. In a passive distribution network, the relay R3 ideally needs to interrupt the fault current contribution of the grid, i.e. $I_{faultGRID}$. However, in the case given in Figure 3.1, there will also be fault current contributions from the DG1 and DG2, namely the $I_{faultDG1}$ and $I_{faultDG2}$. The rating and the settings of R3 should therefore be adjusted accordingly to take into account these extra fault current contributions. When the number of DGs in a system increases, this difference will obviously be higher.

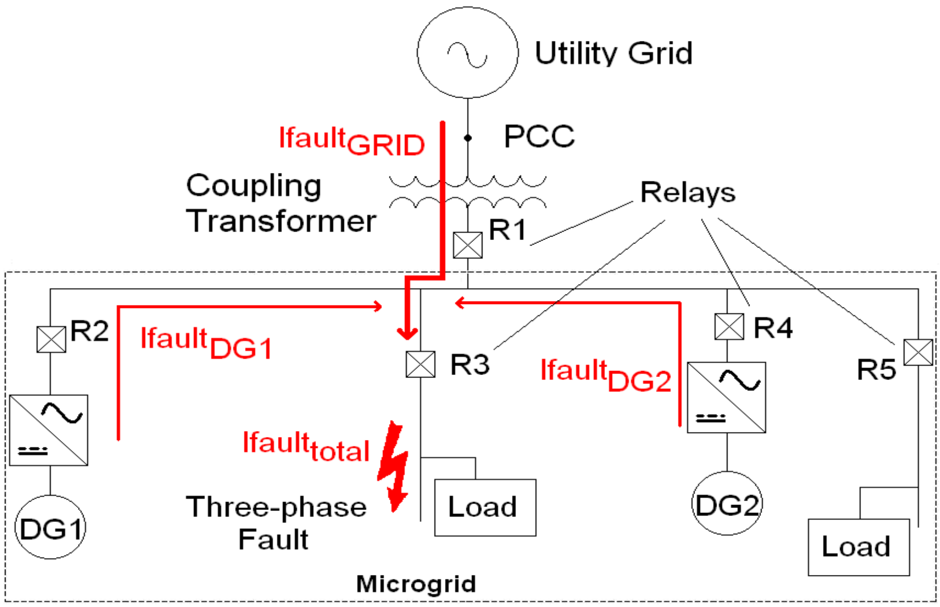

Figure 3.1. Grid connected-Mode, Internal Three-phase Fault

If an external fault occurs in the same system (a fault outside microgrid), it requires that the relay R1 opens and islands the microgrid to protect its stability. This requires R1 to detect not only downstream faults but also upstream ones. Since faults may occur at different locations and there may be several DGs at different places, bi-directional operable relays meet the requirements of microgrid protection much better than traditional unidirectional relays.

Assume that when the microgrid is islanded from the utility, in the case of a power disturbance such as an under-voltage scenario, an internal fault occurs as shown in Figure 3.2. In this case, there will be no grid fault contribution and the overall fault current will only be due to $I_{faultDG1}$ and $I_{faultDG2}$. Relay R3 is now supposed to operate at this fault level, i.e. $I_{faultDG1} + I_{faultDG2}$, while in the previous case it was set to trip a much higher fault current, i.e. $I_{faultGRID} + I_{faultDG1} + I_{faultDG2}$. The operating tripping current of R3 should therefore needs to be adjusted according to the operation mode of the microgrid to ensure proper protection. The related simulation results are given in Chapter 7.

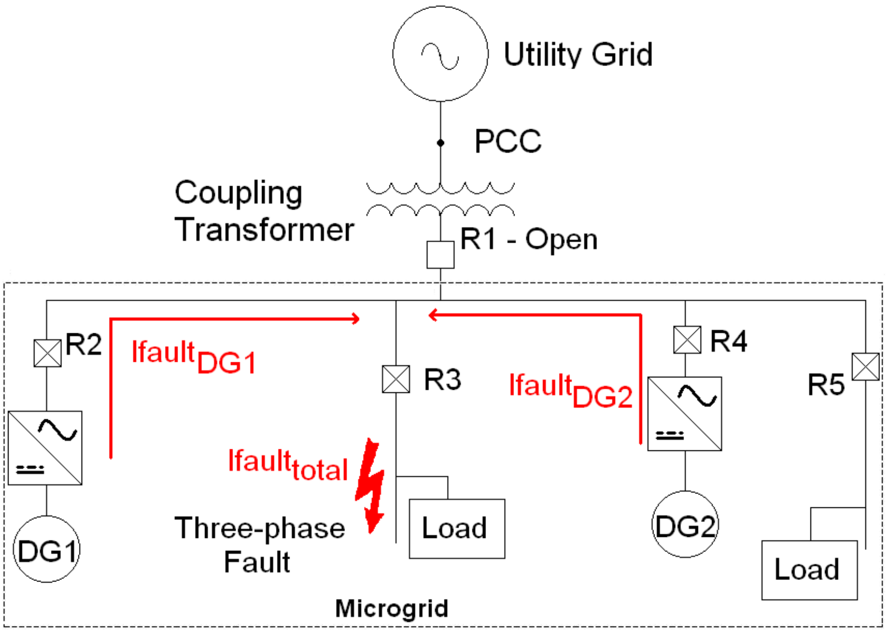

Figure 3.2. Islanded Mode – Internal Three-phase Fault

Using the lower of the two fault currents as the relay operating current may seem like a good idea in the beginning. However, this is not necessarily safe or reliable and may cause unnecessary trippings in larger systems. For example, a microgrid with a different topology is illustrated in Figure 3.3. In this grid connected microgrid, if the tripping current of the relay R2 is set very low then it will trip under normal operating conditions. Alternatively, a small oscillation in the system will trigger R2 to open. This concept is referred as nuisance tripping [14]. These erroneous trippings cause unwanted islanded sections in the microgrid and they may cause power interruption in some parts of the network while there is no fault in the system. Depending on the complexity and size of the microgrid, if the necessary precautions have not been taken, nuisance tripping might become a frequent occurrence. This makes operation impossible and reliability of the network will be put to question. Consequently, both network operators and consumers would like to eliminate nuisance tripping by setting correct operating conditions on the relays.

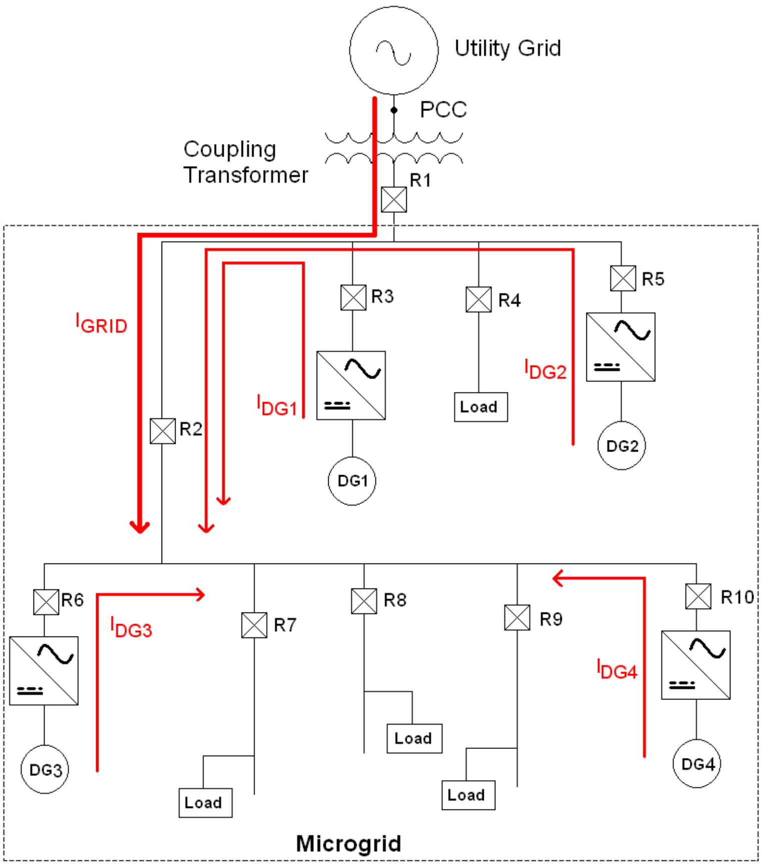

Figure 3.3. Nuisance Tripping

In conventional power networks, the fault current contributions of large generators are much larger than normal operating currents. Therefore, there is a huge gap between the normal operating currents flowing in the network and the trigger currents set for relays to interrupt fault currents. However, IIDGs do not have very large fault current contributions [14, 15, 153, 154]. For this reason, the trigger current settings of relays are relatively closer to normal operating currents flowing in the network. This is inevitable for proper operation in networks with DG penetration. At the same time, it makes nuisance tripping more probable since the operation gap between trigger currents and normal operating currents is much smaller.

Selectivity is another vital concept in protection systems. It means if the downstream circuit breaker (CB) fails to interrupt, then the upstream CB with larger capacity should operate and isolate the fault. It is intended to isolate the fault with the nearest relay so that the rest of the system will not be affected. For better understanding consider the case shown in Figure 3.4. The fault occurring just below R8 draws fault current from all corners of the network. Proper selective operation requires that that the relay R8 operates to single out the fault and the rest of the network remains unchanged.

However, if R2 has not been properly set, then the large fault current coming downstream may cause R2 to operate. In this case, the whole lower bus will be isolated from the system instead of the faulty 8th bus. Similar to the case with nuisance tripping explained above, this will cause undesirable islanded sections in the power network. This may cause convenience problems for the consumers, i.e. power might be interrupted at the healthy sections of the microgrid, as well as protection issues where unexpected topologies may emerge in the microgrid and the protection system may become completely useless. Furthermore, the desirable protection measure is the disconnection of R8 which will completely disconnect the fault from the rest of the microgrid. If R2 is used to isolate the fault, the fault is not completely isolated as there are DG3 and DG4 present in the lower bus which can still provide fault current. This shall create a serious safety infringement.

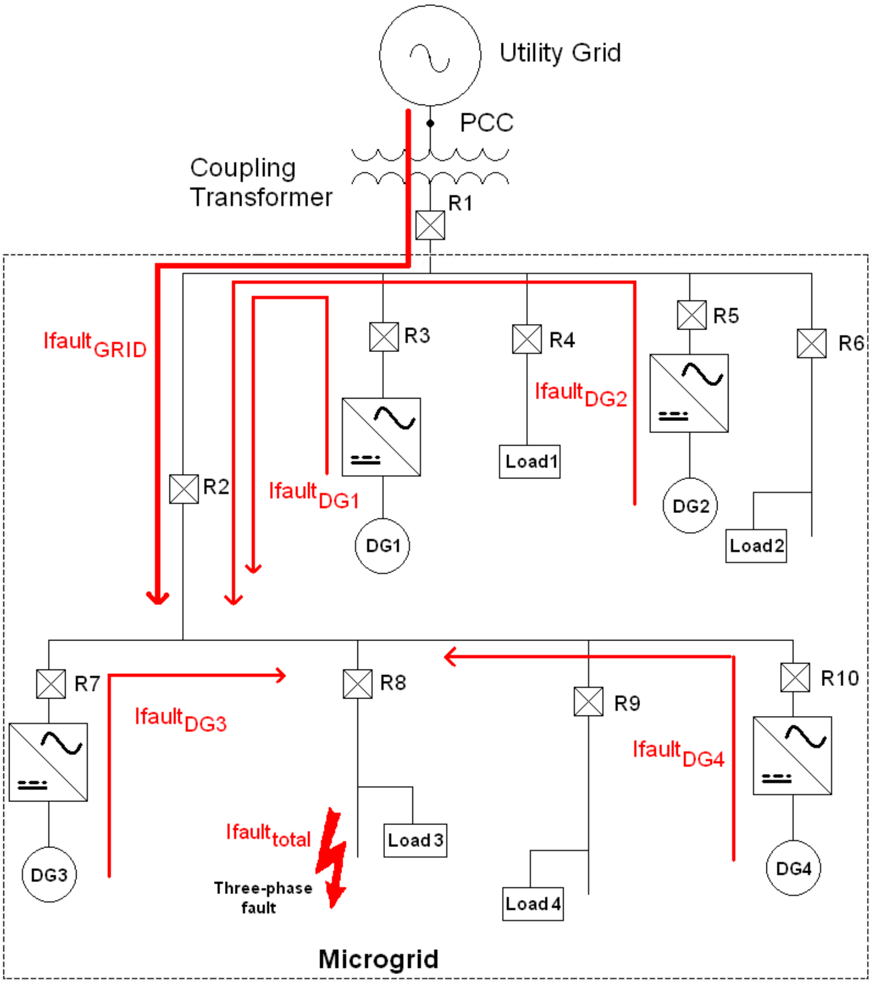

Figure 3.4. Selectivity Issue

Therefore, it is required that not only the current levels but also the time constants of the relays should be controlled dynamically. That is to say, merely changing the operating current levels of R2 or R8 does not warrant proper protection. Also, operation of some relays, which are upstream, may be delayed so that other relays may isolate the fault according to selectivity principles. For the case given above, the fault current flowing might be larger than the triggering currents of R2 and R8. However, with proper time delay operation R2 shall be delayed to see whether R8 can isolate the fault. Should the allocated delay time expire and R8 fail in interrupting the fault current for any reason, e.g. malfunction or insufficient capacity, then R2 shall operate to isolate the fault so that no further damage is caused in the microgrid.

This delay is limited by a number of discriminating time steps as the maximum time allowed before a fault must be cleared, i.e. $t_{operation}$, is preferred to be less than a certain value to prevent microgrid from becoming unstable [73].

Selectivity requires directional operation of relays. Figure 3.5 shows a case where an external fault occurs in a microgrid-power grid connection. In contrast to the case given above in Figure 3.4, the fault currents flow out of the microgrid and the direction of fault currents are different. The amplitude of the currents flowing through some relays, such as R2, is completely different. This shows that the same microgrid topology with same set of grid components requires non-identical operating parameters for faults inside the microgrid and outside of it. The forward and reverse trigger currents of the relays shall be different and assigned accordingly. The proper selective operation in this case shall necessitate R1, coupling relay, to operate first to isolate the fault and disconnect the microgrid from the faulty grid.

Special attention shall be paid to the difference between forward and reverse currents of R1. Forward trigger current is $I_{faultGRID}$ which is a very large value whereas reverse trigger current is a combination of DG fault current contributions which is known to be much less. Protective relays require to be able operate at these different fault current levels. Should there be a problem with the disconnection of R1, then the proper selective operation triggers R2, R3 and R5 to disconnect from the grid to prevent any possible damage on the generators. As seen, selective order is almost reversed in this case. Further precaution can be taken by disconnection loads for protection against oscillations and transient currents.

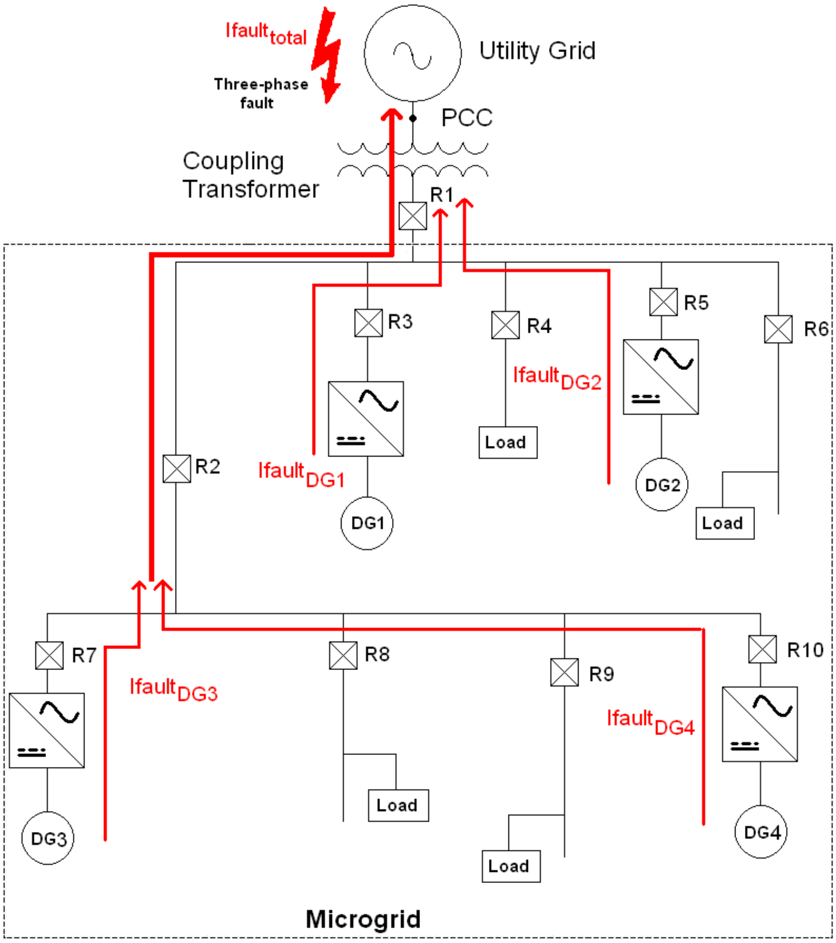

Figure 3.5. Reverse Selectivity for Faults outside the Microgrid

In short, microgrids are very beneficial for the wide-spread use of DGs and simpler management of interconnected systems. However, this unprecedented network structure brings along some less familiar protection issues along with it. Some of these issues have been explained above due to their importance in the development of the conceptual design. In summary, this section has demonstrated that;

a. The connection and disconnection of DGs alter the fault levels in the microgrid,

b. In a microgrid, the fault levels in grid-connected and islanded modes would be different,

c. Nuisance tripping could occur if islanded mode fault levels are taken as the reference,

d. Selectivity is critical and needs to be coordinated for proper fault current protection.

All these demonstrate that for proper protection of microgrids, an intelligent control system is required that using various communication channels and infrastructure continuously monitors the microgrid and updates the protection settings in response to changes occurring. The protection system presented in Section (3.3) has been developed to address these new issues of new generation microgrids.

3.3. Microgrid Protection System with Central Protection Unit and Extensive Communication

As it is discussed in detail, the dynamic structure of microgrids and their versatile operation conditions necessitate the development of alternative protection strategies. Figure 3.6 illustrates the microgrid protection system developed in this research to tackle protection issues encountered in microgrids.

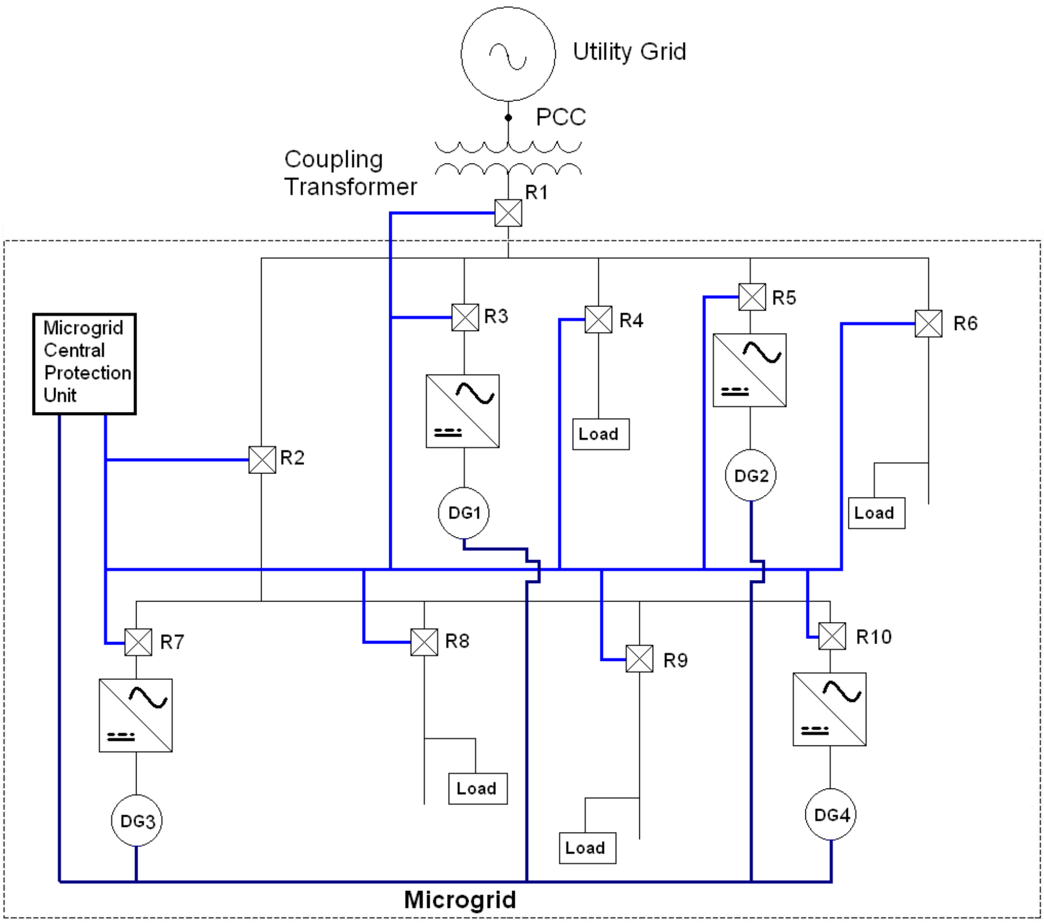

Figure 3.6. Topology of the Developed Microgrid Protection System

In this developed system, the Microgrid Central Protection Unit (MCPU) communicates with every single relay and DG in the microgrid on interruption basis. The communication with relays is necessary to update the triggering currents of the relays and to detect the direction of fault currents and thus isolate the fault properly. Furthermore, time delays required for proper selective operation of relays is ensured through communication lines. On the other hand, the MCPU communicates with DGs to record their status as ON/OFF, their rated currents $I_{ratedDGx}$ and their fault current contributions $I_{faultDGx}$. As it will be discussed, these parameters are essential for safe and reliable operation of the developed protection system.

Use of MCPU is very advantageous for protection of microgrids. The changing nature of microgrids and the variety of microgrid devices require that the microgrid protection is capable of monitoring and following these changes. The ability to communicate with DGs, loads and relays gives MCPU the possibility to be aware of new deployments, connection changes and changes in operating conditions of microgrid components. It is very difficult to handle all these events with a decentralized protection approach. Because this would require pre-estimation of all cases that may occur in the microgrid. Moreover, a new deployment of equipment or a new installation of transmission/distribution lines would render previous protection approach obsolete. Therefore, the use of MCPU in the proposed protection scheme is necessary to be able to operate microgrids under these changing conditions.

In other words, MCPU can be implemented as a real-time protection controller. Other protection approaches require a list of all cases that may occur inside a microgrid in the form a look-up table or in a database. As explained above, microgrids are not predictable as conventional, passive networks. The connection of DGs increase the amount of players, change the power flow directions, fault current contributions, fault levels for proper protection etc. Whenever a DG is turned on, all of these parameters are changed and the protection system needs to be updated in real-time. Making it even more difficult, new deployments in a microgrid change all of the predetermined cases. Consequently, a non-real time protection approach would have serious difficulties in following these developments and in adjusting the protection system accordingly. Being a real-time protection controller gives a solid upper hand to the proposed scheme.

As it will be explained in Chapter 5 and Chapter 8, although the proposed protection system requires communication between MCPU and microgrid components, continuous communication is not required and the decisions are made locally. This effectively reduces the dependence on communication and increases the reliability of the proposed system. Another benefit of making decisions locally is negating the effect of communication delays over the communication lines. The proposed system requires communication to update the protection parameters of relays following a change occurring in the microgrid. When a fault occurs, relays operate individually depending on the last operating condition. The amount of data sent and the communication delay experienced over the communication lines are not crucial for the clearance of the fault. This is another benefit of the proposed protection system with MCPU.

The data map of the MCPU is shown in Table 3.1. Information on each component is stored with the relevant control variables. The very first variable of the central unit is the operating condition of the microgrid. Once the microgrid is islanded or re-connected to the grid, the status of the relay R1 is handled as an interrupt by the central controller algorithm. New operating fault currents of relays will be calculated by considering the fault contribution of the grid, i.e. $I_{faultGRID}$ and updated. The status of the microgrid is stored in Operating Mode bit as `1` for Grid-connected operation and as `0` for islanded or stand-alone operation.

TABLE 3.1. DATA MAPS IN THE CENTRAL PROTECTION UNIT

	Grid-Connected	Islanded	
Operating Mode	1	0	
Grid Fault Contribution	$I_{faultGRID}$		
Relays	Operating Fault Current	Fault Detection (1 – Y, 0 – N)	Time delay for Selectivity
R1	I_{R1}	0	t_1
R2	I_{R2}	0	t_2
R3	I_{R3}	0	t_3
…			
DGs	I_{rated}	$I_{faultDGx}$	Status (1-ON, 0-OFF)
DG1	I_{DG1}	$I_{faultDG1}$	1
DG2	I_{DG2}	$I_{faultDG2}$	1
DG3	I_{DG3}	$I_{faultDG3}$	0
DG4	I_{DG4}	$I_{faultDG4}$	1

DGs will be monitored and two different current values are stored. One of these is the rated current value of the DG, I_{rated}, whereas the second one is the calculated fault current contribution of that particular DG, i.e. $I_{faultDG}$. The fault current contribution of DGs is calculated from its rated current value. A third parameter is required to track the connection of DG with the microgrid. Status variable is introduced for this purpose and determines whether a DG will contribute to the fault current in case of a fault in the system.

In Table 3.1, the status of DG3 shows that it is not in operation. This may be due to maintenance, the intermittent nature of RE resources (no sun or wind) or the excess local generation. In case the local consumption increases and DG3 is put back into operation, it immediately sends an interruption signal to the MCPU. MCPU is informed that a new generator with separate fault current contribution has been connected to the network and thus, needs to be taken into account. The new fault current contribution $I_{faultDG3}$ is updated in the relay operating currents data. Similarly, if DG2 is shut down for a certain reason, it then reports to the central unit that it is no-longer in operation and will not contribute to any fault in the network. Its status bit will then be changed to 0 and new fault current calculations will be performed without $I_{faultDG2}$. In this fashion, individual contributions of DGs are handled and the aggregate affect thereof is reflected on the relay settings to adjust them for the changing conditions of the microgrid.

Three parameters are used for relays in the MCPU. `$I_{relay}$` is the operating current of the relay which is used to program the relays, `fault detection bit` shows the fault detection status of the relay and `time delay for selectivity` indicates the time delays assigned to each particular relay for proper selective operation.

For a particular relay, the operating fault current (i.e. the current level that causes the relay to trip) is calculated as shown in (3.1).

$$I_{relay} = \left(I_{faultGRID} \times OperatingMode\right) + \sum_{i=1}^{m} (k_i \times I_{faultDGi} \times Status_{DGi}) \quad (3.1)$$

where m is the total number of DGs in the microgrid,

k_i is the impact factor of i_{th} distributed generator on the fault current of the relay,

$I_{faultGRID}$, $I_{faultDGi}$ and $Status_{DGi}$ are as described above.

If the microgrid is operating in islanded mode, then the grid’s fault contribution will be multiplied with the ‘Operating Mode=0’ bit which will be equal to 0. Likewise, the fault contribution of a DG which is not in operation will be annulled by its status `$Status_{DGi}$` bit.

In small microgrids, it may be assumed that the distances between components are small and the fault contribution of a certain distributed generator will be the same for all parts of the microgrid. In this case, the equation may be simplified by taking k = 1, i.e. it is assumed that the fault current contribution of any particular DG is constant for all relays in the network. In larger or more complex networks this may not be the case and a combination of various fault current contributions along with their impact coefficients might be required to be taken into account. This phenomenon is studied in detail in Chapter 5.

Determination of a distributed generator's fault contribution can be performed in various ways. It can be determined by means of simulation studies which require the modeling of the microgrid. However, an easier approach might be adopted on the grounds that most of the DGs need PE interface for grid connection. It is well known that PE interfaces do not supply fault currents as rotating machines do. Their contribution can then be approximated to $I_{faultDG}=1.2 * I_{ratedDG}$ [78, 80, 153]. Should this approach be implemented, new DG deployments can be made without making fundamental changes in the protection system. They can be treated as plug-and-play devices once their rated currents and fault contributions are reported to the MCPU. MCPU can track their status bit and perform calculations according to the reported fault current contribution. Hence, the communication between a PE interfaced DG and the MCPU could be limited to only status updates.

The MCPU uses an interrupt based algorithm shown in Figure 3.7. Once a new connection or disconnection occurs in the network, an interrupt is received by the MCPU and new fault currents are calculated based on the current situation of the network. Then, new operating conditions are updated in relays for adaptive protection. It is worthy to note that once the MCPU performs these tasks and re-programs the operating conditions of the relays, they operate independently to open the connections through CBs without the need for further communication. Once the current flowing over the relay exceeds the latest operating current received from MCPU, the relay opens the connection with CB and sends a signal back to MCPU in order to report the fault and set the fault detection bit.

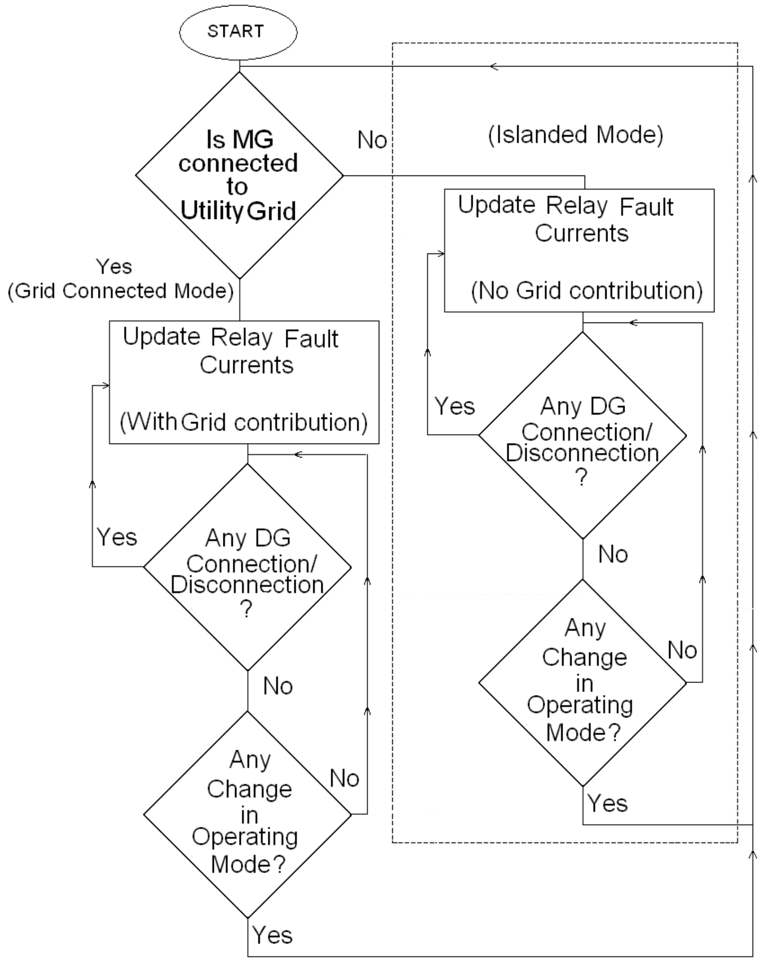

Figure 3.7. Interrupt-based Protection Algorithm

Once there is a fault in the system, the relays on the fault path shall experience the fault current. Each relay shall wait for its own time delay to expire after the detection of the fault. These time delays are set to ensure proper selectivity in the system and stored in MCPU as well as in the relays. Obviously central relays such as R1 and R2 have larger time delays than those of located in branches such as R4 and R8. The system shown in Figure 3.6 does not require rearrangement of time delays for different operating conditions due to the structure of the microgrid. In a more complex system, this might be very well required. In this case, with each interrupt signal MCPU does not only calculate the operating currents of the relays but also determines the selectivity hierarchy and calculates new time delay settings required. Then, these two parameters are updated in the relays. New I_{relay} value ensures that relays detect the fault currents accurately while new time delay setting t_{relay} ensures that proper selectivity procedures are followed in case of a fault. Selectivity hierarchy detection is discussed in detail in Chapter 4 while time delay calculations are explained in Chapter 4 as well as Chapter 5.

3.4. Power Networks with Fault Current Limiters(FCL)

As mentioned earlier, DGs with inverter interface do not supply as much fault currents as the rotating machines. This contribution is not enough to operate CBs or fuses. Conversely, being composed of solid state devices, inverters cannot operate under fault conditions for long time. Disconnection of inverters under fault conditions is not desirable to sustain a certain level of power quality in the microgrid during and just after the fault conditions [157]. Considering the increasing popularity of DGs, it is certain that large deployments will take place in the near future. In this case, the fault current build up might reach a value higher than the ratings of the protection devices. The existing switchgear has certain capacities, and the extra fault current contributions of the newly added DGs might hinder the overall protection scheme. Since changing every single protection device in a microgrid/network will be very expensive and unfeasible, again, current limitation might be necessary [158].

An ideal FCL should have some basic properties for proper operation [159]. A FCL is required to have zero impedance under normal operation and large impedance under fault conditions. It should detect the fault current rapidly and initiate limiting action before fault current builds up to its prospective value. It should be able to withstand the fault current until fault is detected and cleared in order to sustain a certain level of power quality. It should operate in a fail safe manner; have a long maintenance interval and life time so that the investment can be justified. For easy and wide-spread installation, it should be compact and cost-effective. It is also anticipated that in the future FCLs might be coupled with CBs or DGs and sold as an integral part of the overall equipment [159].

Different types of FCL embodiments exist in the literature which, include solid state FCL topologies, superconducting fault current limiters (SCFCL) and modified inverter control loops with FCL component. Figure 3.8 shows the solid state FCL topology proposed in [158]. It is comprised of a mechanical series switch, a current limiting inductor, a voltage limiting element and a fast solid-state switch pair. The Gate Turn Off (GTO) thyristors are connected in parallel with the current limiting impedance. This configuration is accompanied with a control system that monitors the system and upon detecting a fault sends turn-off signal to GTO thyristors. Now the connection is realized through current limiting impedance and the buildup of the fault current is limited. The voltage limiting element, i.e. the MOV, is in charge of preventing the overvoltage which may arise upon sudden current interruption.

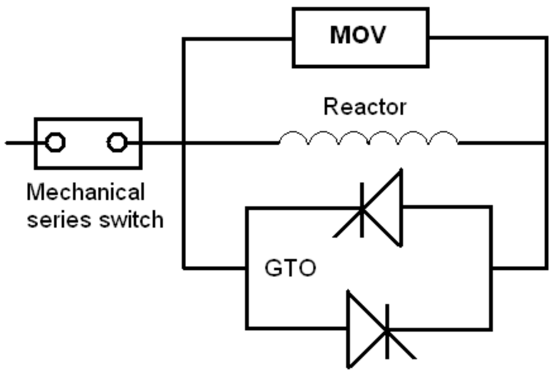

Figure 3.8. Solid state FCL topology in [158].

Figures 3.9 and 3.10 show the inverter interface which connects DG to the grid and the additional loop employed in inverter control to realize FCL in [157]. It is important to note that these topologies require output inductors to control the output current. The control loop shown in Figure 3.9 monitors the output voltage and when a fault is detected it arranges inverter trigger signals so that inductor currents are set to a predetermined maximum value (I_{max}).

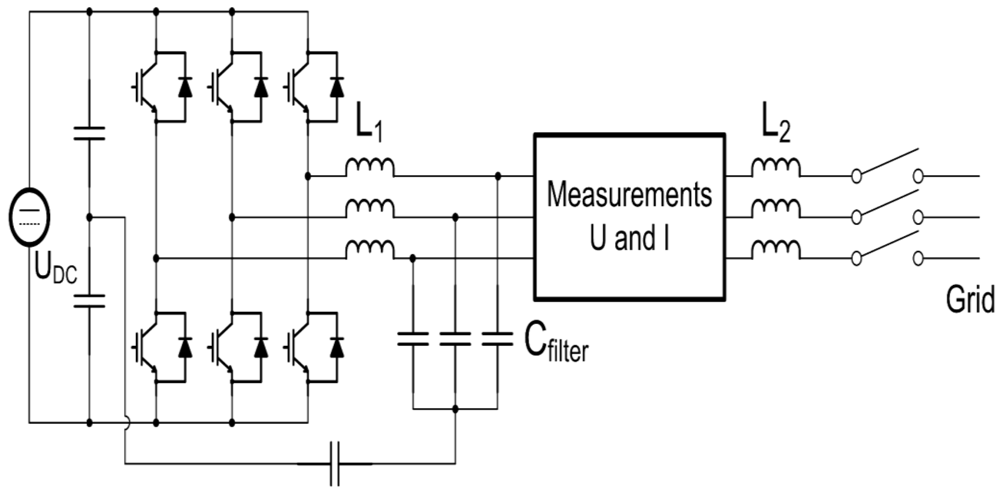

Figure 3.9. The inverter interface used in [157].

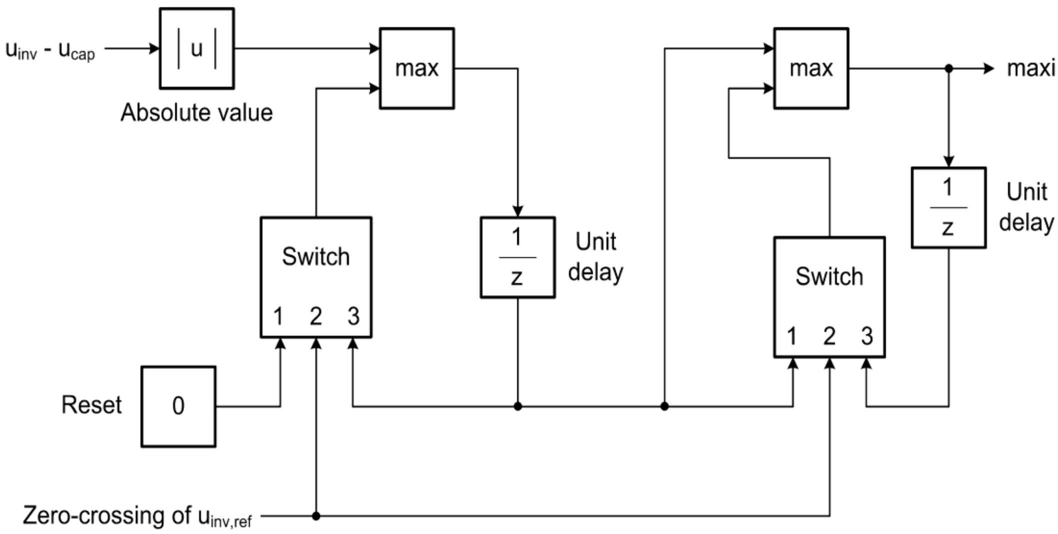

Figure 3.10. Fault current limitation algorithm for the topology in Figure 3.9 [157].

Current limitation in inverter based FCLs can be achieved in three different ways [160]. Firstly, instantaneous limits in the natural reference frame can be forced which results in clipping and distorted waveforms. Alternatively, instantaneous limits in the synchronously rotating reference frame might be forced. This freezes inductor current reference direct and quadrature components when the inductor current exceeds a threshold value. Thirdly, once the inductor current exceeds a threshold a constant predetermined inductor fault current is supplied as shown in Figure 3.11 [160].

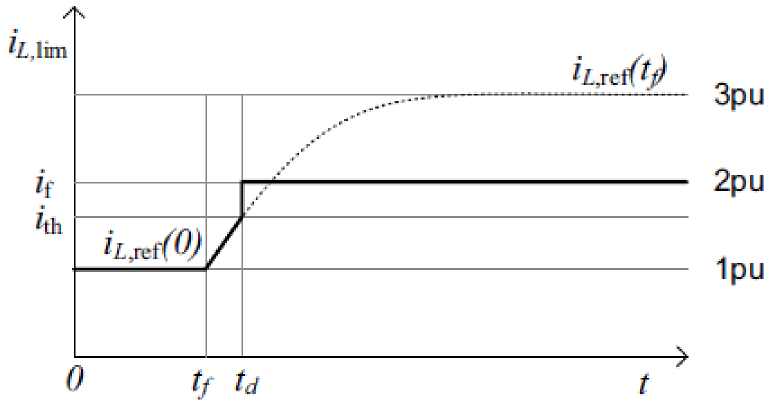

Figure 3.11. Fault current limitation curves for inverter topology [160].

Below the threshold value, there is no control on inductor current, i.e. inverter output current. Once the threshold current, i_{th}, is passed, a predetermined fault current value, i_f is observed at the output. This value is typically set to be twice as much the rated current. The dynamic performance of the FCL is characterized by the difference of two time values. t_f represents the time of fault while t_d represents the instance when the fault is detected by the FCL and the output current is fixed to predetermined i_f value.

3.5. Conceptual Design with Fault Current Limiter

The conceptual design can be adapted to accommodate DGs or networks with FCL connection. As a matter of fact, FCL connection is a special case of the system given above. Here, the exact fault current contribution of each DG is known and not calculated.

When FCLs are utilized, the data map in the MCPU can be updated as shown in Table 3.2. The only difference is with the DG parameters where $I_{faultDG}$ is directly recorded rather than being calculated with the help of k coefficient and the rated current, I_{rated}.

It is assumed that all DGs are interfaced with an inverter that has FCL ability which limits the DG output current to a predetermined $I_{faultDGx}$ value. Since fault currents are known exactly rather than calculated or approximated, the performance of the entire protection system will be more accurate and reliable.

The MCPU continuously monitors the statuses of all DGs in a synchronized manner by communicating with them using a Publish/Subscribe peer-to-peer messaging (similar to IEC 61850's GOOSE [161]) system. The MCPU therefore receives status report from all DGs and records their status as ON/OFF. If a DG disconnects at any time for example, the new fault current levels are re-calculated by considering the fault current contribution ($I_{faultDGx}$) of that particular DG. In this way, the system is ready for any fault condition before any fault, actually, occurs. The operation of the system through communication and calculation is identical with the generic system given above.

TABLE 3.2. DATA MAPS IN THE CENTRAL PROTECTION UNIT

	Grid-Connected	Islanded	
Operating Mode	1	0	
Grid Fault Contribution	$I_{faultGRID}$		
Relays	Operating Fault Current	Fault Detection (1 – Y, 0 – N)	Time delay for Selectivity
R1	I_{R1}	0	t_1
R2	I_{R2}	0	t_2
R3	I_{R3}	0	t_3
…			
DGs	$I_{faultDGx}$	Status (1-ON, 0-OFF)	
DG1	$I_{faultDG1}$	1	
DG2	$I_{faultDG2}$	1	
DG3	$I_{faultDG3}$	0	

Alternatively, the use of FCLs makes it possible to simplify this system further. Since fault contribution of each DG is constant, it may be reported to the MCPU before DG's deployment and the communication line for that might be omitted. Furthermore, the status of a DG can be monitored through the status of its respective relay (e.g. R3 for DG1, R5 for DG2 etc.). For example, if R3 is connected then it means DG1 is in operation and in case of a fault $I_{faultDG1}$ should be taken into account and if R3 is open it implies DG1 is OFF and no fault current is in question. In this case, relay's status is sufficient and the communication lines from the MCPU to DGs can be eliminated altogether. In such a case, fault current contributions of DGs will be stored in the MCPU before deployment and updated in rare cases of modification. In this way, not only the fault currents of DGs will be known precisely but also the burden of installing expensive and complex communication lines to each DG, the dark and light blue lines in Figure 3.6, can be eliminated. This simplification has effects on the MCPU, as the area marked with dashed frames will be eliminated if DG communication is omitted. Thus, the data map in MCPU will include relay parameters and static DG parameters which only require local storage. Worthy to note, though, this simplification does not include intermittent DGs such as Wind turbines or PVs. These DGs may be connected to the grid but may not generate any power due to intermittent nature of their sources, i.e. the wind and the sun. On the other hand, diesel generators, fuel cells and other DGs that have constant power output can be incorporated to this simplified protection scheme.

Under these new conditions, for a particular relay, the operating fault current (the current level that causes the relay to trip) is calculated as in (3.2):

$$I_{relay} = \left(I_{faultGRID} \times OperatingMode\right) + \sum_{i=1}^{m} \left(I_{faultDGi} \times Status_{DGi}\right) \quad (3.2)$$

where m is the total number of DGs in the microgrid,

$I_{faultGRID}$, $I_{faultDGi}$ and $Status_{DGi}$ are as described above.

The MCPU uses a simple algorithm shown in Figure 3.12. The status of R1 has been given a special consideration since it imposes the operating mode and grid fault contribution.

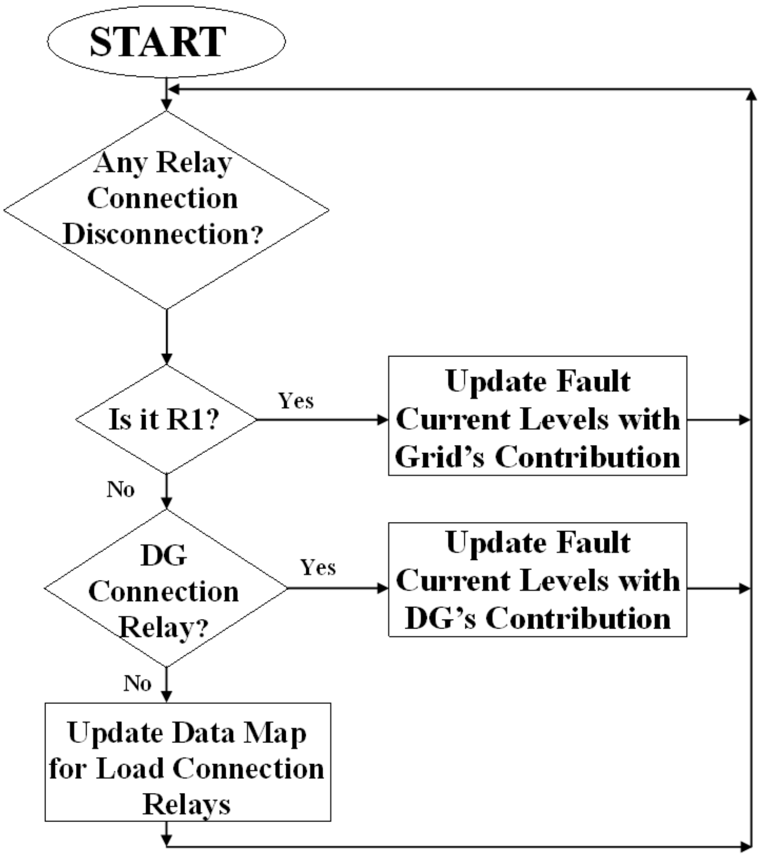

Figure 3.12. Protection Algorithm employed in MCPU for FCLs.

This flow chart is similar to the one given in Figure 3.7 with a fundamental difference. Unlike the algorithm in Figure 3.7, this flow chart only follows the connections of relays. This is thanks to the unique feature of FCL interfaced DGs where the whole monitoring can be realized over relays. In this manner, management and communication processes have been simplified. Here, the operating condition of the microgrid is checked over R1 and the fault contribution of the grid is taken into account. Then, the relays for DG connections are checked to update their fault current contributions. Finally, the new operating current conditions are updated in the relays. In case of a fault in the network, relays operate independently and follow selective protection procedures, as discussed above.

3.6. Conclusion

The studies on microgrids will aid in the development of secure, reliable, and stable real-life networks with greater penetrations of RE sources. This chapter has presented a new protection scheme for microgrids with high DG penetration. An MCPU is utilized to monitor all entities inside the microgrid and new operating conditions are calculated for every change experienced in the microgrid. The developed system considers two events as crucial changes: microgrid's connection/disconnection (i.e. islanding) from the grid and a DG's connection/disconnection from the microgrid. The MCPU is used to perform fault current contribution calculations by considering the rated currents and fault contribution coefficients \`k\` of DGs. After being updated with these operating conditions, relay make decisions locally depending on the local measurements. This makes the system more robust and reliable since continuous communication is not needed in the decision making process.

The system is very versatile and can be developed to suit more specific purposes or meet different purposes. It can be extended to suit much larger and more complex microgrids. Furthermore, it can be adapted to accommodate different grid components such as FCLs. Limited fault current helps anticipate fault conditions and protection system is programmed accordingly. Communication lines and MCPU can be simplified thanks to the constant and predetermined fault current contribution of DGs. Since the exact fault current contribution is known, this protection system is more reliable than the systems which predict or approximate fault conditions. DGs with FCL can be deployed merely by creating an additional record in MCPU. Relative fault current and the relay which is responsible for its connection are recorded.

Specifically, the system is designed to be generic and may serve for plug-and-play purposes. Special attention must be paid to the communication protocol utilized for the communication of data within the system and a standard packet-type for the relay and distributed generator communication can be developed. If each DG unit is equipped with a simple communication device to report its status, rated current and fault contribution, then a universal concept of DG connection can be achieved. This may prove useful for the implementation of plug and play concept in microgrids.

This flexible yet strong conceptual design has been reinforced with various aspects of this research. The automated microgrid structure detection and its impact on selectivity will be discussed in Chapter 4. The specific details of the relay parameter assignments, i.e. fault current and time delay, will be discussed in Chapter 5. Chapter 6 presents the standard communication framework developed in accordance with IEC 61850 to universalize this conceptual design. Chapter 7 provides the results of the simulation works undertaken to investigate behavior of microgrids under different conditions. The conceptual design presented in this chapter has been developed based on these behaviors. Finally, Chapter 8 extends this design further, and shows how this system can be used to support other protection systems where they are insufficient. The eventual system has the ability to address varying challenges of new generation microgrids.

Chapter 4

Object Oriented Modeling of Microgrids and Automated Structure Detection

Publications pertaining to this chapter:

1) ***Taha Selim Ustun, Cagil Ozansoy, Aladin Zayegh, "Implementation of Dijkstra's Algorithm in a Dynamic Microgrid for Relay Hierarchy Detection," in the Proceedings of Smart Grid Communications (SmartGridComm), 2011 IEEE International Conference on , vol., no., pp.481-486, 17-20 Oct. 2011.***

2) ***Taha Selim Ustun, Cagil Ozansoy, Aladin Zayegh, "Using Object Oriented Data Structures for Dynamic Communication and Control in Electrical Networks," in the Proceedings of the Twenty-fifth Canadian Conference on Electrical and Computer Engineering (CCECE), Canada, 29April – 2 May 2012.***

4.1. Introduction

Microgrids have very dynamic structures and automated control and protection of microgrids would only be possible when the microgrid structure is continuously monitored. This chapter details the ideas and concepts developed to enable such a process. Object Oriented (OO) models have first been developed that allow information on various elements of a microgrid systems (power system networks in general) to be defined. The use of the graph theory concept for modeling the structure of the microgrid is then discussed and finally the use of a famous Computer Science algorithm for relay hierarchy detection is explained.

It is known that microgrids have dynamic structures which change very often. The following may be counted among the reasons for the changes in the microgrid structure [146]:

- New DG or load deployments
- Islanding of the system
- Fault conditions
- Reconfiguration of the structure for reasons such as maintenance

This dynamic behavior of microgrids is a major protection challenge since the conventional selectivity methods assume a fixed network structure and a predetermined relay hierarchy [108]. Whenever restructuring occurs, the selective levels assigned prior to that become erroneous. For a proper operation, the selective levels of relays should follow the changing conditions of the network. Whenever a structure variation takes place in a microgrid, new relay hierarchy should be extracted and corresponding settings including time delays should be determined before updating these settings within the relays via communication lines [109, 110]. It is essential that this process is performed automatically so that the processing time is minimal and there is no interruption in power delivery. This requires an algorithm which will determine the current structure of the system and yield the relay hierarchy at all branches of the network.

There are some studies presented in the literature which emphasize on the importance of such an adaptive selective operation such as in [162] and [73]. However, the prior discusses the issue qualitatively without any technical details whereas the latter implements an algorithm which includes a look-up table. The work presented in [162] touches upon the challenging nature of relay hierarchy and selectivity concepts in microgrids. A communication-assisted selectivity approach is explained in concept. However, the technical details of this approach, its implementation in microgrids with different set of components are not discussed. On the other hand, the research presented in [73] provides a robust system for microgrid protection. However, it uses a look-up table which lists all the cases that may exist in the microgrid under consideration. This is a large set-back because it requires the knowledge of all possible microgrid configurations beforehand, plus human input for the preparation of this look-up table and finally it requires that the microgrid should always match one of the predetermined structures. Moreover, any kind of a new deployment, which is very common to microgrids, requires that the whole selectivity table should be re-written.

In order to address all of the above-mentioned challenges, the developed protection system shall be equipped with an automated operation capability that determines the structure of the system and yields the relay hierarch. This chapter details the work carried out as part of this research to address this development need. Firstly, the novel representation of power networks with OO models is explained. Then, the challenging nature of microgrid structure variations is given. OO models have thereby been developed to handle the dynamic and changing nature of microgrids. Accordingly, a microgrid system is modeled based on graph theory where the components are represented as nodes. Later, Dijkstra's algorithm, which is famous for shortest-path calculation purposes, is run over the microgrid to determine the relay hierarchy at any point in time. In this manner, regardless of the dynamic changes occurring in the system, the hierarchy of the network components can be extracted. The implemented algorithm not only ensures proper selective operation under fault conditions but also facilitates the introduction of new connections and new devices to the system. Since the relay hierarchy is detected automatically, even with new connections, this algorithm serves for plug-and-play concepts in electrical networks.

4.2. Object Oriented (OO) Representation of Power Networks

As mentioned in the previous section, the varying structure of the microgrid requires a process which can represent information about the network in a computer environment and monitor the changes occurring therein. When the structure of the system is fully known to the central controller, the operation settings of protective devices, generators, loads and other auxiliaries can be calculated in the central microgrid controller and updated into relative devices [146].

When all the connected devices are recognized as nodes and their connection/disconnection is followed in the modeling system, then the microgrid can be defined in accordance with different methods such as the graph theory [163]. Thus some of the issues listed in literature on microgrid management and protection can be tackled with the well-known procedures of those methods [164] [165].

Over the years, international standards such as IEC 61850 have defined many OO data and communication models for power system networks especially for substations. However, these standards are continuously evolving with new additions and amendments. There is a significant need for a data model to represent the information with regards to the various node points such as bus bars along the distribution network. Such a data model would allow valuable information such as load profile or generation capacity connected to a particular point within the network to be communicated across to control equipment.

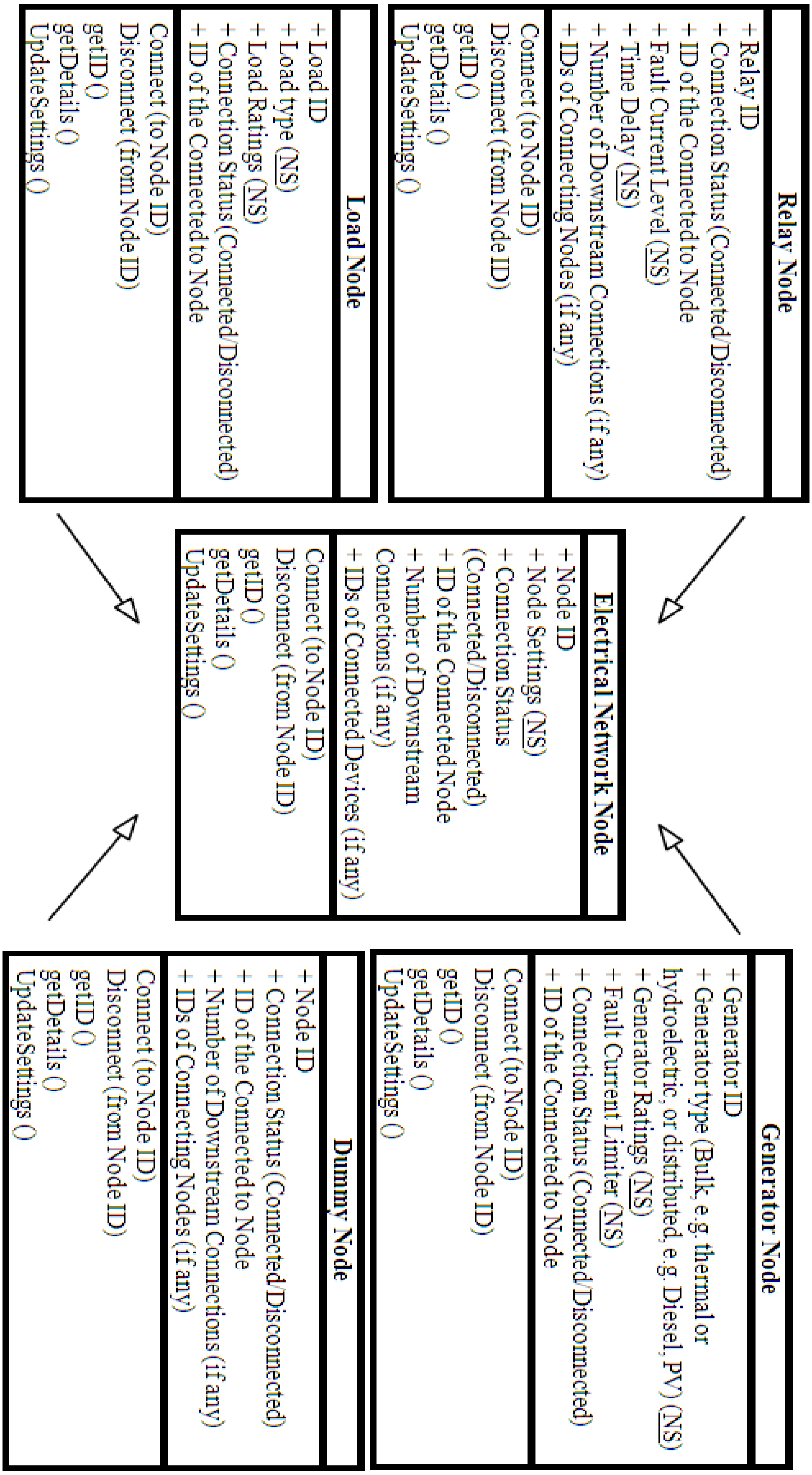

Figure 4.1. Electrical Network Node and 4 specific instances of the model

Therefore, the Electrical Network Node (ENN) model shown in Figure 4.1 has been developed following the IEC 61850 syntax to fill this gap. This node is defined by following OO Modeling rules and Unified Model Language (UML) representation [166]. The node includes some public data to represent its properties such as node ID, operating settings `node settings` which vary for different node classes and connection data such as the nodes which are connected the node under consideration, 'IDs of the connected nodes '. It would be possible to further develop the object class model as a Logical Node (LN) by following the IEC 61850 syntax. The detailed discussion of how the IEC 61850 standard plays a role in the developed communication-assisted microgrid protection system is given in Chapter 6.

The common data sets for different instances of the ENN are node IDs, the connection status of that particular node, ID of the upstream node to which the node is connected to as well as the number of downstream nodes which are connected the node under consideration and their IDs. The different specific instances of the ENN will have different node settings (NS) depending on the type of the node and the relevant characteristics. As shown in Figure 4.1, the general object class ENN has four different sub-classes which are: Relay Node, Load Node, Generator Node and Dummy Node.

These sub-classes could be modeled as Logical Nodes (LN) as per the IEC 61850 standard and various data models already exist in the standard to allow for this. These sub-classes are proposed in the most comprehensive manner so that the modeling shall be versatile and it shall be possible to model different network systems. Despite the fact that different node sub-classes have same data entry 'node settings', depending on the node type this abstraction has different sub-groups for detailed modeling. The different sub-groups of this abstraction are shown in Figure 4.2.

For instance, the relay node should have at least two attributes which represent the operation settings of the relay. The first sub-group of attributes represents the details of a time-inverse relay while the second sub-group of attributes is used to model instantaneous relays [88]. In similar fashion the generators are categorized under two main headings such as bulk generation and distributed generation. The former is required if the microgrid is connected to a larger generation system while the latter is a vital element for distributed generators such as diesel gen-sets, micro hydroelectric power plants (MHEPP) and other renewable energy resources.

The modeling of loads is kept very simple and only two different sub-groups have been proposed which differentiate between the rotating machine loads and resistive loads which are hard-to-control and lightweight loads, respectively.

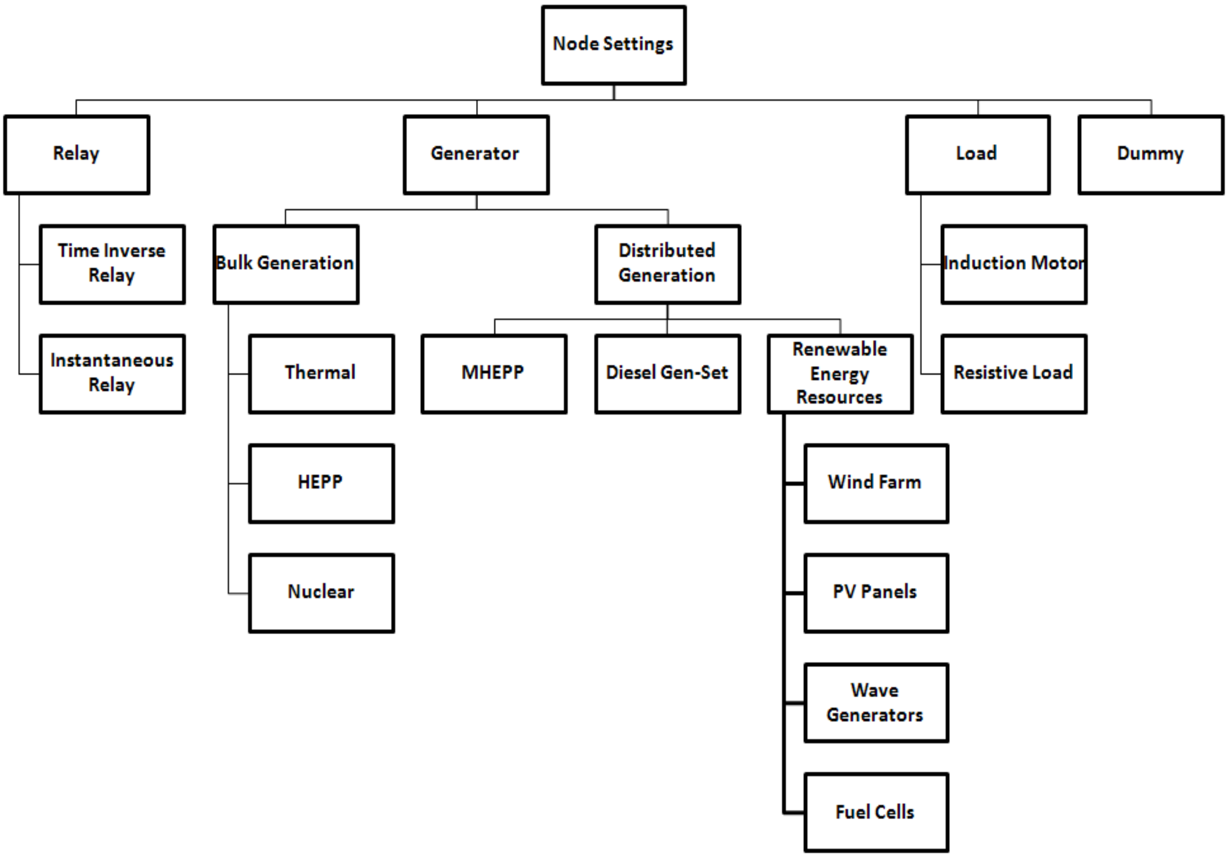

Figure 4.2. Abstraction of NS for different Node types handled by Update Settings Function

It is crucial to attain universal operation with these models where it shall be possible to model same type of equipment from different manufacturers with the same node. For this purpose, the detailed characteristics listed in node settings shall be acquired from an international standard, such as IEC 61850 which is bound to have a significant impact on how electric power systems are to be designed and built for many years to come [167].

Referring back to Figure 4.1, the ENN data model has five different services which are needed to:

1. Get connected to another node,
2. Get disconnected from an already-connected node,
3. Receive the ID of a particular node for identification purposes,
4. Acquire the settings of a particular node for management purposes,
5. Update the current settings of the node with the new operation points stipulated by the MCPU.

Among these nodes, the dummy node might be of particular interest. It, in fact, does not represent a specific device but a common coupling point where different connections meet. For example, the network shown in Figure 4.3 requires a dummy node to connect Circuit Breaker 2 (CB2) to CB3 and CB4. Even if microgrid gets islanded, i.e. CB2 opens, CB3 and CB4 will remain connected over the dummy node.

At any given instance, the new connection or disconnection of a device shall be represented by these OO models with abstracted node setting groups.

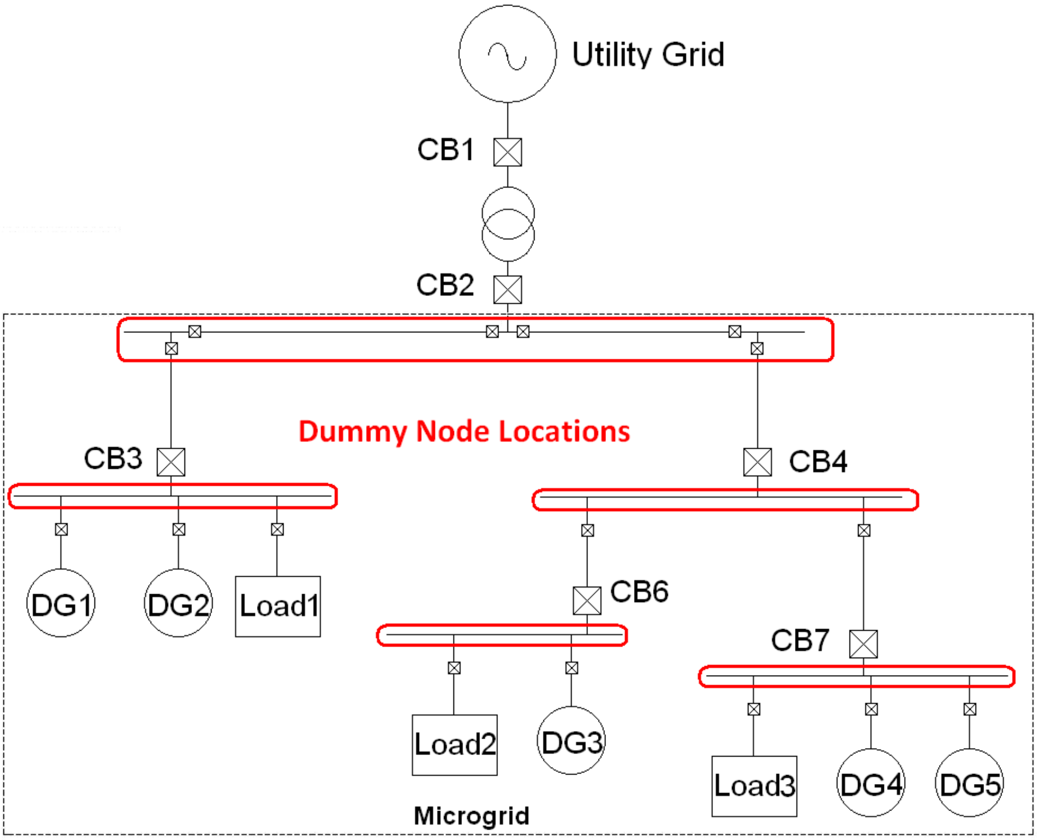

Figure 4.3. Bus bar Locations in a Sample Microgrid where Dummy Node is required

Consider the case shown in Figure 4.4 where a relay is connected at a node, and a relay, generator and load must connect downstream. When each one of these downstream devices requires connecting to *Relay X*, they will send a connection signal with *Connect (Relay X)* service. The variable holding the number of connections in *Relay X* and the array which holds the IDs of connected nodes will be updated. The network as well as the modeling in computer environment will be as shown in Figure 4.5.

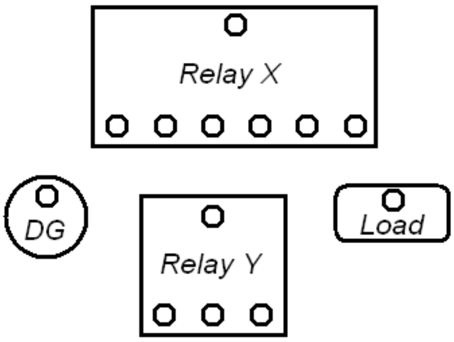

Figure 4.4. A section of a network with various nodes

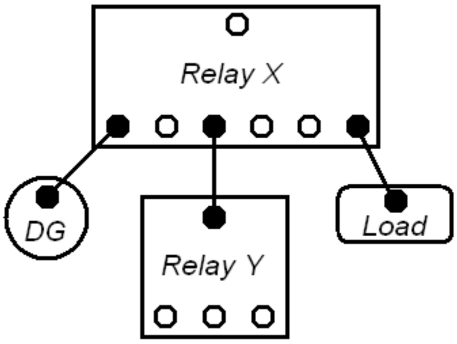

Figure 4.5. Topology After Connect (Relay X) Service

If the details of *Relay X* are retrieved with ***RelayX.getDetails()*** command, in addition to relay characteristics the returned data will be as shown in Table 4.1:

TABLE 4.1. DETAILS OF RELAY X

Data Attribute	***Value***
Number of connections	*3*
IDs of connected Devices	{DG, Relay Y, Load}

When the same service is called for the downstream nodes, for instance DG as in ***DG.getDetails()***, the retrieved data shall include two variables in addition to DG characteristic data. One of them is a Boolean operator, 'Connection Status', which is set to TRUE in this instance signifying that the DG is currently connected. The other attribute 'ID of the Connected to Node' is a pointer towards the upstream node to which DG is connected.

When a connected node requires to disconnecting, for instance Load node, it shall use the service ***Load.Disconnect (Relay X)***. The connection variables in Load will be changed as shown in Table 4.2:

TABLE 4.2. DETAILS OF LOAD

Data Attribute	***Value***
Connected	*False*
ID of the Connected to Node	*N/A*

While the related variables in Relay X will be updated as shown in Table 4.3:

TABLE 4.3. DETAILS OF RELAY X AFTER LOAD.DISCONNECT (RELAY X)

Data Attribute	***Value***
Number of connections	*2*
IDs of connected Devices	*{DG, Relay Y}*

Following this modeling procedure the changes occurring in the microgrid can be monitored instantaneously and the relevant power management, protection or other adjustments can be performed immediately. As it has been expressed before, dynamically following the changes occurring in the microgrids and extracting the resultant microgrid topology is extremely important. The next section elaborates upon this importance from microgrid protection perspective and reveals the approach developed for its achievement.

4.3. Relay Hierarchy and Selectivity Issues

Selectivity is a well-known protection concept which means isolating the fault with the nearest relay in an effort to minimize its effect on the rest of the system (grid) [168, 169]. This requires that in case of a fault, the relays should react according to a certain hierarchy. In conventional protection systems designed for passive networks, the relays which are downstream and closer to the fault point are required to operate first. However, if the fault current is very large and downstream relays are not capable of interrupting it, then other relays with larger capacities are expected to operate and isolate the fault.

That being said, implementation of selectivity is not that straightforward with the introduction of DGs. The very concepts of downstream and upstream relays are prone to change according to the status of the microgrid. The operating mode, i.e. grid-connected or islanded-mode, changing network structure with alternative paths and new deployments are some of the factors that would alter the selectivity parameters.

Consider the system shown in Figure 4.6. In this network, all branches have generation and load, and various alternative network structures can be formed through the combination of CB connections.

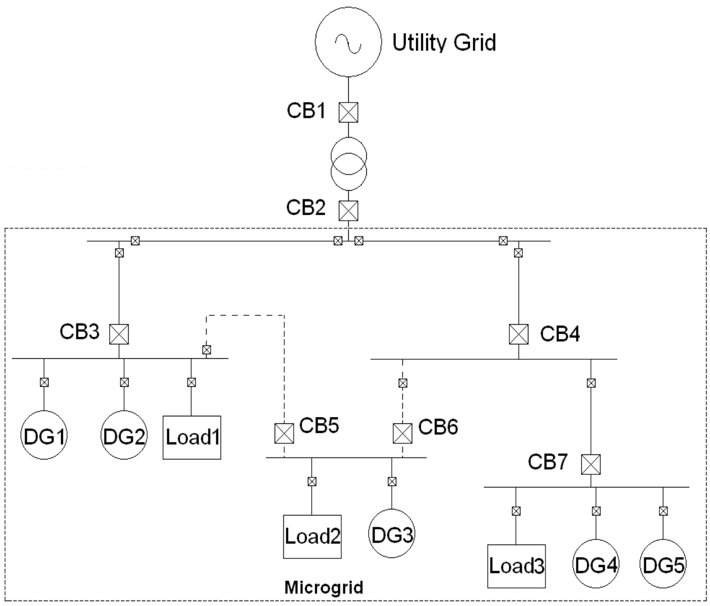

Figure 4.6. A sample microgrid

As first case, assume that the circuit breakers CB1, CB2, CB3, CB4, CB6 and CB7 are closed whereas CB5 remains open, as shown below in Figure 4.7. When a fault occurs at the terminals of Load 2, then the most downstream relay will be Load 2's own relay (represented by the little box) and selectivity implies that it should interrupt the connection. If Load 2's relay fails to achieve that in a predetermined time (delay), then the proper sequence for the selective operation should be CB6, CB4 and finally CB2. In similar fashion, should a fault occur at the terminals of Load 3, the proper selective operation requires the following sequence: Load 3's relay, CB7, CB4 and CB2.

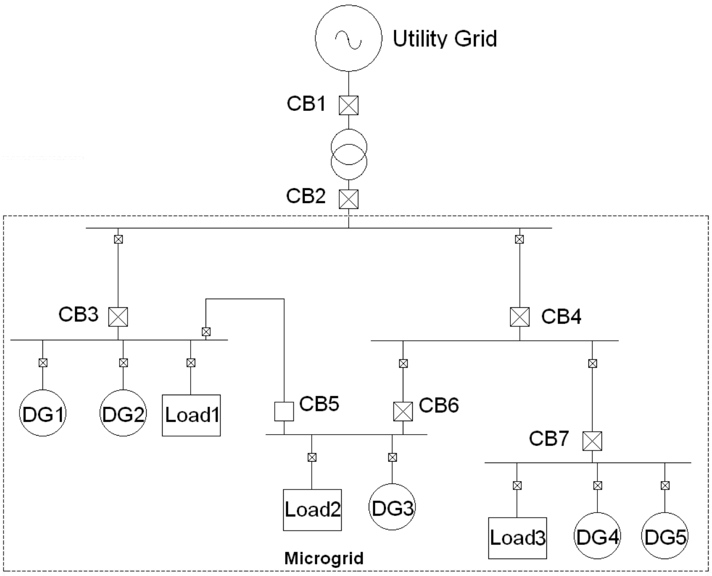

Figure 4.7. The network structure when CB5 is open and CB4 is closed (1st Case)

If CB4 is disconnected for any reason, for example maintenance or breakdown, in order to keep the integrity of the network, CB5 closes. The line between Load 1 and Load 2 (protected by CB5) has therefore been added to form a loop structure when necessary and protect the microgrid against contingencies and failures. When CB5 loses, the structure change from case 1 to case 2 is shown in Figure 4.8.

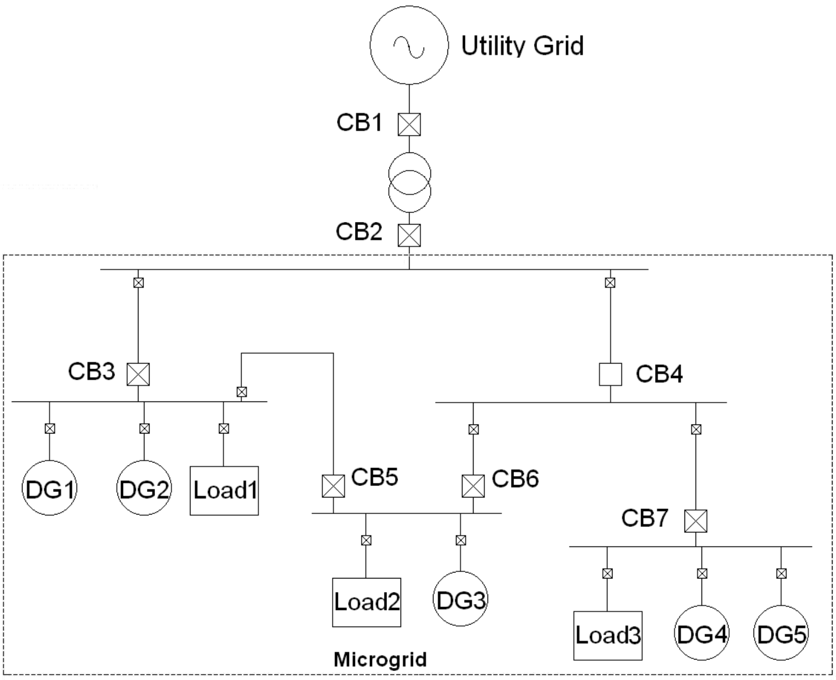

Figure 4.8.The Network structure when CB5 closes and CB4 opens (2nd Case)

As shown, now in Figure 4.8, there is only one branch for the power flow instead of two. For this new microgrid structure all selective levels, time steps and time delay calculations shall be repeated. Following the same examples should a fault occur at Load 2 or Load 3, the proper relay hierarchies are; Load2's relay, CB5, CB3, CB2 and Load 3's relay, CB6, CB5, CB3, CB2, respectively.

One exceptional case arises when a fault occurs at upper levels of the microgrid. In this case, fault should be isolated by the closest relay at the higher level and this requires the inversion of the hierarchy structure. For example, if a fault occurs outside the microgrid, i.e. in the utility grid, the microgrid should be isolated from the system by opening CB2. In this case, the interfacing relay CB2, which is at the top of the selectivity pyramid, is required to operate first. This can be managed by detecting the reverse flow of the fault current and assigning two different time delays to the relays, one for upstream faults and the other for downstream faults.

The above mentioned factors require that the selectivity hierarchy of the relays should be dynamic and updated frequently. An algorithm should be employed which determines the network structure whenever the status of a critical relay is changed. A critical relay refers to a relay the status of which changes the structure of the network. Following this definition relays of CB2, CB3, CB4, CB5 and CB6 are all critical relays whereas Load 2's relay, DG1's relay are non-critical relays.

After determining the microgrid structure and its relay hierarchy, suitable time delays can be appointed easily. Let t_{max} be the maximum time length allowed by the grid code before the fault is cleared in the system. This value is divided into the number of selective levels, *n*, in the relay hierarchy and the base time delay is found as in (4.1).

$$t_{base} = \frac{t_{\max}}{n} \tag{4.1}$$

The time delay for each relay is calculated by multiplying this base time delay with the selective level, *s*, of that particular relay. When calculated with (4.2), the relay at the highest level will be in n^{th} selective level and its time delay will be the largest possible time delay, i.e. t_{max}.

$$t_{relay} = \frac{t_{\max}}{n} \times S_{relay} \tag{4.2}$$

Alternatively, 2-pair selectivity approach can be assumed by the protection system where only two relays are paired up for back-up protection. Therefore, each relay is supposed to monitor its immediate downstream relay and clear the fault if the downstream CB fails. In this case the time delay of the relay can be selected from a large window bounded by the smallest possible time delay dictated by relay capabilities, i.e. t_{min}, and t_{max}.

$$t_{relay} \in [t_{min} , t_{max}] \tag{4.3}$$

The conceptual design depicted in Chapter 3 necessitates that in order to update the operating currents of the relays; some sort of communication of data is required. This will also help detect the direction of fault currents and thus isolate the fault properly. Worthy to note, the developed system is not dependent on any communication network and can work on a wide range of alternatives. The delay occurring over the communication lines is called latency and represented as $t_{communication}$. For proper operation, this latency shall be taken into account and deducted from the calculated relay time delays.

The final relay time delay, $t_{assigned}$, which considers the communications delays, can be calculated as shown in (4.4).

$$t_{assigned} = t_{relay} - t_{communication\_delay} \tag{4.4}$$

4.4. *Dijkstra's Algorithm for Automated Structure Detection*

Dijkstra's algorithm [170, 171] is a graph search algorithm that solves the shortest path problem from a single source to many destinations [163]. It can be implemented on a graph where a node (or vertex) may have more than one connection. The algorithm employs a step by step approach and finds the shortest path to a neighbor vertex and then moves on to its neighbors. For a better understanding, consider the graph given in Figure 4.9.

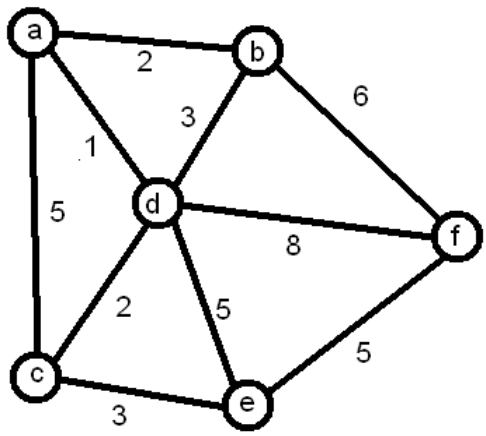

Figure 4.9. A sample graph for shortest path problem

If it is desired to find the shortest path from node (a) to all other nodes, the algorithm runs as follows;

1. Assign all nodes infinite distance and mark all nodes unvisited
2. Mark the initial node (i.e. node a) as current
3. For current node, calculate the distance to all neighbors. If it is shorter than the previously recorded distance update it.
4. If all neighbors are visited, mark current node as visited.
5. Halt, if all nodes are visited. If not, assign the nearest unvisited node as the current node and loop to Step 3.

Figure 4.10 shows the implementation of the first 3-steps given above for `node a`. Node (a) is assigned as the current node and all the distances to the other nodes are set to be unknown.

In Step 3, the distances are calculated to the neighboring nodes. When started from `node a`, this algorithm will calculate the shortest path from `node a` to all the other nodes on the graph. It will also derive the corresponding routes for these paths. This approach proves fruitful when the topology of electrical networks is taken into account. Furthermore, for any node, it is sufficient to know its immediate neighbors and the distances thereof. This is a solid advantage as it is not required to know the complete picture of the microgrid topology.

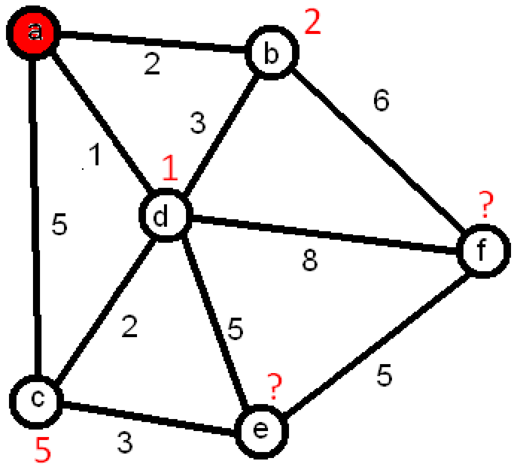

Figure 4.10. 1st Loop, First 3-steps performed on 'node a'

Once the 1st loop is finished, the algorithm moves forward by assigning the closest node to `node a` as the current node, i.e. `node d`, given in Figure 4.11. Same steps are performed with a slight difference. The difference between `node d` and `node a` is now known. In other words, this can be expressed as the distance between the current node and the last visited node. The current node shall always operate on this offset. For unvisited nodes such as `node f` and `node e`, which have not been visited in the first loop, are assigned the distance to `node d` plus the offset. Unvisited nodes are handled in this fashion. The real strength of this approach comes on the surface when the already visited nodes are handled. While visiting `node c` from `node d` the distance already assigned to `node c`, i.e. 5, is compared with the distance to `node d` plus the offset, i.e. 2 + 1. Since 2+1=3 < 5, the shortest path is updated to be over `node d` and the distance is updated as 3 instead of 5. This route selection can be very advantageous for use in the microgrids. Different distances can be assigned to different equipment to represent the preference of use. In this fashion, distance may represent less preference while the shortest path may represent the preference of use.

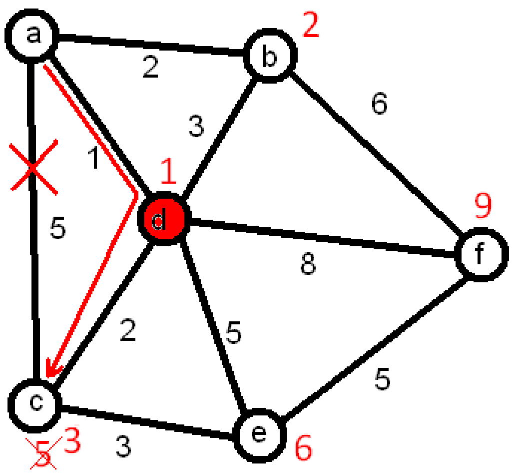

Figure 4.11. 2nd Loop, First 3-steps performed on ‘node d’

In the third loop, illustrated in Figure 4.12, another alternative route is discovered through `node b`. When calculating the distance to `node f` the algorithm compares the distance over `node d`, i.e. 1+8, with the distance over `node b`, i.e. 2+6. Since the latter is shorter than the former, the distance of `node f` to `node a` has been updated as 8 in place of 9.

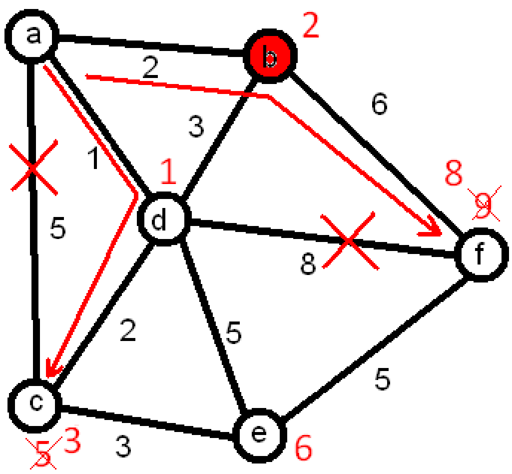

Figure 4.12. 3rd Loop, First 3-steps performed for node b

To sum up, when the algorithm is run, it will start from "node a" and visit every node while keeping track of the shortest path to get to that particular node. The algorithm shall halt when all the nodes have been visited. As a result it will yield a table similar to Table 4.4.

TABLE 4.4. SHORTEST PATH FROM "NODE A"

Node	Distance from "node a"	Path
b	2	a-b
c	3	a-d-c
d	1	a-d
e	6	a-d-e
f	8	a-b-f

As Table 4.4 shows, the algorithm finds that the shortest path to node c is an indirect path over node d. The most important feature of this algorithm is when run once; it determines the shortest distances and the corresponding paths to all nodes.

In order to be able to implement Dijkstra's algorithm, the microgrid should be represented as a graph similar to the one shown in Figure 4.13. This is the graph representation of case 1 given earlier in Figure 4.7. The components have been represented as nodes, or vertexes, while the connections have been represented as edges. This requires storage of network data in an array or a linked list. Also the connections between the DGs, CBs and Loads should also be stored in a matrix or linked list structure.

For real time response of the proposed technique, the real time data should be updated when a node disconnects from the system or an edge disappears and an alternative edge is connected. Such a change is depicted in Figure 4.14 where there are some connection changes as compared to Figure 4.13. All these actions necessitate continuous monitoring of the microgrid and utilization of communication lines between the nodes. This should not be considered as a drawback, since such a system is already needed for smartgrids [172]. Furthermore, most of new generation microgrid protection systems incorporate a central protection unit and communication lines as in [55, 73, 94].

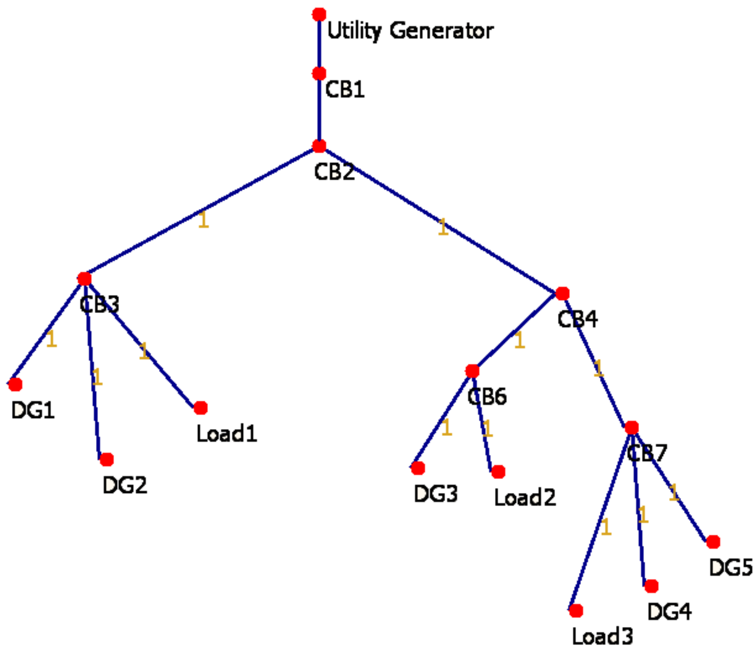

Figure 4.13. Modeling of microgrid in Case 1 according to graph theory

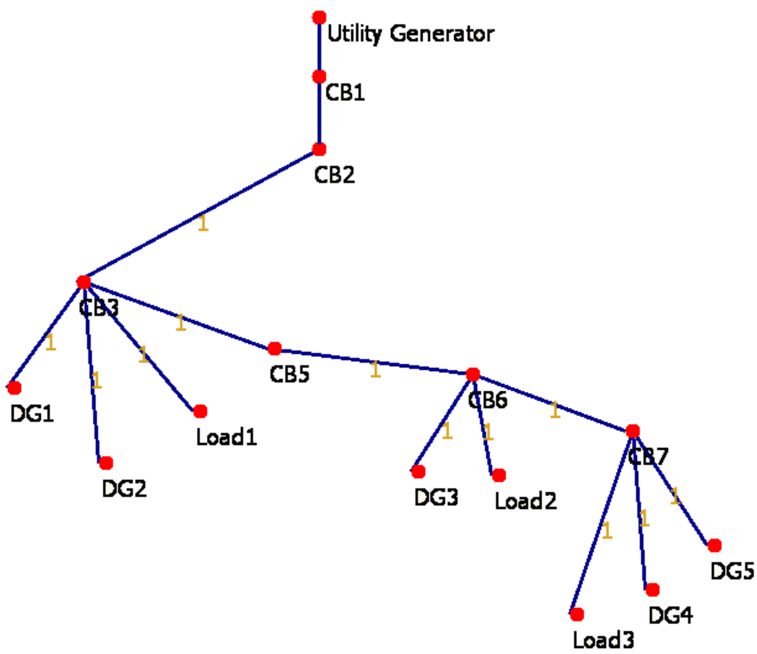

Figure 4.14. Modeling of microgrid in Case 2 according to graph theory

In this research, selectivity application shall be studied as the case study. It must be noted that the proposed method can also be used for power flow, load sharing and/or generation planning purposes. For the proper application of selectivity, the main goal is to determine the relay hierarchy. It is evident that, there is only one path between the point of origin, i.e. CB2, and the destinations, i.e. all leaf nodes such as DG1, DG2, Load1, and Load2. This eliminates the effect of distance and simplifies the existing problem to a *path finding problem*. In other words, Dijkstra's algorithm will be used to find the paths between CB2 and leaf nodes and identify the relay hierarchy.

In these graphs, all the distances are marked as one, since the shortness of the path is of no concern. Nevertheless, there is another reason for using unit distances as it has a usage for selectivity purposes. The distance yields number of the selective levels, n, between the origin and the destination. If the leaf nodes are not assigned any time delay (meaning that they will react immediately in case of a fault) the base time delay is calculated based on the parameter n. Alternatively, if it is desirable to assign time delays for the relays of the leaf nodes then the calculations will be based on value "n+1". These calculations and the assignments of the parameters will be discussed in Chapter 5, Parameter Assignment.

For the implementation of Dijkstra's algorithm on these graph representations, a C# implementation provided in [173] is used. In this simplistic software, the nodes are placed on the field and the necessary connections are added between the nodes. The distance of the path is represented by the cost variable. As mentioned above, all distances are set to 1 for various reasons.

When the graph is prepared, the software is used to select the origin and the destination nodes. When the algorithm is run on the software, the shortest path is highlighted and the details of the route are given in terms of the nodes it passes through. It is also possible to save and load a particular graph in the software.

Firstly, the algorithm is run to find the shortest path (i.e. the only path in our case) between CB2 and DG4 for Case 1. Figure 4.15 shows that the path is successfully highlighted on the graph and the proper hierarchy is shown in `Report` area.

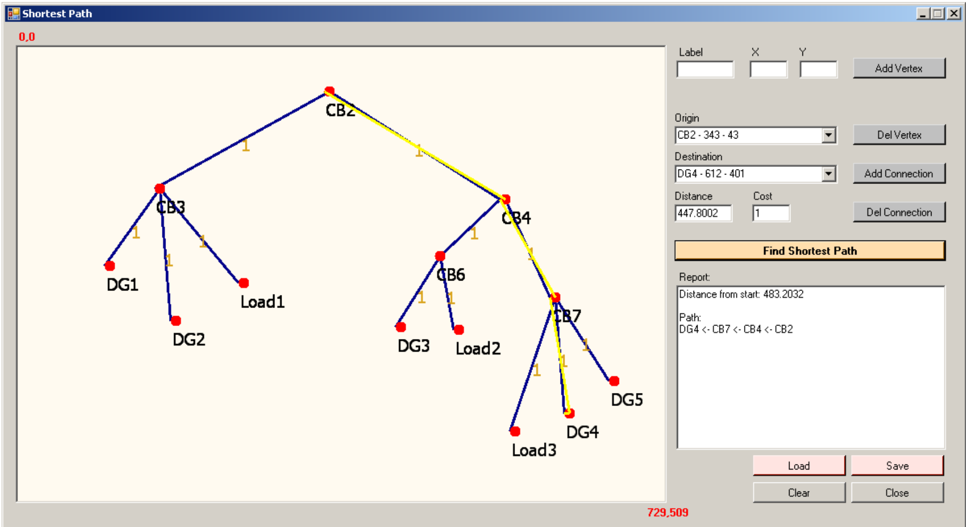

Figure 4.15. Dijkstra's Algorithm run for case 1, Path from CB2 to DG4

In order to change from Case 1 to Case 2 following services are executed to perform required connections/disconnections:

Relay4.Disconnect(Relay2)

Relay6.Disconnect(Relay4)

Relay7.Disconnect(Relay4)

Relay5.Connect(Relay3)

Relay6.Connect(Relay5)

Relay7.Connect(Relay6)

It is observed that while using Dijkstra's algorithm, OO models developed earlier are utilized. The services included in these models are also executed to reflect the changes occurring on the electrical network. As shown above, the OO models and services of Relays are utilized to represent the electrical network in virtual world. In this manner, OO modeling developed for microgrids facilitate the use of Dijkstra's Algorithm for automated structure detection purposes.

The algorithm is executed again to find the path between CB2 and DG4. As shown in Figure 4.16, the path is successfully found without a centralized monitoring for grid structure.

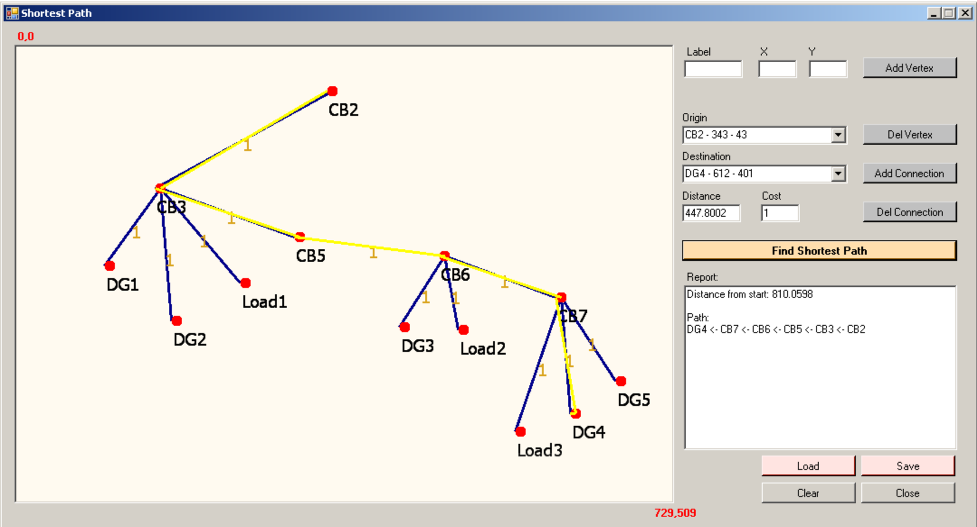

Figure 4.16. Dijkstra's Algorithm run for case 2, after grid re-configuration, Path from CB2 to DG4

The shortest paths and the distances obtained for both of the cases are given in Table 4.5.

TABLE 4.5. THE PATH FROM "CIRCUIT BREAKER 2"

	Case 1		**Case 2**	
Node	Dist	Path	Dist	Path
CB3	1	CB2-CB3	1	CB2-CB3
CB4	1	CB2-CB4	-	-
***DG1**	2	CB2-CB3-DG1	2	CB2-CB3-DG1
***DG2**	2	CB2-CB3-DG2	2	CB2-CB3-DG2
***Load1**	2	CB2-CB3-Load1	2	CB2-CB3-Load1
CB5	-	-	2	CB2-CB3-CB5
CB6	2	CB2-CB4-CB6	3	CB2-CB3-CB5-CB6
CB7	2	CB2-CB4-CB7	4	CB2-CB3-CB5-CB6-CB7
***DG3**	3	CB2-CB4-CB6-DG3	4	CB2-CB3-CB5-CB6-DG3
***Load2**	3	CB2-CB4-CB6-Load2	4	CB2-CB3-CB5-CB6-Load2
***DG4**	3	CB2-CB4-CB7-DG4	5	CB2-CB3-CB5-CB6-CB7-DG4
***DG5**	3	CB2-CB4-CB7-DG5	5	CB2-CB3-CB5-CB6-CB7-DG5
***Load3**	3	CB2-CB4-CB7-Load3	5	CB2-CB3-CB5-CB6-CB7-Load3

* denotes the leaf nodes

The extracted data, the relay hierarchy and the distances, can be used to do necessary adjustments for management and protection purposes. Whenever the structure of the microgrid changes, due to disconnections or new deployments, knowledge of the point of origin and the destinations (which are CB2 and leaf nodes, respectively) is sufficient to extract the new relay hierarchy.

It is worthy to note that leaf nodes will be DGs, loads or storage devices. When connected to the network, they may have a special heading or a label which indicates that they are leaf nodes.

4.5. Plug-and-play for new deployments

In Figure 4.17, three new deployments, i.e. CB8, DG6 and Load 4 are added to Figure 4.15. The following three commands are realized for this change:

Relay8.Connect(Relay6)

Load4.Connect(Relay8)

DG6.Connect(Relay8)

Consequently, a new relay, i.e. Relay 8, is connected to Relay 6 while a new load, load 4, and a new generator, DG6, are connected to Relay 8.

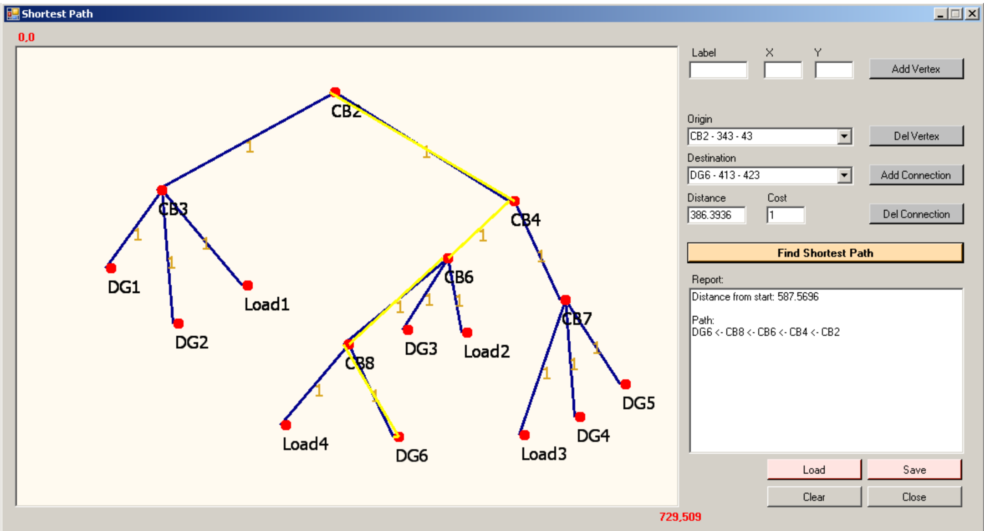

Figure 4.17. Dijkstra's Algorithm run after new deployments, Path from CB2 to DG6

Dijkstra's algorithm is run on the graph and the new deployments are successfully identified in grid hierarchy. It is shown that with this simple arrangement, the path from the known origin to known destinations can be found for any possible network structure. It is sufficient to track the connection of nodes with the preceding and following nodes. Thanks to this feature, a centralized monitoring approach is not required and de-centralized automated method is made possible. The shortest paths and the distances updated after new deployments have been given in Table 4.6.

The OO modeling and Automated Structure Detection can easily be implemented inside the MCPU which is explained in Chapter 3. The microgrid control center is already in communication with all grid components. Their parameters and services required for OO modeling are reported to MCPU via communication lines. In this way, every new deployment can report its parameters to MCPU. After receiving these details, MCPU can create an object to represent this new device in terms of its parameters and services. The central protection unit and the communication lines proposed in Chapter 3 are sufficient for the implementation of OO modeling for microgrids.

TABLE 4.6. THE PATH FROM "CIRCUIT BREAKER 2" AFTER NEW DEPLOYMENTS

	Case 1	
Node	Dist	Path
CB3	1	CB2-CB3
CB4	1	CB2-CB4
***DG1**	2	CB2-CB3-DG1
***DG2**	2	CB2-CB3-DG2
***Load1**	2	CB2-CB3-Load1
CB5	-	-
CB6	2	CB2-CB4-CB6
CB7	2	CB2-CB4-CB7
CB8	3	CB2-CB4-CB6-CB8
***DG3**	3	CB2-CB4-CB6-DG3
***Load2**	3	CB2-CB4-CB6-Load2
***DG4**	3	CB2-CB4-CB7-DG4
***DG5**	3	CB2-CB4-CB7-DG5
***Load3**	3	CB2-CB4-CB7-Load3
***Load4**	4	CB2-CB4-CB6-CB8-Load4
***DG6**	4	CB2-CB4-CB6-CB8-DG6

* denotes the leaf nodes

Once all of the microgrid components and their connections are represented with OO models, as explained above, MCPU runs Dijkstra's algorithm over this graph and extracts the structure of the microgrid automatically. Considering the dynamic structure of the microgrids, this is feature is very important since it can extract new structures without any prior knowledge.

4.6. Conclusion

A microgrid modeling scheme based on OO methods has been developed due to the fact that recent developments in the electrical networks and microgrids necessitate a modeling system which will help manage the electrical network in a fast and dynamic manner. This OO modeling is aimed at representing microgrids in the virtual world for dynamic monitoring and control. The former management and protection methods used in utility grid (passive grid) systems are no longer valid for rapidly changing microgrids which can receive multiple connections simultaneously.

This type of modeling is based on the electrical nodes and the connections between the nodes being extracted from the pointers pointing to/from the nodes. In this manner, the changing structure is followed by the model and the new operating points can be calculated, then updated. The ability to follow dynamic nature of microgrid is a crucial asset provided by OO modeling of the network and Automated Structure Detection. Consequently, the modeling of electrical networks with the OO models presented in this chapter will make microgrid management easier from power flow, generation, load sharing and/or protection aspects.

Microgrids have dynamic structures which change more often than the conventional large networks. Supplying power through alternative paths, new deployments and other factors hinder the selective operation in case of a fault. This requires that a new method should be implemented which updates the selective operation of relays in parallel with the existing microgrid structure. However, in order to achieve this goal a robust method is required to extract the relay hierarchy for a specific microgrid structure and assign suitable selective levels (or time delays). Some of the previous publications incorporate look-up tables with predetermined network structure data. This approach cannot respond to the dynamic changing structure of the network.

Therefore, a new method for determining relay hierarchy and appointing selective levels has been presented in this chapter. The method models the microgrid according to graph theory where relays are represented as nodes and connections are represented as edges. In order to find the path from the point of common coupling to the relays at lowest level, Dijkstra's algorithm is used. This algorithm extracts the relay hierarchy for any network structure. The run time is short since the hierarchy for all relays is extracted with a single execution. The algorithm allows for new deployments and automatically includes them in the calculations. This feature is very crucial for plug and play purposes in electrical networks. It also makes the protection system developed in this research to be generic and implementable on a diverse set of power networks.

Chapter 5

Fault Current and Time Delay Assignment for Relays

Publications pertaining to this chapter:

1) ***Taha Selim Ustun, Cagil Ozansoy, Aladin Zayegh, "Fault Current Coefficient and Time Delay Assignment for Microgrid Protection System with Central Protection Unit," IEEE Transactions on Power Systems, vol. PP, pp. 1-1, 2012 (accepted-early access).***

5.1. Introduction

Chapter 4 focuses on the automatic adaptation of the microgrid to changing conditions such as new deployments or equipment connections. As mentioned therein, this chapter reveals the details of the concept developed for the calculation and setting of protection device parameters. Chapter 4 proposed a unique approach for the detection of a microgrid structure. Once the microgrid structure is appropriately detected, then two key settings can be accurately determined and set for the protection devices participating in the protection of the microgrid. These are crucial for safe and reliable operation and are the relay triggering current and time delay for selectivity. These parameters have been introduced in Chapters 3 and 4; and their relevance has been touched upon. The calculation approach which can be implemented in a central real time automation and protection controller such as the MCPU is presented in the following sections.

In the case of a fault, DG systems contribute to the fault currents and the transient characteristics of the network become completely different [3]. Since the Inverter Interfaced DGs (IIDGs) have highly variable characteristics, they alter the grid structure and jeopardize safe and reliable operation of the microgrid [4] . How to calculate the new fault currents and fault levels for any change occurring in the system is a major concern. Current systems use some sort of database or event tables to search the current status and take pre-determined precautions [73, 90]. These systems necessitate the knowledge of microgrid conditions beforehand so that certain precautions can be assigned in the event tables. However, since microgrids are designed to accommodate new generators and loads, these schemes are not practical.

Some sort of algorithm which dynamically calculates fault currents and manages to adjust the protection settings and scheme as appropriate to the new state of microgrid is direly needed. When coupled with the automated grid structure detection approach presented in Chapter 4, the dynamic parameter calculation method presented in this chapter contributes to the literature by satisfying this demand.

5.2. Calculation of Grid Fault Current Contribution

In this developed protection system, for a given relay \`$r$\` in the network, the operating current is calculated as in (5.1). Operating current represents the current level when the relay picks up the fault and instructs Circuit Breaker (CB) to interrupt the connection. This equation considers the grid's and all DGs' fault current contribution on that particular relay.

$$I_{relay} = (I_{faultGRID} \times OperatingMode) + \sum_{i=1}^{m} (k_{ir} \times I_{faultDGi} \times Status_{DGi}) \quad (5.1)$$

where m is the total number of DGs in the microgrid,

k_{ir} is the impact factor of i_{th} distributed generator on the fault current of the relay r,

$I_{faultDGi}$ is the maximum fault current contribution of i_{th} DG

Operating Mode bit defines the status of the microgrid as grid-connected or islanded.

$Status_{DGi}$ shows whether a particular DG is in operation or not.

If the microgrid is operating in islanded mode, then the grid's fault current contribution will be multiplied with the 'Operating Mode' bit which will be equal to 0. Likewise, the fault current contribution of a DG which is not in operation will be annulled by its status bit.

The contribution of the fault current grid is calculated, as shown in (5.2), by taking the Thevenin equivalent of the electric network as in traditional fault current calculations [174, 175].

$$I_{fault\_grid} = \frac{V_{th}}{Z_{th}} \tag{5.2}$$

As shown in Figure 5.1, $\boldsymbol{V_{th}}$ denotes the Thevenin equivalent of the utility grid and remains the same for different parts of the microgrid.

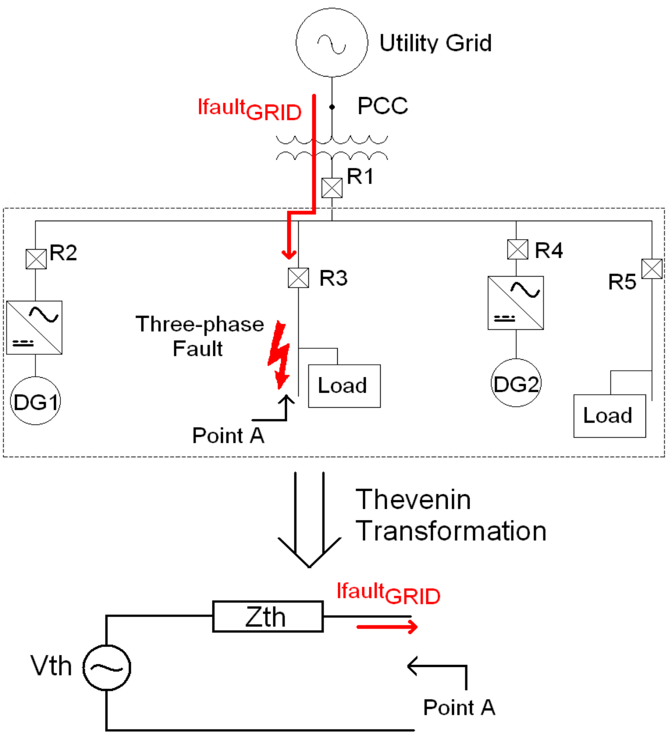

Figure 5.1. Thevenin Equivalent Circuit taken from Point A

However, $\boldsymbol{Z_{th}}$ which denotes the Thevenin impedance between the utility grid and point of interest varies with respect to distance. Therefore, in the above equation, $\boldsymbol{V_{th}}$ is a constant value while Z_{th} is a function of distance, i.e. $\boldsymbol{Z_{th}}\,(d)$. In this case, the fault current contribution of the grid also becomes a function of the distance and can be defined as:

$$I_{fault\_grid}(d) = \frac{V_{th}}{Z_{th}(d)} \tag{5.3}$$

The signal $status_{DGi}$ indicates whether that DG is in operation or not. Depending on the type of the DG, i.e. whether it is inverter interfaced or with rotating machines, $I_{faultDGi}$ is calculated as in (5.4) and (5.5), respectively. In the literature, the fault contribution of the Inverter Interfaced DGs is reported to range between 1.2 and 2 times their rated currents [4, 80, 155]. In order to be practical and more realistic, in this research, the coefficient of 1.5 has been selected for use since the extreme conditions (where the fault contribution is 1.2 or 2) will not occur as frequent as conditions which require fault contribution coefficient to be 1.5 [153, 154]. On the other hand, rotating machines have mechanical characteristics similar to large generators and, therefore, provide larger fault current [145].

$$I_{faultDGi} = I_{ratedDGi} \text{ x } 1.5 \tag{5.4}$$

$$I_{faultDGi} = I_{ratedDGi} \text{ x } 5 \tag{5.5}$$

The impact factor, namely $\boldsymbol{k}$, has been introduced to calculate the fault current contributions of DGs at various points in the microgrids. It takes a value between 0 and 1 and represents the decrease in the fault current due to the impedance of low voltage distribution lines. The impact of the fault current contribution of a particular DG lessens as we get further away from the source of that DG due to increasing impedance between that DG and the point of concern. Thus, the relays closer to the DG under consideration will have higher `$\boldsymbol{k_{ir}}$` levels whereas those which are further downstream or upstream will have lower coefficients. In this way, not only the effect of distribution lines can be taken into account but also a more flexible and versatile protection system can be designed. This is especially desirable for growing networks with potential new deployments.

The fault currents of IIDGs do not vary with distance but with their control loops [176]. Therefore, the impact factor ***k*** does not apply to IIDGs. It has been introduced to account for the variation of fault current contribution of rotating DGs such as diesel generators or wind generators. In fault current calculations, the impact factors of IIDGs can be adjusted to fine tune the fault current calculated in (5.4). This introduces extra versatility to the proposed system, if in the future, better fault current estimation schemes are developed for different inverters with different topologies and control schemes. However, in this study the impact factors are taken as 1 for IIDGs and their fault contributions are worked out from (5.4). On the other hand, the calculation of the ***k*** factor for rotating DGs is a crucial part of this protection system and has been detailed in the following sections.

5.3. Calculation of DG impact factor – k

Figure 5.2 shows a section of a microgrid where DG1 and Relay 4 are separated by a distance of "x". At point **A**, which is the connection point of the DG1, the entire fault current contribution ($I_{faultDG1}$) of DG1 is experienced.   . At a distance of x from DG1, at point B, this current decreases to k_{14} * $Ifault_{DG1}$.

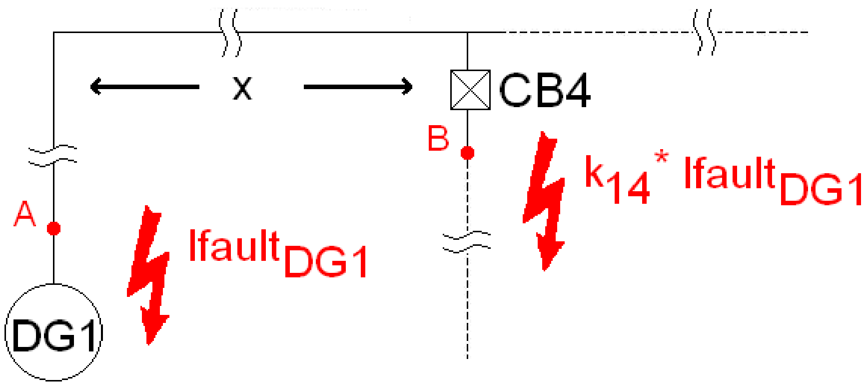

Figure 5.2. Fault Contribution of DG at different locations

In order to calculate the impact coefficient, consider the symmetrical representation of this system under fault conditions given in Figure 5.3. This representation is based on the symmetrical components calculations [177].

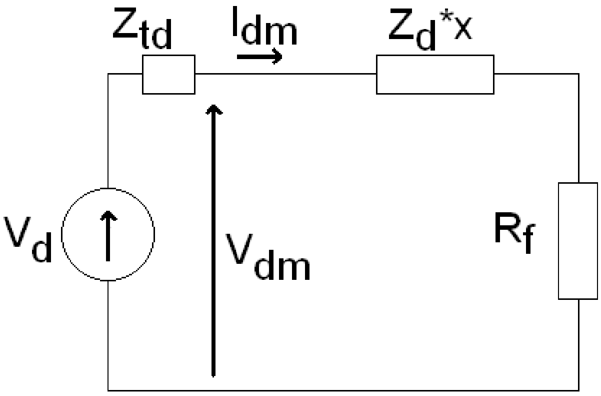

Figure 5.3. Symmetrical components scheme

Since these faults are steady faults, R_f is assumed to be zero [178]. From the electrical equation for the direct loop voltage, the following equation can be written:

$$V_d = I_{dm}(Z_{td} + Z_d \times x) \tag{5.6}$$

Where $\boldsymbol{V_d}$ is the direct voltage output of DG, $\boldsymbol{Z_{td}}$ is the output impedance, and $\boldsymbol{V_{dm}}$ is the rated output voltage of DG which is regulated by the stability and safety code of the grid. $\boldsymbol{I_{dm}}$ is the fault current supplied, $\boldsymbol{Z_d}$ is the impedance of the transmission/distribution line per length and $\boldsymbol{x}$ is the distance between DG and the relay under consideration.

The fault current supplied is the maximum fault current available, i.e. $I_{faultDG}$; and $\boldsymbol{V_d}$ becomes the rated voltage of the DG. Different fault current capacities of DGs are represented by this output impedance. Rearranging (5.6), the fault current equation can be written in terms of the impedances and the distance as:

$$I_{dm} = \frac{V_d}{Z_{td} + (Z_d \times x)} \tag{5.7}$$

There are two unknown parameters in this equation. In order to work them out, an additional equation is required. This is the voltage relation between $\boldsymbol{V_d}$ and $\boldsymbol{V_{dm}}$, which is the voltage that needs to be sustained according to the stability and safety code of the grid. It can be written as in (5.8):

$$V_d = V_{dm} + (I_{dm} \times Z_{td}) \tag{5.8}$$

Replacing V_d in (5.6), $\boldsymbol{I_{dm}}$ can be expressed as:

$$I_{dm} = \frac{V_{dm}}{(Z_d \times x)} \tag{5.9}$$

In this fashion, a DG's fault current contribution at a distance x can be calculated. Note that all the parameters on the right hand side of (5.9) are known before any fault occurs. This allows the MCPU to calculate all fault contributions and assign overcurrent thresholds to the relays for proper operation. Once the fault current contribution $\boldsymbol{I_{dm}}$ is calculated, the impact factor can be expressed as the ratio of $\boldsymbol{I_{dm}}$ to $\boldsymbol{I_{faultDG}}$:

$$k_{ri} = \frac{I_{dmi}}{I_{faultDGi}} \tag{5.10}$$

Where ***i*** and ***r*** denote the DG and the relay under consideration. The protection system will create a **K** matrix by calculating the impact factors of ***i***-many DGs on **r** many relays.

$$K = \begin{bmatrix} k_{11} & k_{12} & k_{13} & \dots & k_{1r} \\ k_{21} & k_{22} & k_{23} & \dots & k_{2r} \\ k_{31} & k_{32} & k_{33} & \dots & k_{3r} \\ \dots & \dots & \dots & \dots & \dots \\ k_{i1} & k_{i2} & k_{i3} & \dots & k_{ir} \end{bmatrix} \tag{5.11}$$

From (5.4) and (5.5), the maximum fault currents of every DG can be calculated and the vector $\boldsymbol{I_{faultDG}}$, having dimensions [1, ***i***] can be represented as shown in (5.12).

$$\overrightarrow{I_{faultDG}} = \begin{bmatrix} I_{faultDG1} \\ I_{faultDG2} \\ I_{faultDG3} \\ \dots \\ I_{faultDGi} \end{bmatrix} \tag{5.12}$$

The overcurrent thresholds of relays which represent the thresholds for relay operation can be calculated by the cross product of matrix $\boldsymbol{K^T}$ and vector $\boldsymbol{I_{faultDG}}$. The result is the relay overcurrent threshold vector of dimension [$\boldsymbol{r}$, 1], $\boldsymbol{I_{relay}}$.

$$\overrightarrow{I_{relay}} = \left[I_{relay1}\ I_{relay2}\ I_{relay3}\ ...\ I_{relayr}\right]$$

$$= \begin{bmatrix} k_{11} & k_{12} & k_{13} & \dots & k_{1r} \\ k_{21} & k_{22} & k_{23} & \dots & k_{2r} \\ k_{31} & k_{32} & k_{33} & \dots & k_{3r} \\ \dots & \dots & \dots & \dots & \dots \\ k_{i1} & k_{i2} & k_{i3} & \dots & k_{ir} \end{bmatrix} \otimes \begin{bmatrix} I_{faultDG1} \\ I_{faultDG2} \\ I_{faultDG3} \\ \dots \\ I_{faultDGi} \end{bmatrix} \tag{5.13}$$

This equation can be written in compact form as;

$$\overrightarrow{I_{relay}} = K^T \otimes \overrightarrow{I_{faultDG}} \tag{5.14}$$

MCPU will assign each row of the vector $\boldsymbol{I_{relay}}$ to the related relay in the network. With the help of communication lines, the network will be monitored and these values will be constantly re-calculated and updated.

During the course of this work, only balanced three-phase to ground faults have been considered. It is assumed that the microgrids are considerably smaller than the conventional electrical networks. This means that the size of a microgrid is suitable for protection with delayed-type instantaneous relays which implement definite-time grading technique. In the case of a communication failure, the protection scheme can still provide reliable protection until the communication is restored. This is because the communication infrastructure is only critically needed for the update of protection settings. The latest fault current settings shall be kept in the relay until the link reconnects.

Thanks to the local decision making scheme of the proposed method, the relays will be able to operate based on these fault current settings. In this fashion, though it may not have the most desirable settings, the protection system will be active in case of a communication failure and the microgrid will be protected from catastrophic conditions. The likelihood of a communication system failure right at the point when protection setting updates would be required is very low. It is possible to design a redundant communication network by having multiple meshed lines connect to various switches that relays connect to. Although this will add to the overall implementation cost, it is quite often realized in star topology communication networks especially when high reliability is required.

In this research, only the faults occurring in the microgrid have been considered. Faults in other feeders and/or grids are not discussed in this work. Since the microgrids under consideration are assumed to be sufficiently small, the relays are close to the fault locations in each branch. That is to say, the fault current magnitude does not differ significantly between the actual location of fault and the location of the relay for which the calculations are carried out. This protection scheme has been developed for radial electrical networks. Should an algorithm be developed to assign proper fault current settings and adjust relay hierarchy, the system can be extended to non-radial networks such as ring or meshed networks.

5.4. Relay Hierarchy adjustment for selectivity

Selectivity is a vital concept in protection systems. It refers to isolating the fault with the nearest circuit breaker so that the rest of the system will not be affected in case of a fault. It requires circuit breakers to react according to a hierarchy. The circuit breakers which are downstream and closer to the fault point are required to operate first. However, if the fault current is very large and the downstream circuit breaker fails to interrupt, then the upstream circuit breaker with larger capacity should operate and isolate the fault. With the introduction of DGs, the very traditionally accepted concepts of downstream and upstream circuit breakers are prone to change according to the status of the microgrid. Consider the system shown in

Figure 5.4. This network has generators connected to all branches. Through the combination of circuit breakers, various alternative network structures can be formed.

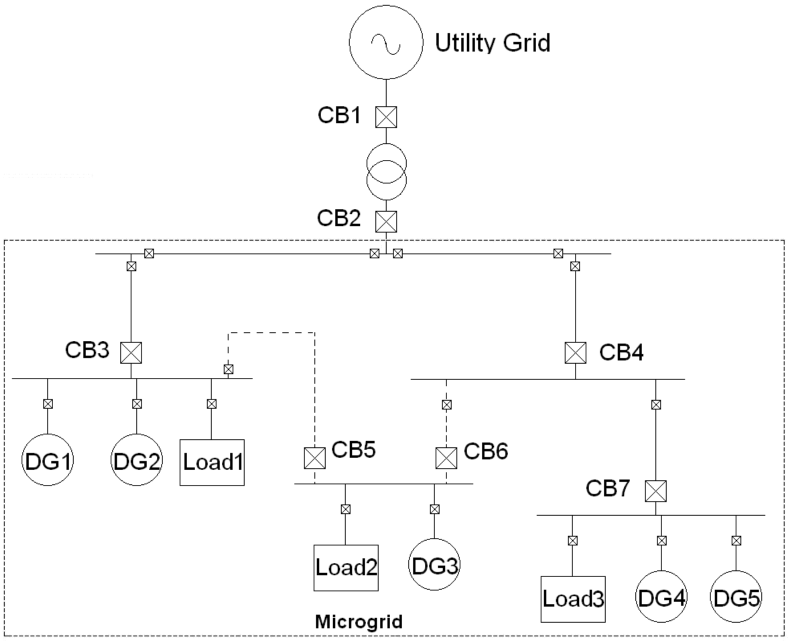

Figure 5.4. A sample microgrid

Throughout this section, relays will be referred to being closed or open as a shortcut to indicate the open/closed status of the Circuit Breakers (CBs) associated with each relay. Assume that R1, R2, R3, R4, R6 and R7 are closed whereas R5 remains open. When a fault occurs at the terminals of Load 2, then the most downstream CB will be Load 2’s own CB (represented by the little box) and selectivity implies that its associated relay should interrupt the fault. If Load 2’s circuit breaker fails to achieve that in a predetermined time (delay), then the proper selectivity requires that R6 operates.

The proposed algorithm employed by the MCPU determines the network structure according to the status of critical relays. The status of a critical relay changes the structure of the network. Following this definition R1, R2, R3, R4 and R6 are all critical relays whereas Load 2’s relay and DG1’s relay are non-critical relays. After determining the microgrid structure, MCPU assigns 2-pair selectivity couples. Table I shows the 2-pair selectivity data for the left branch of the example given above.

TABLE 5.1. 2-PAIR SELECTIVITY METHOD DATA

Relay ID	**Operating Current**	**Downstream Relay ID**	**Downstream Relay Operating Current**
R2	$Irelay_{R2}$	R3	$Irelay_{R3}$
R3	$Irelay_{R3}$	IR_{DG1}	$Irelay_{IRDG1}$
R3	$Irelay_{R3}$	IR_{DG2}	$Irelay_{IRDG2}$
R3	$Irelay_{R3}$	IR_{Load1}	$Irelay_{IRLoad1}$

The method owes its name to the fact that every relay is paired up with its downstream relay. The information provided includes; the operating current of that particular relay and the operating current of its downstream relay. Whenever a fault occurs, the relay which is closest to the fault operates to isolate the fault. If it proves to be unsuccessful in a predetermined time (i.e. time delay of the upstream relay), then its upstream relay will recognize and isolate the fault. Figure 5.5 shows the flow chart implemented by each relay for 2-pair selectivity method.

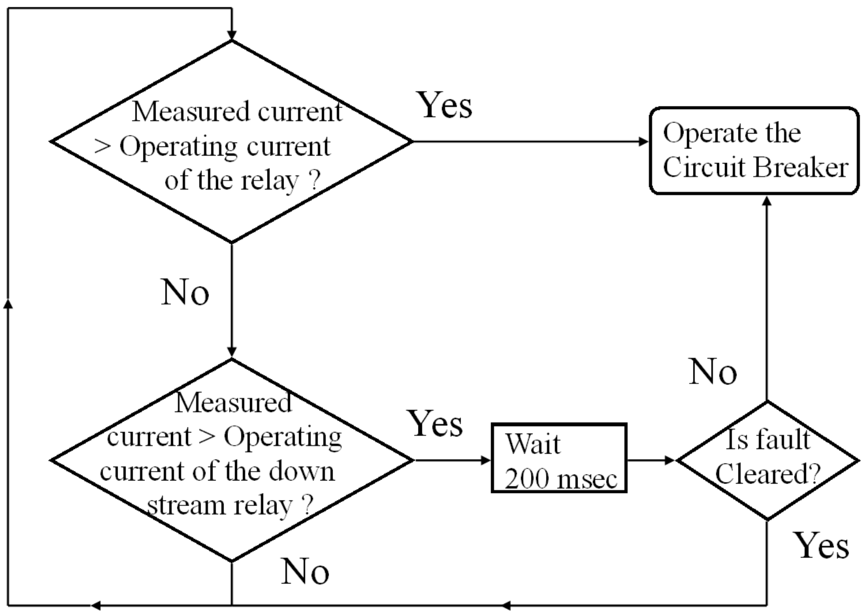

Figure 5.5. 2-pair Selectivity Method Algorithm

Let’s consider the case in Table 5.1 the pairs are R2-R3 and R3-I.R. Should a fault occur at Load 1, Individual Relay (I.R.), which is the connecting relay of generators or loads, should isolate the fault. If unsuccessful, when the predetermined time expires (e.g. 200 msec), its upstream relay, i.e. R3 isolates the fault. In this manner, the proposed system can be implemented in simple and complex microgrids.

The value of the time delay (i.e. 200 msec) has been assigned by considering different factors. It is enforced by the stability parameters that a fault shall be cleared before a maximum time when the network becomes unstable [179]. At the same time, practical considerations for over-current relay communication and operation imply that there is a minimum time that these CBs can operate [180, 181]. Therefore, the time delay has been selected to be between these minimum and maximum time values.

To further clarify the operation of the algorithm four different structures of the system shown in Figure 5.4 are studied. These are;

1. R2, R3, R4 and R6 are closed. The middle bus is fed through R6 connection.
2. R2, R3, R4 and R5 are closed. The middle bus is fed through R5 connection.
3. R2, R3, R5 and R6 are closed. The middle bus and the right bus are fed through R5 and R6 connections, respectively.
4. R2, R4, R5 and R6 are closed. The left bus and the middle bus are fed through R5 and R6 connections, respectively.

It is required that these cases are studied by engineers and proper hierarchy of the critical relays should be determined and saved in the MCPU. While monitoring the network, MCPU will also monitor the status of critical relays. In accordance with the changes in their status, MCPU will compare the present structure with the predetermined structures saved in the memory. After determining the present structure, MCPU will retrieve the critical relay hierarchy pertaining to it and assign 2-pair selectivity. Alternatively, the graph theory-based approach developed by the authors [182] and presented in Chapter 4 can be utilized to extract the relay hierarchy. In this fashion, the system acquires higher independence and plug-and-play concept can be realized.

For each case given above, the proper critical relay hierarchy is given in Table 5.2. As shown, these cases have independent branches in microgrid. That means critical relays in these branches are elements of discrete sets and do not belong to same 2-pair distribution. For instance, in Case 1, R3 and R4 are discrete from each other and thus they are not considered simultaneously for 2-pair distribution. R3 is considered for 1^{st} branch whereas R4 is considered for 2^{nd} branch.

TABLE 5.2. CRITICAL RELAY HIERARCHY FOR VARIOUS CASES

Case No.	**1^{st} Branch**	**2^{nd} Branch**	**3^{rd} Branch**
1.	R2>R3>I.R*	R2>R4>R6>I.R	R2>R4>R7>I.R
2.	R2>R3>I.R	R2>R3>R5>I.R	R2>R4>R7>I.R
3.	R2>R3>I.R	R2>R3>R5>I.R	R2>R3>R5>R6>R7>I.R
4.	R2>R4>R6>R5>I.R	R2>R4>R6>I.R	R2>R4>R7>I.R

*I.R. – Individual Relays of components (small boxes in figures)

TABLE 5.3. RELAY PAIRING FOR CASE 1

Relay Hierarchy	1^{st} branch	Selectivity pairs
3	R2	
2	R3	
1	I.R.	
	2^{nd} branch	
4	R2	
3	R4	
2	R6	
1	I.R.	

Case 3 can be considered as a single branch since, due to its single line structure, 3^{rd} branch covers 1^{st} and 2^{nd} branches. In these cases, none of the relays are discrete and they are all considered in the same time for 2-pair distribution. If the network operates under Case 1 then, 1st and 2nd branches will have the 2-pair assignments shown in Table 5.3.

As shown in Figure 5.6, when R3 opens and R4 closes the structure changes from that of Case1 to that of Case 3. For this new microgrid structure, the relay hierarchy and 2-pair assignments shall be updated. The place of relays in the relay hierarchy may, also, change. R6 for instance is at 2nd level of 2nd branch in Case 1 while it is placed at 3rd level in Case 3.

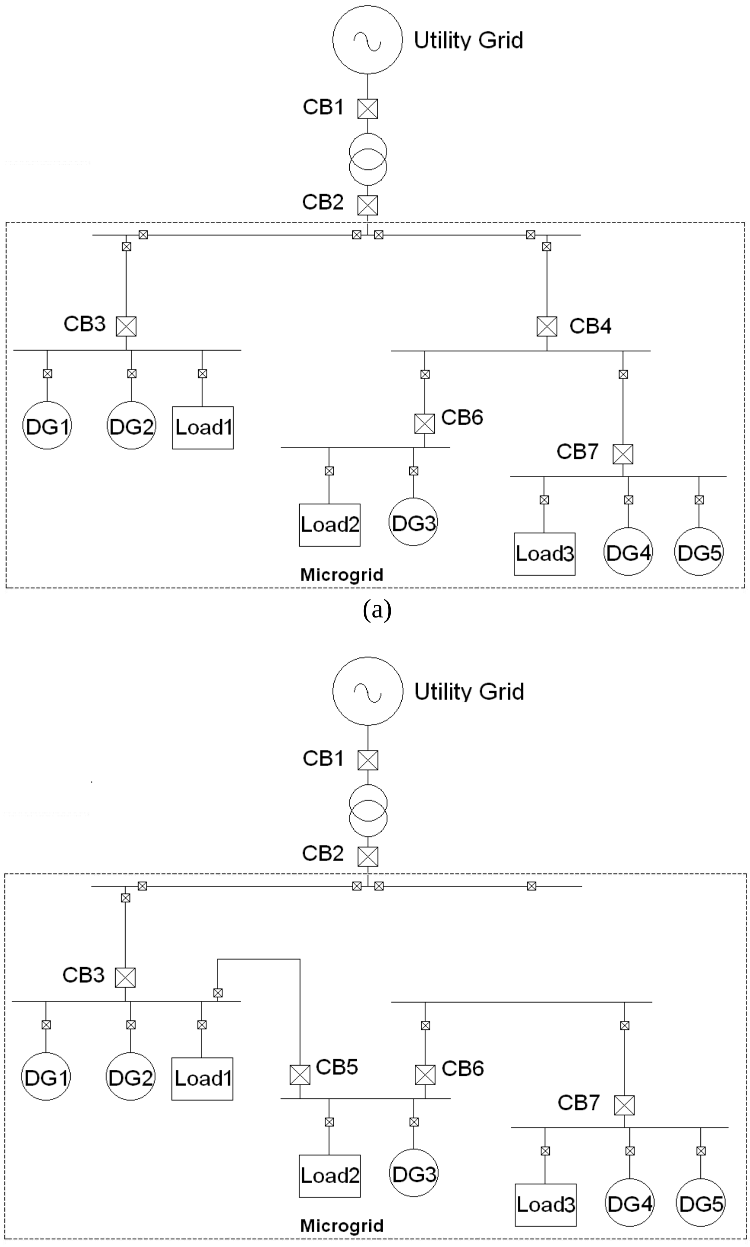

Figure 5.6. The network structure change from Case 1 (a) to Case 3 (b)

As shown in Table 5.2, for Case 3, there is only one branch with 5 hierarchy levels. Therefore, 2-pair assignment for this case is as shown in Table 5.4. When Table 5.3 and Table 5.4 are compared, it becomes evident that the pairing of the relays change and they need to be updated. A reliable communication is vital for this purpose. In similar fashion, the protection system will recognize any new structure and repeat pairing process according to Table 5.2.

TABLE 5.4. RELAY PAIRING FOR CASE 3

Relay Hierarchy	1st branch	Selectivity pairs
5	R2	
4	R3	
3	R5	
2	R7	
1	I.R.	

If an automatic relay hierarchy detection algorithm such as in [182] is not utilized, then it has utmost importance that the network operators have their power engineers study possible network structures of the microgrid, list the proper hierarchy of the relays and prepare Table 5.2. MCPU will automatically operate according to these data.

5.5. Faults outside the microgrid

One exceptional case arises when a fault occurs outside the microgrid, i.e. in the utility grid. Since the fault is in the utility grid, the microgrid should be isolated from the system by opening R1. In this case, the interfacing relay R1, which is at the top of the relay hierarchy, is required to operate first. Figure 5.7 shows the fault currents and the inversed selectivity hierarchy under these circumstances.

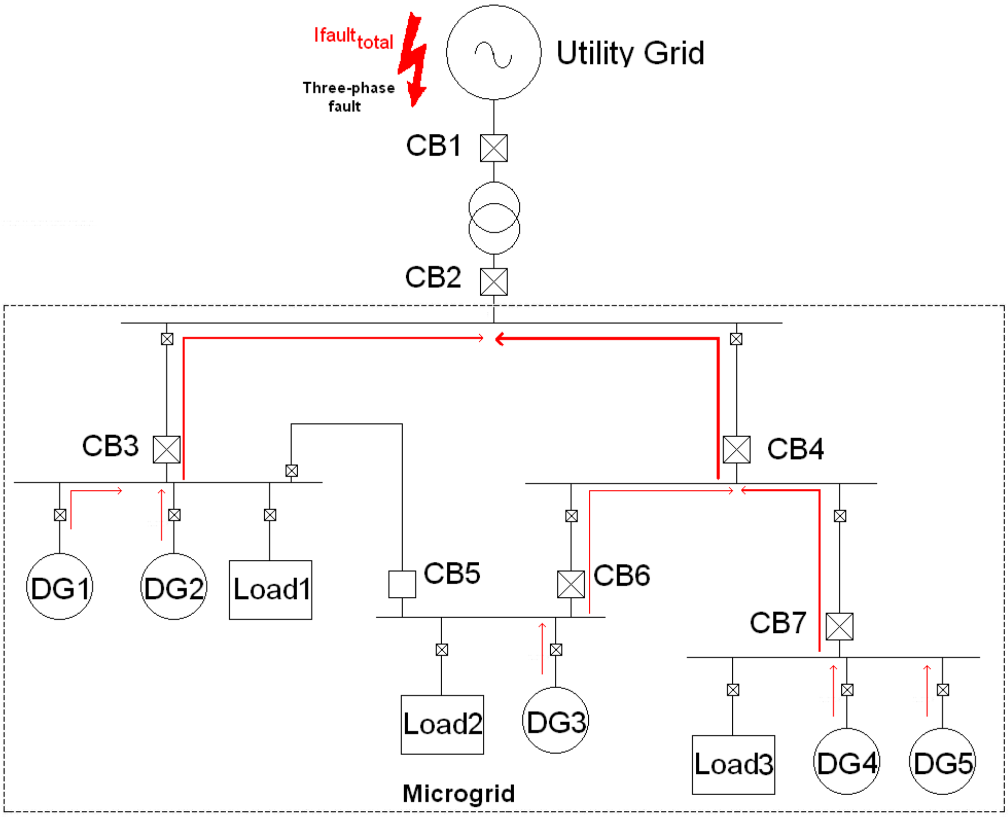

Figure 5.7. Faults in the Utility Grid

In order to address this issue, it is requires that relays must have directional overcurrent and directional power capabilities. As proposed earlier, these capabilities are necessary for bidirectional operation [73, 162]. The proposed system, which is a combination of fault current and relay hierarchy assignment, is implemented bidirectionally. DGs' fault contribution will be calculated for the critical relays through which they are connected to the utility grid.

Referring to the system in Figure 5.7, for instance, reverse overcurrent threshold of R2 will include the contributions of DG1 and DG2. Once the reverse overcurrent thresholds are calculated, the relay hierarchy order will be exactly the opposite of order given in Table 5.2. This means when a fault outside the microgrid occurs and the fault current flows in reverse direction (i.e. upstream), R1 will act first and isolate the microgrid from the fault. If, for any reason, it fails to interrupt the current, reverse selective hierarchy imposes that R2 must interrupt the reverse fault current.

TABLE 5.5. BIDIRECTIONAL PARAMETERS FOR CASE 1

1st branch	R2	R3	I.R.	
Forward Pair	R3	I.R.	N/A	
Reverse Pair	R1	R2	R3	
Forward Current	$IrelayF_{R2}$	$IrelayF_{R3}$	$IrelayF_{I.R.}$	
Reverse Current	$IrelayR_{R2}$	$IrelayR_{R3}$	$IrelayR_{I.R.}$	
2nd branch	R2	R4	R6	I.R.
Forward Pair	R4	R6	I.R.	N/A
Reverse Pair	R1	R2	R4	R6
Forward Current	$IrelayF_{R2}$	$IrelayF_{R4}$	$IrelayF_{R6}$	$IrelayF_{I.R.}$
Reverse Current	$IrelayR_{R2}$	$IrelayR_{R4}$	$IrelayR_{R6}$	$IrelayR_{I.R.}$
3rd branch	R2	R4	R7	I.R.
Forward Pair	R4	R7	I.R.	N/A
Reverse Pair	R1	R2	R4	R7
Forward Current	$IrelayF_{R2}$	$IrelayF_{R4}$	$IrelayF_{R7}$	$IrelayF_{I.R.}$
Reverse Current	$IrelayR_{R2}$	$IrelayR_{R4}$	$IrelayR_{R7}$	$IrelayR_{I.R.}$

In order to realize this in a systematic way, relays should have four different parameters, as shown in Table 5.5. In this table, each relay has two relay-pairing (forward & reverse) and fault current parameters, one for forward (downstream) and one for reverse (upstream) fault current flows. Two relay currents shall be calculated individually by considering fault current contributions of various DGs. Pairing of the relays for 2-pair selectivity, on the other hand, can be calculated at once. The reverse relay hierarchy is extracted by inverting the forward hierarchy and the assignment is trivial.

This additional feature can easily be implemented in the MCPU if the relays have the capability to operate in both directions. Such relays are called directional overcurrent relays and an example can be found in [183]. MCPU will calculate two different overcurrent thresholds, namely forward and reverse fault currents, and should the fault current flow in reverse direction, the Critical Relay Hierarchy will be reversed.

5.6. Reliability considerations

The protection systems in electrical networks play a vital role in sustaining stability and ensuring safe operation. With the development of new technologies, protection systems became more complex. Significant progress has been recorded in power system reliability modeling and computation by applying quantitative analysis based on probability theory [184]. In recent years, different reliability assessment methods have been proposed such as Reliability Block Diagram (RBD) [185], 3RF Technique [186], and Software Reliability Allocation [187]. The failures are classified and new parameters are introduced to design a more comprehensive reliability assessment scheme [184, 188].

These systems consider issues related to relay hardware, relay software, ancillary equipment, communication units and human errors. [186, 188]. All of them consider the probability of a failure occurrence and its impact on system dependability and security as defined by IEEE standard C37.100-1992 [189]. The probability of a failure is defined by [187, 190]:

$$P[failure] = \sum component_{failure} \tag{5.15}$$

where all the individual probability components are added to find the overall value. If there is more than one event that is required for a failure to occur then the combined probability can be expressed as in (5.16).

$$P[failure_{combined}] = \prod_{i=1}^{n} P[probability_i] \tag{5.16}$$

where n is the total number of independent events.

As mentioned in earlier sections, in case of a communication failure, the developed protection system implements a “last-setting-valid” approach. Figure 5.8 shows the local decision making mechanism employed to activate the circuit breakers. As shown, the operation is independent of the communication link and this ensures that relays are always set to operate, though it may not be the most desirable operation point.

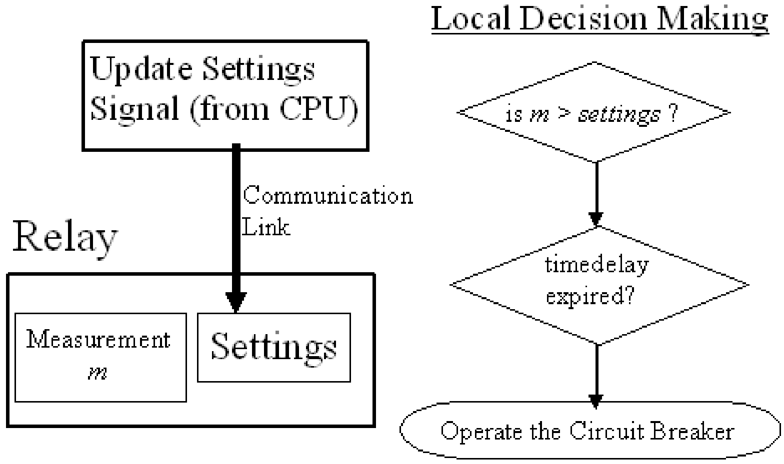

Figure 5.8. Local Decision Making scheme in Relays

However, this requires two events: 1) a failure in the communication line, 2) an electrical fault in the network before the communication line is restored. Therefore the probability of a relay operating following “last-setting-valid” method is the multiplication of the probabilities of communication link failure and electrical fault:

$$P[comm_{fault}]=P[comm] \text{ x } P[fault] \tag{5.17}$$

where P[comm] is the probability of a communication failure occurring in the microgrid while P[fault] is the probability of an electrical fault occurring in the same microgrid. Equations 15 and 16 hold for all conditions except for extreme climate conditions where power system fault follows power law distribution instead of exponential distribution [191]. Extreme weather conditions are not considered in this study.

It is clearly mentioned in the literature that with the improving technology the hardware failures are less frequent [187]. Consequently, the value of probability of communication failure is very small. The values assumed for these probability values are on the order of 10^{-2} or 10^{-3} [188, 190]. For short term analysis these values may drop as low as 10^{-5}[192]. Accordingly, replacing these characteristic values in (5.17) yields:

$$P[comm_{fault}]=0.01 \times 0.001 = 10^{-5} \tag{5.18}$$

As a result, the developed protection system proves to be reliable in accordance with the requirements of the standards [189]. Considering the value of $P[comm_{fault}]$, it is concluded that the possibility of relays operating when there is a communication failure is very small. Even if they are forced to operate before the communication is restored, the implementation of “last-setting-valid” method ensures that no catastrophic condition occurs.

As long as the communication speed is at permissible levels, the communication speed is not vital. Communication is only required for updating relay settings and this occurs when a DG connects to or disconnects from the grid. In case of a fault, no communication is required as relays operate based on Local Decision Making. If, as an exceptional case, a fault occurs just after a Relay Setting Update process has started, then the regular communication speed is around 80 ms [193] and this ensures that relay settings will be updated and the fault will be cleared before maximum allowed time expires.

5.7. Conclusion

This chapter has presented two procedures to assign two key parameters in a microgrid protection system with a real time protection controller such as an MCPU. The first of these parameters is the DG impact factor ‘k’ which is important in accurately anticipating the fault current contributions of DGs’ over a relay. The calculation of the impact factor involves parameters which are known beforehand. Hence, ‘k’ can be calculated before the fault actually occurs. Secondly, an algorithm to adjust the hierarchy of relays for proper selective operation in microgrids has been presented. The concepts of critical relay and 2-pair selectivity have been introduced. The procedure is automated as much as possible by decreasing human input to minimum. The developed system can work autonomously when the possible network structures and corresponding relay hierarchies are supplied in a table. Alternatively, automatic relay hierarchy extraction algorithms, such as the one discussed in Chapter 4, can be utilized and this makes the protection system more robust and independent.

The faults occurring outside the microgrid have also been considered. It is explained how this situation necessitates the protection system to be able to detect and act on directional over-currents. The proposed protection system has been adapted as it is but the calculation and assignment of the k factor and relay selectivity has been modified to suit all cases including the possibility of faults outside the microgrid. As a result, a complex centralized microgrid protection system has been developed and its operation principles and calculation/assignment procedures have been presented in detail.

Finally, the reliability considerations performed in accordance with the reliability assessment methods presented in the literature, has shown that the developed protection system is very reliable in the case of a fault. The selectivity pairs ensure that even if a malfunction occurs in one of the protective devices, total collapse of protection system will be avoided.

In summary, the main intellectual contribution of the work presented in this Chapter has been the development of an adaptive algorithm, which calculates and assigns protection settings on the go. The developed adaptive scheme is able to follow the dynamic changes occurring in the microgrid, easily accommodate new deployments and adjust the necessary settings.

Chapter 6

IEC 61850-Based Modeling of the Microgrid Protection System

Publications pertaining to this chapter:

1) ***Taha Selim Ustun, Cagil Ozansoy, Aladin Zayegh, "Modeling of a Centralized Microgrid Protection System and Distributed Energy Resources According to IEC 61850-7-420," IEEE Transactions on Power Systems, , vol. PP, pp. 1-8, 2012.***

2) ***Taha Selim Ustun, Cagil Ozansoy, Aladin Zayegh, "Distributed Energy Resources (DER) Object Modeling with IEC 61850-7-420," In the Proceedings of the Australasian Universities Power Engineering Conference, AUPEC '11, Brisbane, Australia, 2011.***

3) ***Taha Selim Ustun, Cagil Ozansoy, and Aladin Zayegh; "Extending IEC 61850-7-420 for Distributed Generators with Fault Current Limiters"; In the Proceedings of IEEE PES International Conference on Innovative Smart Grid Technologies ASIA (ISGT Asia),, Perth, Australia, 13-17 Nov., 2011.***

4) ***Taha Selim Ustun, Cagil Ozansoy, Aladin Zayegh,, "Implementing Vehicle-to-Grid (V2G) Technology with IEC 61850-7-420," , IEEE Transactions on Smartgrids, vol.PP, (accepted).***

6.1. Introduction

The preceding chapters explain the modular approach assumed in this research, for the design of the protection system. Firstly, a conceptual design has been developed with contemporary protection challenges in mind. It has been shown that the design is flexible and can be adapted for different grid components such as FCLs. Secondly, the automated microgrid structure detection which is a key part of this research has been explained. This feature enables the developed microgrid protection system to be versatile so that it can be applied on microgrids with changing structures. It also facilitates new deployments. Thirdly, it has been shown how the necessary protection parameters are calculated in this system. It has been elaborated upon how the first two research steps are utilized in the parameter calculation process and thus, a complementary system is achieved.

Similar to previous chapter, this chapter builds upon the previous achievements of this research. It shows how the developed conceptual design with automated approach and parameter assignment features can be implemented with an international communication standard, i.e. IEC 61850 and its recent extension for DER based systems IEC 61850-7-420. This is an important aspect of the developed microgrid protection system, especially from universality, versatility and flexibility perspectives. The work presented in this chapter shows that the developed multi-dimensional protection system can be implemented with international and universal communication standards. Hence, it is suitable for various implementations in different microgrid topologies. It fills a major gap that is related to the need of a standard communication infrastructure which does not depend on the microgrid structure, its components or the manufacturers thereof.

6.2. IEC 61850 International Standard

It has been expressed earlier that in order to sustain a safe operation in dynamic microgrid structures, which have numerous parameters and variables (data) to be monitored, communicated and controlled, a new management strategy with extensive communication capability is required. The need for extensive communication between the microgrid components is widely accepted in the Power Engineering field. In an effort to standardize the communication methods and the data to be communicated, the IEC 61850 standard is issued by International Electrotechnical Commission (IEC). Furthermore, this standard has been extended with IEC 61850-7-420 for the modeling of DER based generators.

In this chapter, the developed protection system has been modeled with logical nodes and data sets provided by IEC 61850-7-4 [194] and IEC 61850-7-420 [132]. Using a standardized method to model these systems and their components is crucial for wide-spread acceptance of microgrids [195]. Having universal data and information exchange models for microgrid protection systems will ease the modeling and the system will be open to new deployments or alterations [196]. Since the models do not depend on the manufacturer or the ratings of the components, this is a major step toward realization of plug-and-play concept [133, 167].

IEC 61850 is an international communication standard aimed at reaching a universal communication infrastructure in electrical systems. It uses Object Oriented (OO) modeling for the equipment and their functionalities. IEC 61850 effectively reduces the burden of communication infrastructure modeling by virtual modeling of physical devices in a standard manner. Furthermore, it also defines necessary procedures for data transfer and client/server interactions between the equipment in an electrical network.

The Generic Object Oriented Substation Event (GOOSE) is widely accepted as the most important one of the data transmission services defined in IEC 61850. GOOSE is a fast connection-less communication service used for the transfer of time critical data where high speed and security are achieved by the repetition of messages a number of times. One of the most significant architectural constructs of the IEC 61850 is the adoption of an “abstracting” technique, which involves the creation of objects that are independent of any underlying protocol. The isolation of the information models and information exchange services from the underlying on-the-wire protocols is usually seen as one of the most powerful capabilities of the IEC 61850 standard. Abstract means that the standard focuses on describing what the services are indented to provide rather than how they are build.

The abstract nature of the definitions permits the mappings of the data objects and services to any other protocol, which provides adequate communication procedures meeting the data and service requirements of the IEC 61850 standard. Currently, IEC 61850 only specifies mappings on a communication stack that includes the Manufacturing Message Specification (MMS) over the Transmission Control Protocol/Internet Protocol (TCP/IP) and Ethernet.

However, the potential need to support mappings to different communication models has clearly been recognized in the industry and examples do exist in the literature detailing such mappings. Although not addressed in IEC 61850, it is possible to implement the standard’s object models and services by mapping to other different communication stacks such as the Distributed Component Object Model (DCOM) or Common Object Request Broker Architecture (CORBA).

Substation Automation Systems (SASs), used for controlling substations, are usually composed of a number of Intelligent Electronic Devices (IEDs) interconnected through a network of high-speed communications with widespread routers and switches [9]. IEC 61850 has the objective of enabling interoperability between IEDs within a substation by defining standard object (information) models for IEDs and functions within a SAS [10]. As a result, it standardizes the language of communication between the SAS devices allowing for the free exchange of information. Although the IEC 61850 set of documents is comprised of 10 parts, the most important contents are found in Parts 7-x:

- IEC 61850-7-1: Principles and models.
- IEC 61850-7-2: Abstract Communication Service Interface (ACSI).
- IEC 61850-7-3: Common Data Classes (CDCs)
- IEC 61850-7-4: Compatible logical node classes and data classes.

Functions in a SAS are defined by modeling the syntax and semantics of the exchangeable application-level data in devices as well as the communication services required to access this data. An important point to clarify is that the IEC 61850 standard only attempts at standardizing the communication visible behaviors of functions rather than their actual internal operations.

Parts 7-2, 7-3, and 7-4 form the three levels of this process. Part 7-2 specifies the basic layout for the definition of the substation-specific information models and information exchange service models. Part 7-3 specifies CDCs and common data attribute types, which are the main building blocks of the LN and Data classes described in Part 7-4. The Logical Node (LN) and Data classes form the elements that allow the creation of the information model of a real substation device. They are the most vital concepts used in the standard to describe real-time substation systems. Further information on IEC 61850 and its application can be found in these references [11] [12].

The model-driven approach of the IEC 61850 standard describes the communication between devices in a substation and the related system requirements. Throughout the preparation of IEC 61850 standard International Electro-technical Commission identified the several aspects of devices which are crucial for proper operation. [197]

6.3. Modeling DER Systems with IEC 61850-7-420 Extension

Soon after its publication IEC 61850 received much attention in power engineering circles as it addressed a vital aspect of communication lines in power systems. In an effort to encourage its utilization in microgrids which have more DG deployments, IEC formed the Workgroup (WG17) to publish an extension of IEC 61850-7-4 Compatible logical node classes and data classes. This extension aimed at having logical nodes and data classes that will help in modeling DER systems effectively. In addition, IEC 61850-7-420 can be further extended for components which are not readily available in this standard. An example of this can be seen under Section (6.4) "Extending IEC 61850-7-420 for New Grid Components" where the said standard has been extended with information and data exchange models for fault current limiters [149] and EVs [147].

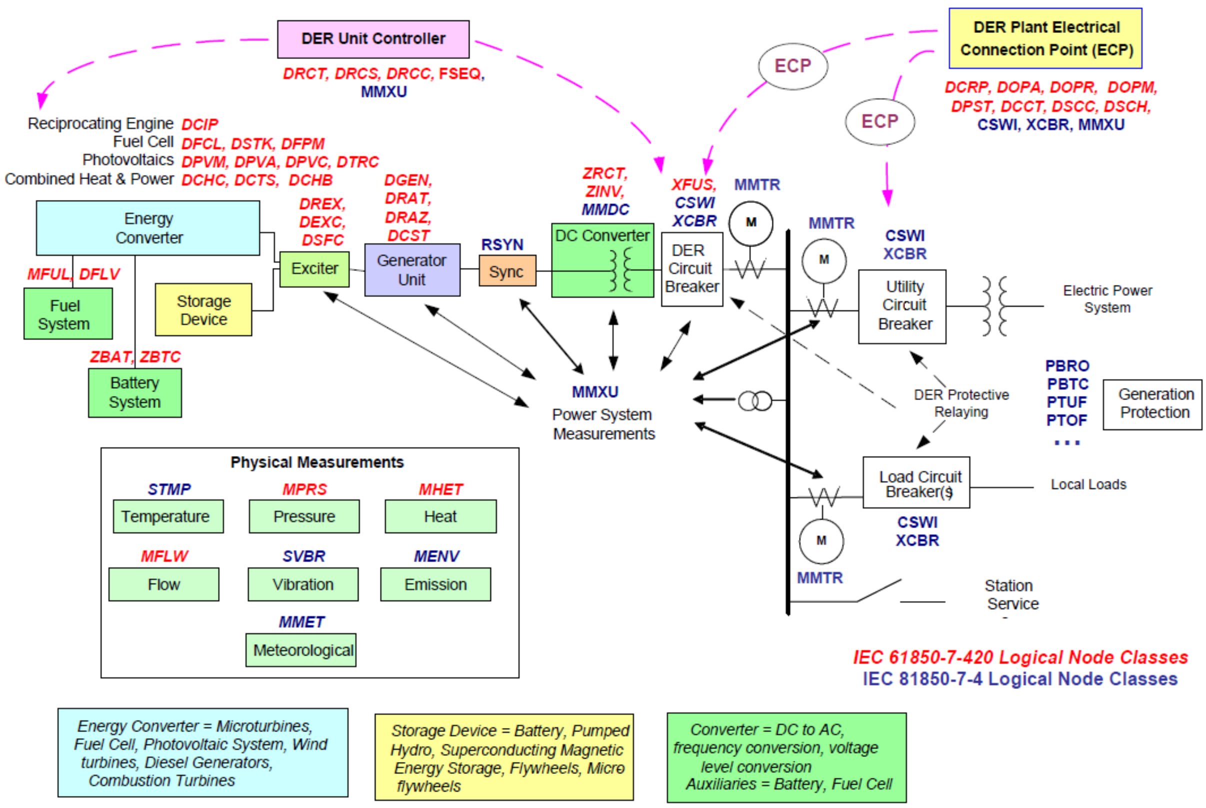

Figure 6.1. Generic DER system in IEC 61850-7-420 [197]

The overall system given in Figure 6.1 is used a template for modeling the DER systems given below; (See Appendix – D for examples of DER modeling with IEC 61850-7-420)

- Diesel Generators
- Solar panels (PV)
- Fuel Cells
- Combined Heat and Power

In addition to switching DERs on and off, DER systems involve:

- Management of the interconnection between the DER units and the power systems they connect to, including local power systems, switches and circuit breakers, and protection.
- Monitoring and controlling the DER units as producers of electrical energy
- Monitoring and controlling the individual generators, excitation systems, and inverters/converters
- Monitoring and controlling the energy conversion systems, such as reciprocating engines (e.g. diesel engines), fuel cells, photovoltaic systems, and combined heat and power systems
- Monitoring and controlling the auxiliary systems, such as interval meters, fuel systems, and batteries
- Monitoring the physical characteristics of equipment, such as temperature, pressure, heat, vibration, flow, emissions, and meteorological information

It has been observed that two distinct colors have been used to denote LNs. The blue color indicates that this particular LN has been included in IEC 61850-7-4 Logical Node Classes list whereas red color indicates that this LN has been introduced with the recent extension IEC 61850-7-420 Logical Node Classes.

The system assumes a holistic sense in which the DER systems are modeled considering their internal parameters, their grid connection types and parameters, and microgrid operator command and control units. This may include fuel type for diesel generators, battery test results for solar panels or hydrogen level for fuel cells. Having detailed characteristics variables and measurement values entrenched inside, this modeling system serves for a rigorous communication system. In order to give a better insight about modeling DER systems according to the mentioned publication, the new LN classes and data classes shall be explained in four groups which are; DER unit controller, internal parameters, grid connection and network operator units.

6.3.1. DER Unit Controller

The four LNs given at the top of Figure 6.1, under this heading *DRCT*, *DRCS*, *DRCC* and *FSEQ* comprises the DER unit controller Logical Device (LD). These LNs are aimed at providing extensive information on the DER controller characteristics, its status and the supervisory control actions that can be undertaken.

DRCT represents a controller which controls a single DER or a group of DERs connected to a single controller. Among other parameters it is required to input the number of DERs connected to it, types of these DERs and maximum output power values.

DRCS provides information on the status of the controller such as its electrical connection, operation mode: automatic or manual, control mode: local or remote etc. By changing these parameters, it is possible to control a DER's electrical connection to the grid from a remote controller or, if it is required, only local and manual control might be enabled. In either case full representation of these data will be present in this logical node.

DRCC represent the supervisory control on DER and it has a full list of actions that can be executed for desired control. Setting different operating points, changing time delays, transient behavior, turning on and shutting down can all be performed thanks to this particular LN. Finally, the LN *FSEQ* is required to provide information on the sequence of actions during starting up or shutting down of a DER.

6.3.2. Internal Parameters

These parameters indicate the internal status of the DG, the characteristics of the fuel (if any), storage systems, battery, exciter, generator unit, converter and the physical measurements to monitor the operation of the DG. Depending on the DER type, i.e. reciprocating engine, fuel cell, photovoltaic, combined heat and power; the energy converter LN is selected from the new LNs provided such as, in proper order, *DCIP*; *DFCL*, *DSTK* and *DFPM*; *DPVM*, *DPVA*, *DPVC* and *DTRC*; *DCHC*, *DCTS* and *DCHB.*

The reason for having more than one LN for the same DG type is to control and model different aspects of that particular DG. For example a fuel cell is modeled with *DFCL* which has fuel cell controller characteristics, *DSTK* which models the fuel cell stack and DFPM which represents the fuel processing module. Diesel generators, on the other hand, are modeled only with *DCIP* which includes all the ratings, measurements and control pertaining to the diesel generator. However, due to its structure, the diesel generator requires an exciter modeled with *DREX*, *DEXC* and *DSFC,* and a generator unit modeled with *DGEN*, *DRAT*, *DRAZ* and *DCST*. In modeling fuel cells these components are out of question.

Both of these DER systems require a fuel system modeled with *MFUL* and *DFLV* which represent fuel characteristics and fuel delivery systems. On the contrary, solar panels which depend on the solar energy do not require such modeling. The LNs given in Physical Measurements box in Figure 6.1 cover physical measurements including temperature by *STMP*, pressure by *MPRS*, heat by *MHET*, flow by *MFLW*, vibration by *SVBR*, emission by

MENV, meteorological conditions by *MMET*. These measurements may belong to the fuel, generator, and auxiliary systems for heating, cooling, lubrication; and environmental conditions that are crucial in ensuring safe and efficient operation.

6.3.3. Grid Connection Units

These LNs comprise the components which are required, or might be required depending on the DER type, for proper gird connection. DER circuit breakers and Utility Circuit breakers which are modeled with *CSWI* and *XCBR* are required for every DG connection. In a unique fashion, IEC 61850-7-420 proposed a LN named *XFUS*, which is used to model a fuse and it can be compared to a circuit breaker for one-time use.

The diesel generator requires the synchronizer *RSYN* so that its output is synchronized with the grid. As known, fuel cells and solar panels yield DC output. A DC switch modeled with *XSWI* or *CSWI* is required to feed the output to the converter. The converter converts the DC output to AC voltage and synchronizes the output in this process. Depending on the situation, converters are modeled with *ZRCT* and *ZINV*.

ZRCT is used in modeling rectifiers which converts generator output AC to intermediate DC. Properties can be set in detail such as types of commutation, isolation, voltage regulation, conversion (AC-DC, AC-AC-DC, AC-DC-DC), cooling method, AC system and filter types. Furthermore, current and voltage limits can also be set. *ZINV* is used in modeling inverters which converts DC input (either directly from a generator or intermediate DC fed by *ZRCT*) to AC. Properties can be set in detail such as switch type, cooling method, type of commutation, isolation, switching frequency and current connect mode. Furthermore, current and voltage limits can also be set.

6.3.4. Network Operator Units

These LNs are required to model Electrical Connection Point (ECP) LDs and aimed at sorting out the issues related to Network operation such as legal information (ownership, authority, obligations and permissions), technical characteristics (types of DER devices, connection types, operation modes, ratings), control authority permissions and other management information.

In brief at each ECP, *DCRP* includes DER plant corporate characteristics (such as ownership, contractual obligations and permission), *DOPR* has DER plant operational characteristics (such as DER device types, ratings, connection types, operation modes), *DOPA* has information on DER operational control authorities (who has the authority to switch on/off DGs or switches), *DOPM* is used to either get information about or set the operating mode of DGs, *DPST* represents the actual status at ECP including alarms and connection status, *DCCT* has the economic dispatch parameters, *DSCC* is used to control energy and ancillary services schedules and *DSCH* is the schedule for DER plant to provide energy and/or ancillary services.

6.4. Extending IEC 61850-7-420 for New Grid Components

Due to the amount of attention IEC 61850 received worldwide, the IEC formed Work Group 17 (WG17) to develop and publish an extension to the IEC 61850-7-4: Compatible logical node classes and data classes, i.e. IEC 618520-7-420 [12] aimed at developing and publishing LNs and data classes so that one common standard could be established for all DER devices. Although this extension gives a comprehensive list of models and parameters to represent various types of DERs, the standard is far from complete and still information models for some devices are not included such as models for FCLs or EVs.

The ever-evolving of microgrid technologies require that the communication standard intertwined with these technologies shall also evolve constantly and keep up with the latest developments. During the course of this research, two important extensions have been made to the IEC 61850 standard to include models for FCLs and EVs. The motivation behind choosing these devices is their potential in microgrids and expected wide-spread us thereof.

Following two sub-sections reveal the details of the LNs, which have been developed for FCLs and EVs and are being proposed in this thesis as a contribution to knowledge. The contributions made have been discussed around the parameters chosen for command and control, the overall modeling with LNs from IEC 61850 and from IEC 61850-7-420, the point of connection in the grid and virtualization of the devices.

6.4.1. Fault Current Limiter Extension for IEC 61850-7-420

Regardless of the structure of the microgrid management system utilized, the development of a comprehensible model for DGs with FCL is inevitable. The operation principle of different FCLs outlined in the previous chapters is almost identical. Regardless of its type, an FCL follows the fault current limitation characteristics given in Figure 6.2. Below the threshold value, there is no control on output current and it is free-flowing. Once the threshold is passed, a predetermined i_{fault} is observed at the output after the reaction time ($t_d - t_f$).

Therefore, the control parameters that are required in the communication system are the same. These are; the threshold current (i_{th}), the limited fault current (i_f), the time required for the FCL to react ($t_d - t_f$). These parameters are required to anticipate the behavior of the FCL and, hence, estimate and control the transients in a network.

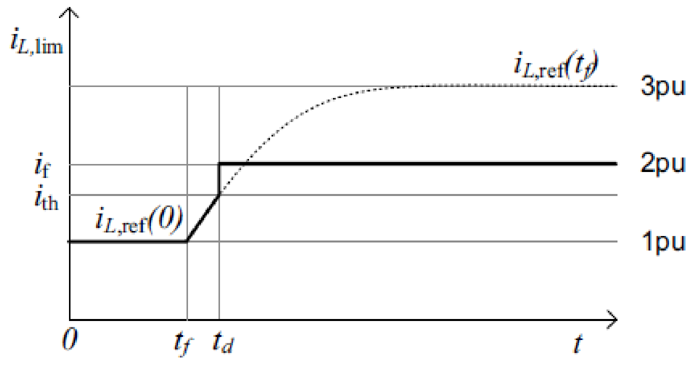

Figure 6.2. Fault current limitation for inverter topology [160].

The extension of IEC 61820-7-420 to accommodate FCL can be achieved in three different ways:

1. Updating *DRAT* (direct-coupled DGs) *ZINV* (inverter interfaced DGs) with FCL control parameters
2. Updating *DRCT* (both for direct-coupled and inverter interfaced DGs) with FCL control parameters
3. Proposing a new block, *FACL*, for FCLs at DG output (placed before DER Circuit Breaker in Figure 6.1)

The first method requires repetition of the same adjustment for each DG type while the second method already encompasses both types of the DGs through updating *DRCT* block. Since *DRCT* is a universal block for all types of DGs, updating its structure shall be sufficient. Therefore, following sub-sections focus only on the latter two methods above.

6.4.1.1. Updating the DER controller LN (DRCT)

Table 6.1 shows the updated version of *DRCT* class which includes the data given in IEC 61850-7-420 [197] as well as the appended FCL parameters. Following the definition of IEC 61850 - Part 7.3 [198], Common Data Classes, the two current values \`ThrshldCrnt\` and \`FCLCrnt\` are defined as Analogue Setting (ASG) class while \`FCLDelay\` is defined as Integer Status Setting (ING). These parameters are indicated to be Optional ‘O’ since *DRCT* is a universal class for all DG controllers including DGs without a fault current limiter.

TABLE 6.1. UPDATED DRCT CLASS

<table>
<tr><th colspan="5">DRCT class</th></tr>
<tr><th>Data Name</th><th>CDC</th><th>Explanation</th><th>T</th><th>M/O/C</th></tr>
<tr><td>LNName</td><td></td><td>Shall be inherited from logical-node class (see IEC 61850-7-2)</td><td></td><td></td></tr>
<tr><td colspan="5">Data</td></tr>
<tr><td colspan="5">System logical node data</td></tr>
<tr><td></td><td></td><td>LN shall inherit all mandatory data from common logical node class</td><td></td><td>M</td></tr>
<tr><td></td><td></td><td>Data from LLN0 may optionally be used</td><td></td><td>O</td></tr>
<tr><td colspan="5">Settings</td></tr>
<tr><td>DERNum</td><td>ING</td><td>Number of DER units connected to controller</td><td></td><td>M</td></tr>
<tr><td>DERtyp</td><td>ING</td><td>Type of DER unit:
<table>
<tr><td>Value</td><td>Explanation</td></tr>
<tr><td>0</td><td>Not applicable / Unknown</td></tr>
<tr><td>1</td><td>Virtual or mixed DER</td></tr>
<tr><td>2</td><td>Reciprocating engine</td></tr>
<tr><td>3</td><td>Fuel cell</td></tr>
<tr><td>4</td><td>Photovoltaic system</td></tr>
<tr><td>5</td><td>Combined heat and power</td></tr>
<tr><td>99</td><td>Other</td></tr>
</table></td><td></td><td>M</td></tr>
<tr><td>MaxWLim</td><td>ASG</td><td>Nominal max output power</td><td></td><td></td></tr>
<tr><td>MaxVarLim</td><td>ASG</td><td>Nominal max output reactive power</td><td></td><td>M</td></tr>
<tr><td>StrDlTms</td><td>ING</td><td>Nominal time delay before starting or restarting</td><td></td><td>M</td></tr>
<tr><td>StopDlTms</td><td>ING</td><td>Nominal time delay before stopping</td><td></td><td>M</td></tr>
<tr><td>LodRampRte</td><td>ING</td><td>Nominal ramp load or unload rate, power versus time</td><td></td><td>M</td></tr>
<tr><td>ThrshldCrnt</td><td>ASG</td><td>Threshold current for the Fault Detection</td><td></td><td>O</td></tr>
<tr><td>FCLCrnt</td><td>ASG</td><td>The Fault Current of FCL</td><td></td><td>O</td></tr>
<tr><td>FCLDelay</td><td>ING</td><td>Time required for the fault detection</td><td></td><td>O</td></tr>
</table>

If a FCL is implemented in DG, these data can be updated and the microgrid management and/or protection system can retrieve the related current and timing values through communication system. Transient behavior estimation or fault condition planning of the microgrid, or the DG in particular, can be done accordingly.

6.4.1.2. Information Modeling for the FCL Logical Device

The IEC 61850 standard identifies all known functions in a system and splits them into sub-functions or so called Logical Nodes (LNs). In other words, a LN is a sub-function located in a physical node, which exchanges data with other separate logical entities. LNs are virtual representations of real devices [161]. Conforming with the same approach, a new LN, *FACL*, which will be used in the representing FCLs in the virtual data communications world, has been designed. Figure 6.3 depicts the association between FCL devices in the real world and the LNs used in their virtualization. In this figure, FCL LD has a single LN, *FACL*, which includes the necessary control and communication parameters.

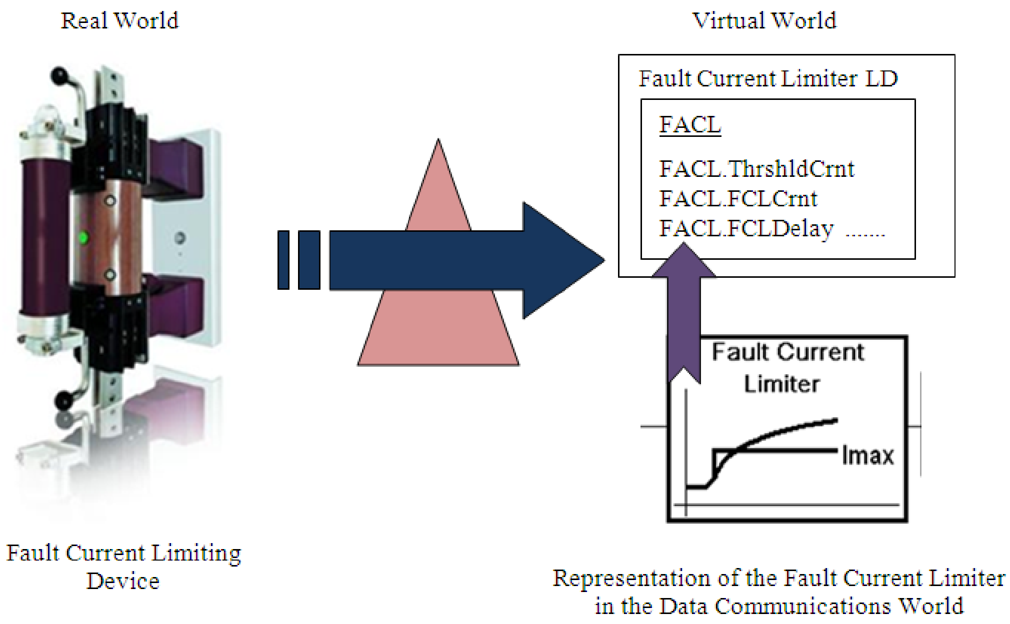

Figure 6.3. Virtualization of Fault Current Limiters with proposed LNs

Table 6.2 shows the new model designed for the modeling of FCLs in an independent manner. In addition to the parameters added in sub-section A, (`ThrshldCrnt`, `FCLCrnt`, and `FCLDelay`) the proposed class *FACL*, includes several other entries on ratings which are proposed in parallel with the existing FCL devices and datasheets [199]. There are four rating entries which are all defined as ASG class. Of these, `VRtg` holds the rated voltage, `IRtg` holds the rated current, PfVRtg holds the rated power-frequency withstand voltage and `LiRtg` holds rated lightning impulse withstand voltage values. Since they are not vital to the operation of FCL these rating entries are defined as optional (O) parameters.

TABLE 6.2. FACL CLASS

FACL class				
Data Name	**CDC**	**Explanation**	**T**	**M/O/C**
LNName		Shall be inherited from logical-node class (see IEC 61850-7-2)		
Data				
System logical node data				
		LN shall inherit all mandatory data from common logical node class		M
		Data from LLN0 may optionally be used		O
***Setting*s**				
ThrshldCrnt	ASG	Threshold current for the Fault Detection		M
FCLCrnt	ASG	The Fault Current Value of FCL		M
FCLDelay	ING	Time required for the fault detection		M
VRtg	ASG	Rated Voltage		O
Irtg	ASG	Rated Current		O
PfVRtg	ASG	Rated power-frequency withstand voltage		O
LiRtg	ASG	Rated lightning impulse withstand voltage		O
Status Information				
FaultCount	INS	Count of Fault Occurrences		M
FCLStatus	SPS	True: Fault Current Limitation is ON False: Fault Current Limitation is OFF		M
FaultDetect	SPS	True: Fault is Detected False: No Fault is Detected		M
FCLOpticSignal	SPS	True: Fault Current Limitation Indicator is ON False: Fault Current Limitation Indicator is OFF		O
FCLAudibleSignal	SPS	True: Fault Current Limitation Audible Signal is ON False: Fault Current Limitation Audible Signal is OFF		O
Controls				
FCLControl	DPC	Switch on/off, Fault current limitation, On=True, Off=False		M
Measured Values				
OutACV	MV	FCL voltage in AC volts		O
OutACA	MV	FCL current in AC amps		O

Furthermore, *FACL* class provides more information on the status of the FCL. \`FaultCount\`, for example, holds the count of the fault occurrences for protection system planning. \`FCLStatus\` belongs to Single Point Status (SPS) data class and indicates whether FCL is switched on or off. This operation is performed with \`FCLControl\` variable which belongs to Controllable Double Point (DPC) class. \`FaultDetect\` indicates whether the existing current value is higher than \` ThrshldCrnt\` and a fault is detected. \`FCLOpticSignal\` and \`FCLAudibleSignal\` are optional (O) entries which indicate whether these signals are activated.

Two different entries are proposed as measurement parameters. OutACV holds FCL voltage in AC volts while OutACA holds FCL current in AC amps. Both of these parameters are defined as Measured Value (MV) class. Not every FCL topology requires or has a measurement device equipped on them. Therefore these measurements are defined as optional (O). The connection of the proposed block, *FACL*, will be as shown in Figure 6.4.

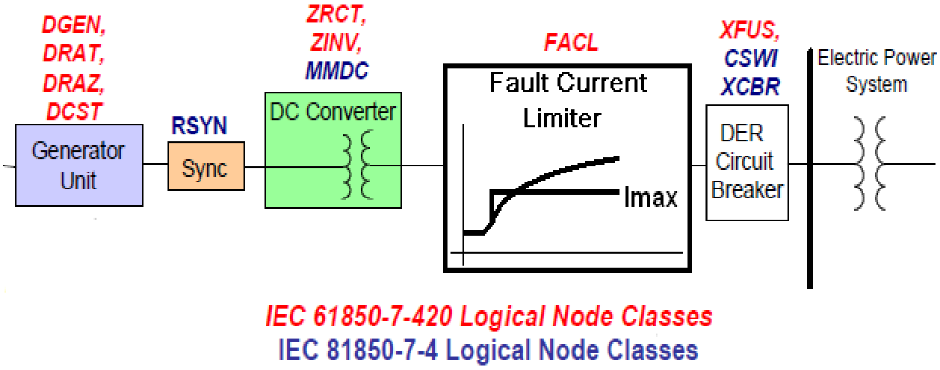

Figure 6.4. FACL Class in Generic DER system (IEC 61850-7-420)

6.4.2. *Electric Vehicle (EV) Extension*

Climate change concerns and carbon emission reduction schemes make the use of EVs more popular. The availability of the technology and the promising acceptance of Hybrid Electric Vehicle Cars (HEVs) encourage car manufacturing companies to take solid steps towards the EV market. Accordingly, in recent years the awareness of people about EVs increased significantly. In addition to the well-known advantages such as zero direct emissions, less oil-dependency, cheaper fuel, more silent operation through smart grids, EVs also offer a unique benefit called Vehicle to Grid (V2G) technology. Through the V2G, EVs can support better operation of smart grids in terms of reliability and storage. The statistics indicate that the growing population demands more cars and acceptance of EVs could have benefits in different fields such as environment, finance and energy.

Different car manufacturing companies have already manufactured Plug-in Hybrid Electric Vehicles (PHEVs), EVs and Hybrid EVs (HEVs) [200-203]. The variety of EV technology makes it possible to meet demands under different circumstances. HEVs and PHEVs can be used for increasing the fuel efficiency and gradual introduction of EVs until the necessary infrastructure is prepared. All the technology required for EV is readily available and the research work focuses on improving the performance or efficiency [134].

When coupled with the smart grid technology, an EV can act as a load as well as a distributed storage device. Being connected to the grid when not in use, battery of the EV can supply power at peak load times and thus increase the reliability of the grid. This technology is called the V2G technology [139]. Considering the total number of vehicles in a locality, distributed storage capacity provided by V2G can have very large impact on the economical operation of smart grids.

Therefore, it is a well-acknowledged fact that EVs will become an indispensable part of our daily lives [204] as well as the electrical network [205] in near future. Being a technology which became popular recently, EV has not been included in international communication standards prepared for electrical networks. This section extends IEC 61850-7-420 with EV models and, thus, fills an important knowledge gap in the literature.

6.4.2.1. Current Status of EV Technologies

There are various EV technologies available in the market. Some of the manufacturers use HEVs to increase the efficiency of the car while others take another step towards all-electric mode with PHEVs. Some other manufacturers, such as Tesla Motors, dedicate their efforts on pure EVs which do not even have a tail pipe [200]. HEVs are classified as series, parallel and series parallel [206]. Figure 6.5 shows the typical diagram of a series hybrid power train. Fed by fuel tank, the internal combustion engine (ICS) charges the batteries through the generator. The traction is provided to the wheels through battery-propulsion motor couple. In a series power train, the ICS engine is mechanically decoupled from the wheels. This gives the freedom to relocate ICS engine as desired. Despite expensive manufacturing costs, series power trains are easy to design, control and implement[206]. They are also popular for larger vehicles [134].

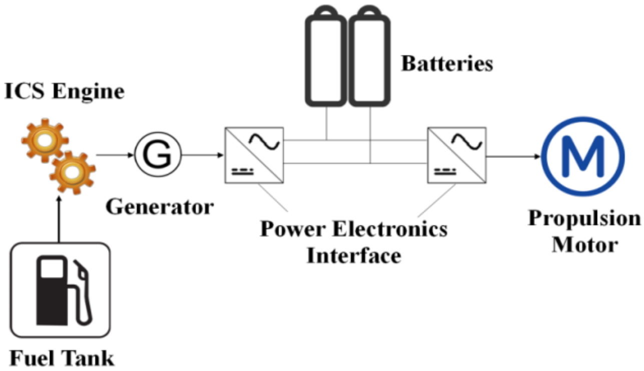

Figure 6.5. A HEV with a series hybrid power train

Figure 6.6 shows the topology of a parallel hybrid power train where both ICS engine and the electric motor are mechanically coupled to the wheels. The electric motor helps increase the efficiency of ICS engine and decrease its carbon emissions. One drawback of parallel power trains is the inability to operate in all-electric mode at high speeds [134].

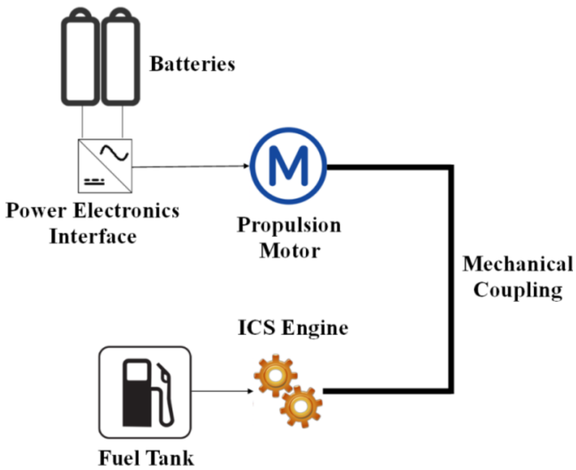

Figure 6.6. A HEV with a parallel hybrid power train

Figure 6.7 shows a PHEV with series-parallel hybrid power train. It possesses the advantages of both the series and parallel hybrid trains. Since it has more components, an additional generator compared with parallel power train and an additional mechanical link compared with series power train. Hence, it is more expensive. Thanks to advancements in control and manufacturing technologies, these costs are reduced and series-parallel power trains are adopted more frequently [206]. Figure 6.7 also depicts the fundamental difference between HEVs and PHEVs. The battery system in PHEVs has an external connection and can be recharged independently from the operation of the ICS engine.

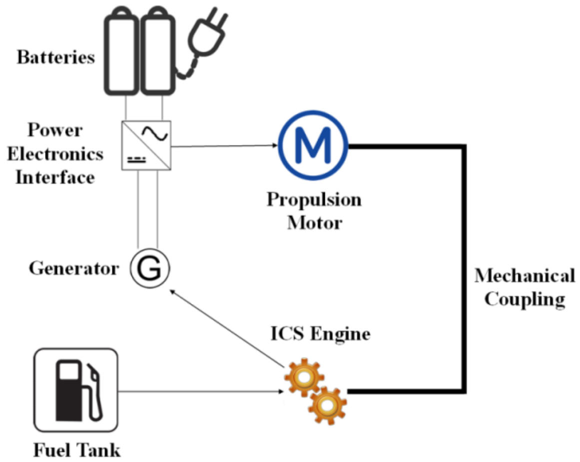

Figure 6.7. A PHEV with a series-parallel hybrid power train

The motivation behind hybridization is to increase the overall efficiency of the engines and decrease emissions per unit distance. The benefits of hybridization can be summarized as follows [134]:

- Higher efficiency is obtained since electric propulsion machines are more efficient and faster than other systems
- The flexibility provided by the electric propulsion systems makes it possible to operate heat engine at higher-efficiency region
- Regenerative braking can be utilized to charge the batteries during braking

The hybridization factor of the vehicles may vary depending on the classification of HEVs. Micro hybrids have a hybridization factor of 5-10 % while mild hybrids have 10-25 %

hybridization factor. Higher values are found in energy hybrids [134]. Needless to say, when the need for ICS engine and the liquid fuel is completely eliminated, a pure EV is obtained. Furthermore, due to their external electrical connection, PHEVs as well as pure EVs allow for V2G operating modes. The standard modeling presented in this chapter provides a generic model for the smartgrids. The manufacturer, model or the type of PHEV or EV is not required for proper operation. This is a massive advantage for microgrids, especially when diversity of car manufacturers and their technologies are considered.

Battery charging seems to be a challenge for manufacturers, customers and other parties. EV charging may require special charging stations, supply devices and connectors. In addition to several issues such as charging through third parties, the most important concern is the time required to charge the batteries. Depending on the network parameters and availability of the special charging equipment, charging time varies between 18 hours and 20-50 minutes. Table 6.3 shows different set of charging options developed for an EV [134].

TABLE 6.3. TYPICAL SET OF EV CHARGING OPTIONS

Charging Set	Utility Service	Usage	Charge Power (kW)
Level 1	110 V, 15 A	Opportunity	1.4
Level 2a	220 V, 15 A	Home	3.3
Level 2b	220 V, 30 A	Home/Public	6.6
Level 3	480 V, 167 A	Public/Private	50-70

Only Level 1 may not require an upgrade of the existing electrical networks while the remaining three charging sets definitely would require a through electrical network improvement. Level 1 is called the \`Opportunity\` charging since it uses low-peak periods, costs less but takes very long. Level 2 can be used for home use. Public usage means charging EVs when parked in a public place such as railway stations or public car parks. Level 3, which is also called fast charging, can be used by private charging stations. EV owners can use these stations for charging in a similar fashion to petrol stations. Yet, in addition to electric network upgrades, Level 3 charging may require special charging equipment [139].

TABLE 6.4. BATTERY CHARACTERISTICS OF DIFFERENT EVS

Manufacturer	Model	EV Type	Electric Range (km)	Battery Size (kWh)
Toyota	Prius	PHEV	8	4
Buick		PHEV	16	8
Chevrolet	Volt	EREV	64	16
Fisker	Karma	PHEV	80	22
Nissan	LEAF	EV	160	24
Toyota	RAV4 EV	EV	190	27
Cooper (BMW)	Mini E	EV	251	28
Tesla	Roadster	EV	354	53

The battery characteristics of different EVs are given in Table 6.4 [200-203]. The corresponding charging curves for different EVs using different charging options are plotted in Figure 6.8. As shown, Level 1 is not feasible for some pure EVs with large battery sizes. Level 3 seems to be practical for all types, although it is expected to be the most expensive option of all. It is shown that Level 2a and 2b are quite sufficient for almost all EVs and can be implemented parking places for short to medium parking times (such as parks near schools, universities etc.)

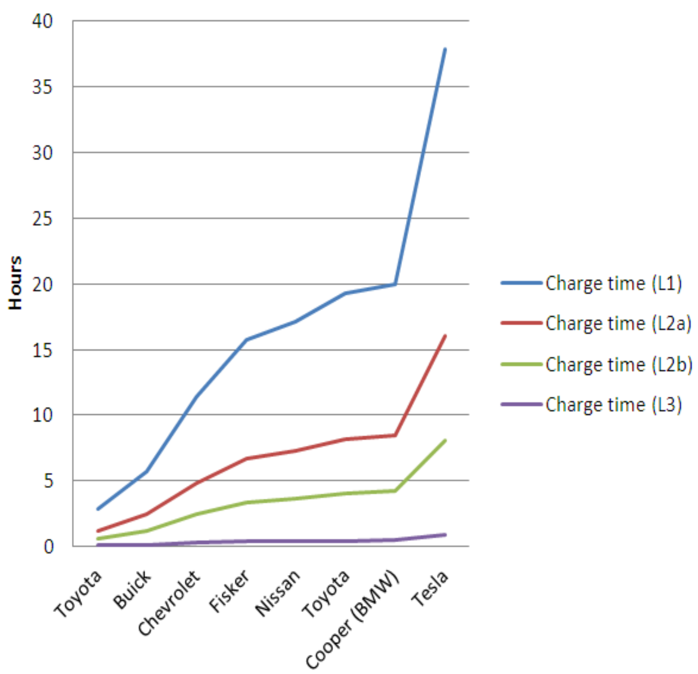

Figure 6.8. Charging time of Several Vehicles for Different Charging Options

6.4.2.2. Modeling EVs with IEC 61850-7-420 for communication in Smartgrids

Large deployments of EVs and their extensive use in smart grids require additional work from network operation perspective. A communication link with each EV is vital to extract its mode of operation (such as load (charging) or storage (charge/discharge)). IEC 61850 [194] communication standard regulates substation communication and its recent extension IEC 61820-7-420 [132] aims at abstract modeling of the information/data models associated with the distributed generation components. However, EVs and V2G technology are yet to be dealt with in this standard. In an effort to fill this gap, an extension to the IEC 61850-7-420 has been made in this research to fully accommodate EVs in smart grids. Whilst IEC 61850 has originally been developed for Ethernet-based substation communications, it is perhaps going to grow beyond that in the future and become the widely used standard for the entire state of the art distribution system, i.e. the smart. The ongoing amendments such as the IEC 61850-7-420 [149] to the original documentation are a clear sign of that.

The large acceptance of EVs will definitely have impacts on electrical networks. It is expected that V2G shall be one of the key technologies in smartgrid strategies [207]. By making use of the V2G technology, EVs not only draw power from the network but also act as distributed storage devices and support it during peak-load times. Through demand side management and demand response, the charge and discharge times of EVs can be scheduled in accordance with the load profile [208]. In this manner, EV owners can sell the stored energy in their vehicles' batteries during peak times and recharge them once the peak hour expires and the price reduces [209]. It is possible to pool several EVs together and provide larger support to the electrical networks where owners can obtain incentive costs [210].

In order to achieve all of these advantages, there shall be communication and synchronization between the components of smartgrids. Similar to other electrical network components, EVs should also be modeled in communication systems. This is important to receive crucial information such as the battery size of the vehicle, amount of the stored energy, time period when V2G is allowed by the owner and the time when EV is required to be fully charged. If these data are provided, network operators can exercise more precise planning data and smartgrids can be operated more effectively and efficiently.

TABLE 6.5. UPDATED DRCT CLASS

<table>
<tr><th colspan="5">DRCT class</th></tr>
<tr><th>Data Name</th><th>CDC</th><th>Explanation</th><th>T</th><th>M/O/C</th></tr>
<tr><td>LNName</td><td></td><td>Shall be inherited from logical-node class (see IEC 61850-7-2)</td><td></td><td></td></tr>
<tr><td colspan="5">Data</td></tr>
<tr><td colspan="5">System logical node data</td></tr>
<tr><td></td><td></td><td>LN shall inherit all mandatory data from common logical node class</td><td></td><td>M</td></tr>
<tr><td></td><td></td><td>Data from LLN0 may optionally be used</td><td></td><td>O</td></tr>
<tr><td colspan="5">Settings</td></tr>
<tr><td>DERNum</td><td>ING</td><td>Number of DER units connected to controller</td><td></td><td>M</td></tr>
<tr><td>DERtyp</td><td>ING</td><td>Type of DER unit:
<table>
<tr><th>Value</th><th>Explanation</th></tr>
<tr><td>0</td><td>Not applicable / Unknown</td></tr>
<tr><td>1</td><td>Virtual or mixed DER</td></tr>
<tr><td>2</td><td>Reciprocating engine</td></tr>
<tr><td>3</td><td>Fuel cell</td></tr>
<tr><td>4</td><td>Photovoltaic system</td></tr>
<tr><td>5</td><td>Combined heat and power</td></tr>
<tr><td>6</td><td>Electric Vehicle (with V2G)</td></tr>
<tr><td>99</td><td>Other</td></tr>
</table></td><td></td><td>M</td></tr>
<tr><td>MaxWLim</td><td>ASG</td><td>Nominal max output power</td><td></td><td></td></tr>
<tr><td>MaxVarLim</td><td>ASG</td><td>Nominal max output reactive power</td><td></td><td>M</td></tr>
<tr><td>StrDlTms</td><td>ING</td><td>Nominal time delay before starting/restarting</td><td></td><td>M</td></tr>
<tr><td>StopDlTms</td><td>ING</td><td>Nominal time delay before stopping</td><td></td><td>M</td></tr>
<tr><td>LodRampRte</td><td>ING</td><td>Nominal ramp load or unload rate, power versus time</td><td></td><td>M</td></tr>
</table>

IEC 61850-7-420 standard which is explained above focuses on DER modeling. However, it does not cover EVs and the functions related to EVs. It is possible to model EVs as distributed storage systems with a smart charging and discharging control. For this, *DRCT* class must first be updated as shown in Table 6.5 where 'DERtyp = 6' would represent an EV.

Figure 6.9 shows the block diagram representation of EV model in data communication world. The battery and its charger are modeled with *ZBAT* and *ZBCT* classes. The grid connection of the EV is realized through a DC switch, modeled with *CSWI* and *XSWI*, and an inverter, modeled with *ZCRT* and *ZINV*. *EVCT* (Electric Vehicle Control) is a new class which is proposed to govern the properties of EVs such as charge/discharge times, V2G control, power measurements, etc. The details of *EVCT* class are presented in Table 6.6.

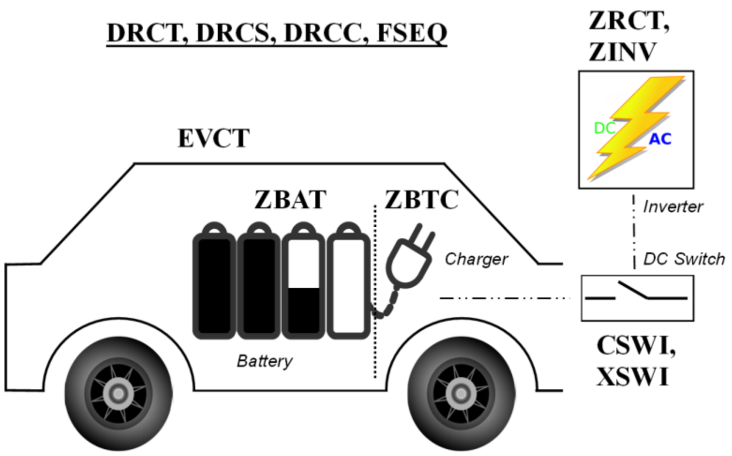

Figure 6.9. Modeling EVs with IEC 61850-7-420.

The settings section includes three items. Through these, in relation with load profiles and peak times, the owner or the network operator can assign V2G start and end times. ChrgReady indicates the time when owner desires EV to be fully charged and ready to move.

First three items in status information section are mandatory. ConnCount keeps the grid connection count for life-time estimation and maintenance purposes. V2GStatus indicates whether the EV under consideration participates in V2G while EconStatus indicates whether the owner opts for economical charging during non-peak times or immediate charging regardless of the cost. Last two variables show the status of visible and audible signals.

There are two control inputs to control V2G participation and economic charging, V2GEnable and EconCharge. These can be toggled either locally by the owner for demand response or by the central network control for demand side management. The optional measurements are aimed at keeping record of energy transfer between the grid and the EV. However, measurement can also be performed through smart meters and in that case separate modeling would be required. Figure 6.10 shows the virtualization of EVs by modeling with IEC 61850-7-420 classes.

TABLE 6.6. PROPOSED EVCT CLASS

EVCT Class				
Data Name	**CDC**	**Explanation**	**T**	**M/O/C**
LNName		Shall be inherited from logical-node class (see IEC 61850-7-2)		
Data				
System logical node data				
		LN shall inherit all mandatory data from common logical node class		M
		Data from LLN0 may optionally be used		O
***Setting*s**				
V2GStart	ASG	V2G-Allowed Period Start time		O
V2GEnd	ASG	V2G-Allowed Period End time		O
ChrgReady	ASG	Time when EV should be fully charged		O
Status Information				
ConnCount	INS	Count of Grid Connection		M
V2GStatus	SPS	True: V2G Participation is ON False: V2G Participation is OFF		M
EconStatus	SPS	True: Economic Charging is selected False: Immediate Charging is selected		M
ChargingSignal	SPS	True: Charging Indicator is ON False: Charging Indicator is OFF		O
BattFullAudibleSignal	SPS	True: Battery Full Audible Signal is ON False: Battery Full Audible Signal is OFF		O
Controls				
V2GEnable	DPC	Switch on/off V2G participation, On=True, Off=False		M
EconCharge	DPC	Toggle between Economic and Immediate Charging, Economy=True, Immediate=False		M
Measured Values				
SuppliedPower	MV	The amount of power supplied to Grid through V2G scheme		O
ReceivedPower	MV	Power received for charging the batteries		O

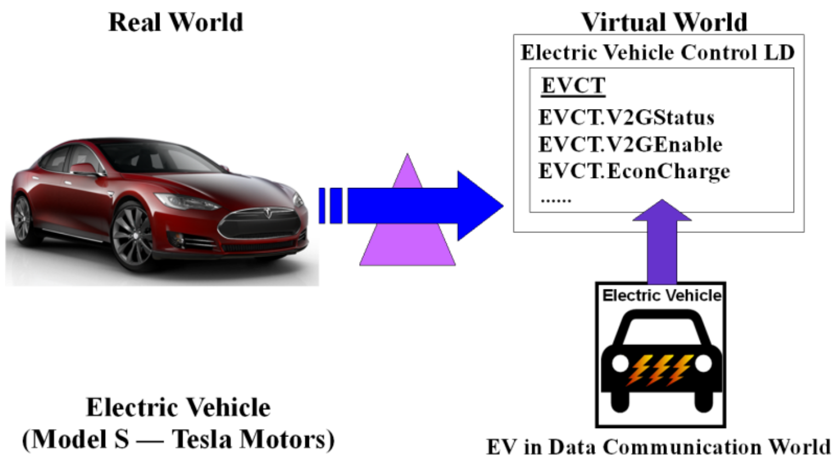

Figure 6.10. Virtualization of Electric Vehicles with proposed LNs

The overall modeling of EV as a DER in compliance with IEC 61850-7-420 is shown in Figure 6.11. *EVCT* class is the interface between battery system and grid connection. *ZBAT* and *ZBTC* classes can be fully adopted as it has very comprehensive battery and charging information [12]. Similar to fuel cells and solar panels, EVs are connected to grid over a DC switch and an inverter. Extended *DRCT* (Table 6.5), *DRCS*, *DRCC* and *FSEQ* can be used for additional network control as in other DER models.

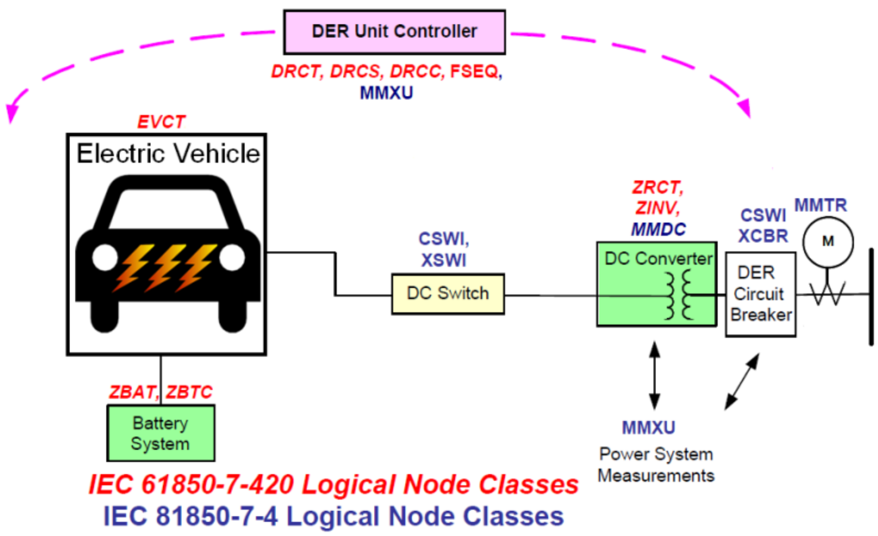

Figure 6.11. EVCT Class in Generic DER system (IEC 61850-7-420)

These models can be used for an individual EV as well as aggregated V2G pools which consist of several EVs. The generic nature of *EVCT* class makes the proposed model very versatile. Various EVs produced by different manufacturers can be conveniently modeled and used separately or in a pool. The integration between car manufacturers and the network operators becomes trivial thanks to the proposed method of presenting EV parameters in a standard fashion.

6.5. MCPU Modeling with IEC 61850-7-420

In this section, the components of the proposed microgrid system have been modeled by using the Logical Nodes (LNs) defined in the international communication standard IEC 61850 and its recent extension for DERs IEC 61850-7-420. Initially, relays and distributed generators have been modeled by equipping them with communication modules which are essential for the realization of the proposed scheme. Figure 6.12 shows the new model designed for relays. It shows how the various appropriate functions for the relay could be modeled using the LNs proposed in the IEC 61850 standard.

In the relay model, *IHMI* and *ITCI* provide the interface for remote control and communication purposes. According to the proposed protection systems, there are two key parameters for the proper operation of relays: operating fault current I_{relay} and the time delay for selectivity t_{relay}. These parameters have been explained in Chapter 3 and Chapter 4 while the calculation and assignment details have been given in Chapter 5.

Depending on the microgrid structure, suitable time delays for selectivity can be calculated and embedded in the communication and control module (CCM). Alternatively, the selectivity can also be calculated by the MCPU on the fly and fed to the relays. This feature will make the system very versatile and new connections can be performed easily. The anticipated drawback is the design and implementation of an appropriate algorithm which can analyze the current status of the network and assign incremental time delays to the relays.

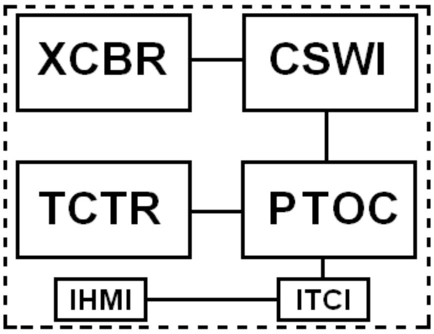

Figure 6.12. Relay LD incorporating various functions modeled with LNs

Once these parameters are calculated by the MCPU, they are sent to each individual relay through *IHMI-ITCI* interface. These critical values are stored in *PTOC* which detects AC over-current flow in a predetermined direction. Therefore, the detection threshold I_{Relay} is stored in *PTOC*. The time delay t_{relay}, which represents the delay applied on detection signal sent to *CSWI*, is also stored inside *PTOC*. *CSWI* is used to send a trigger signal to the *XCBR*, circuit breaker, in case an over-current signal is received from *PTOC*. It is worthy to note here that in modeling the relay, instead of logical node *PIOC*, which detected instantaneous over-current or rate-of-rise, *PTOC* which has the capability to detect fault currents according to their directions, is utilized. This modification is required since fault currents may flow in both directions in microgrids. Furthermore, the relay model is equipped with a remote CCM to update operating fault currents and time delays calculated by the MCPU. This relay model is used for all relays regardless of their positions as load connecting, DG connecting or inter-bus relays.

For a proper communication to be achieved in the network, DGs need to be modeled in accordance with IEC 61850-7-420 and equipped with a communication module which will report the parameters such as status, rated current and DG type to the MCPU. Due to their distinct features each DG type is modeled individually. Figure 6.13 shows the reciprocating engine information model with the LNs from the IEC 61850 standard

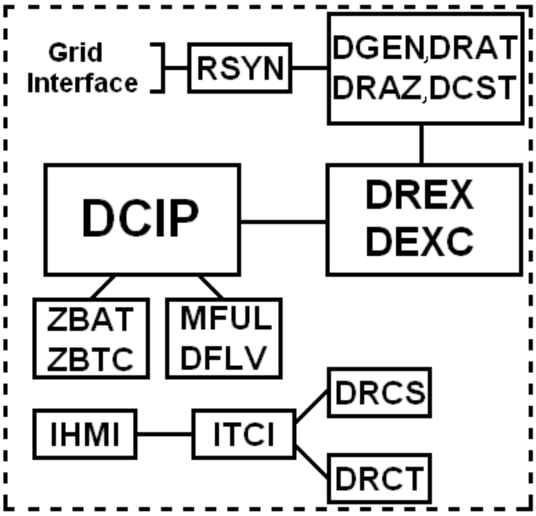

Figure 6.13. Reciprocating Engine Information Model

In this figure, *DCIP* is used to model the reciprocating engine which converts mechanical energy into electrical energy. *ZBAT*, *ZBTC* represent the battery, if any, used in the control and/or start of the engine. *MFUL, DFLV* represent the fuel characteristics and the delivery system of the fuel. The specific fuel type that can be selected in MFUL includes diesel, wind, hydro and the like. Therefore, this DG model can be used to model at least three different DG types which are diesel gen-sets, wind turbines and micro hydroelectric power plants (MHHP). In this section, this structure is used to model DG3 which is a diesel generator.

DREX and *DEXC* model the excitation phenomena while *DGEN*, *DRAT*, *DRAZ* and *DCST* list the ratings, name plate information, maximum power/current values etc. *DRAT* in particular is very useful in calculating fault current contribution which will be described below. Finally, *RSYN* is used to synchronize the generator output with the microgrid and the DG is connected to microgrid through a relay.

The remote communication and control is achieved by *IHMI* and *ITCI* interface. *ITCI* unit is connected to *DRCS* and *DRCT* which represent DER controller status and DER controller characteristics, respectively. In the proposed system, MCPU requires three parameters from every DG. These are DG status, DG type (i.e. inverter-interface or rotating machine) and the rated current value.

The following discussion demonstrates how the various data attributes in the LNs modeling the behavior of the Reciprocating Engine LD can be used in the proposed microgrid protection system and specifically in the proposed MCPU for data logging, decision making and control purposes. The first parameter can be extracted from DRCS. The data **DRCS.ModOnConn** indicates whether the DG is `On and Connected`. When the DG is in operation, i.e. it is ON, and connected, then **DRCS.ModOnConn** is set `True`. The data **DRCS.ModOffAval** and **DRCS.ModOffUnav** indicate whether the DG is `OFF but available to start` or `OFF and not available to start`. In either case the DG will be OFF and will not contribute any fault current. Therefore, if **DRCS.ModOffAval** or **DRCS.ModOffUnav** is set `True` it means the D is not in operation. $Status_{DG}$, the signal which is used to represent whether a particular DG is on or off, can be extracted from values of **DRCS.ModOnConn**, **DRCS.ModOffAval** and **DRCS.ModOffUnav**. This can be represented with the logical expression given in (6.1):

$$\begin{aligned} Status_{DG} &= DRCS.ModOnConn\ \& \\ &(DRCS.ModOffAval \vee DRCS.ModOffUnav)! \end{aligned} \tag{6.1}$$

The DG type is required for fault current estimation and it is listed in **DRCT.DERtyp**. This parameter can be set to 2 to represent rotating machines. This will imply that a factor of 5 shall be used in estimating fault current of the DG.

The rated operating current of the DG can be extracted from *DRCT*. **DRCT.MaxWLim** represents the maximum power rating of the generator. From rated current, the fault current can be extracted as in (6.2):

$$I_{faultDG} = (DRCT.MaxWLim/Voltage) * 5 \quad (6.2)$$

Alternatively, *DRAT* block might be useful in supplying the fault current of the DG. The two parameters **DRAT.FltARtg** and **DRAT.MaxFltRtg** represent the maximum fault and short circuit currents supplied by the generator and they can be directly used by MCPU. The only drawback is that these parameters are listed as `Optional` in the Logical Node, *DRAT*, and they may be omitted for some models. The other parameters used above, on the other hand, are all listed as `Mandatory` in their respective LN.

Figure 6.14 depicts the modeling of a Fuel Cell which is DG2 in the system. It also shows how the various data, data attributes for a Fuel cell LD can be modeled using the LN models defined in IEC 61850. The energy converter is modeled with *DFCL*, *DSTK* and *DFPM*. The reason for having more than one LN for the same DG type is to control and model different aspects of that particular DG.

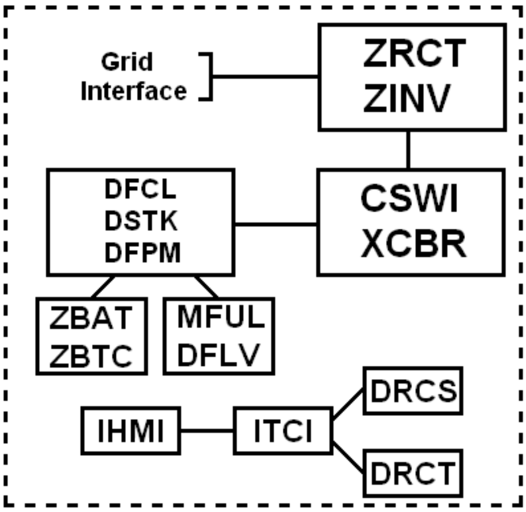

Figure 6.14. Fuel Cell Modeling

For example in a fuel cell, *DFCL* has fuel cell characteristics which reflect those required for remote monitoring of critical functions and states of the fuel cell. Since fuel cells are stacked together to provide the desired voltage level, *DSTK* models the fuel cell stack characteristics required for remote monitoring of the fuel cell stack. *DFPM* represents the fuel processing module which is used to extract hydrogen from other types of fuels before the hydrogen is used in a fuel cell to generate electricity.

ZBAT, *ZBTC* represent the battery, if any, used in the control and/or operation of the Fuel cell. *MFUL*, *DFLV* represent the fuel characteristics and its delivery system.

CSWI and *XCBR* represent the DC switch between the fuel cell and the inverter. The inverter which inverts DC input to AC output according to microgrid voltage and frequency requirements and ensures synchronization is modeled with *ZRCT* and *ZINV*. *ZRCT* is used in modeling rectifiers which converts generator output AC to intermediate DC. Properties can be set in detail such as types of commutation, isolation, voltage regulation, conversion (AC-DC, AC-AC-DC, AC-DC-DC), cooling method, AC system and filter types.

Furthermore, current and voltage limits can also be set. *ZINV* is used in modeling inverters which converts DC input (either directly from a generator or intermediate DC fed by *ZRCT*) to AC. Properties can be set in detail such as switch type, cooling method, type of commutation, isolation, switching frequency and current connect mode. Furthermore, current and voltage limits can also be set.

The remote control and communication module is exactly the same with reciprocating engines. *IHMI* and *ITCI* provide a control interface while critical values are extracted from *DRCT* and *DRCS*. DG status can be extracted similar to the logical expression given in (6.1).

The following discussion once again attempts to show how the various data and data attributes in the Fuel Cell model relates to the developed communication-assisted protection system and how when communications across various network elements enable data logging, decision making specifically in the MCPU.

The DG type listed in **DRCT.DERtyp** can be set to 3 to represent fuel cell. This will imply that a factor of 1.5 shall be used by the MCPU in estimating fault current of the DG since fuel cells are inverter-interface DGs. The rated operating current of the DG can be extracted from *DRCT*. **DRCT.MaxWLim** represents the maximum power rating of the generator. From the rated current the fault current can be extracted as in (6.3):

$$I_{faultDG} = (DRCT.MaxWLim/Voltage) * 1.5 \tag{6.3}$$

Alternatively, *ZINV* block might be useful in supplying the fault current of the DG. The parameter **ZINV.Wrtg** represents the maximum power rating of the inverter. This value can be used instead of **DRCT.MaxWLim** in (6.3). This replacement does not improve the accuracy, since the same calculation is carried out, and this parameter is listed as `Optional` in the Logical Node, *ZINV*.

DG3 used in the modeled system is a PV panel system. The model used for DG1 is given in Figure 6.15. The PV panel has four components which constitute the energy conversion part: *DPVM*, *DPVA*, *DPVC* and *DTRC*. The photovoltaic module ratings covered in *DPVM* describes the photovoltaic characteristics of a module.

The PV characteristics given in *DPVA* describe the configuration of PV array. Information on the number of strings and panels or the number of sub-arrays in parallel can be provided. *DPVC* represents photovoltaic array controller and reflects the information required for remote monitoring of critical photovoltaic functions and states. *DTRC* provides information on tracking system to users.

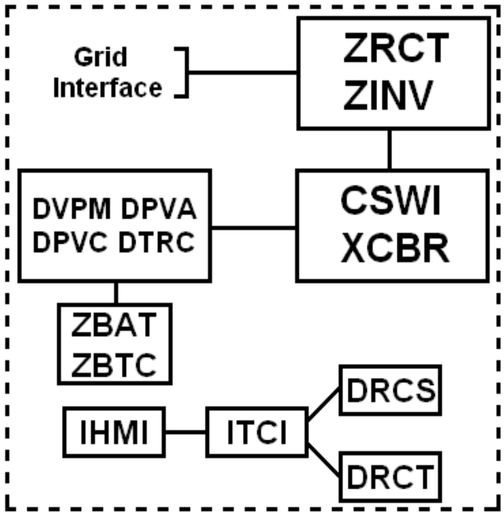

Figure 6.15. PV Panel Modeling

ZBAT, *ZBTC* represent the battery, if any, used in the control and/or operation of the PV arrays. As the PV panels solely depend on solar radiation there is no need for *MFUL*, *DFLV* components as there is no fuel input. Similar to the fuel cell systems *CSWI* and *XCBR* represent the DC switch between the PV arrays and the inverter. The inverter is, again, modeled with *ZRCT* and *ZINV*.

The remote control and communication module is made up of *IHMI* and *ITCI*, as usual, and provides a control interface while critical values are extracted from *DRCT* and *DRCS*. DG status can be extracted similar to the logical expression given in (6.1). The DG type listed in **DRCT.DERtyp** can be set to 4 to represent PV arrays. This will imply that a factor of 1.5 shall be used in estimating fault current of the DG since fuel cells are inverter-interface DGs. The fault current contribution of the DG can be extracted from *DRCT* from **DRCT.MaxWLim** as in (6.3). Alternatively, module short circuit current listed in *DPVM*, i.e. **DPVM.MdulSrtCctA**, can be directly used by the MCPU instead of estimation. This improves the accuracy however, the parameter **DPVM.MdulSrtCctA** is listed as `Optional` in the Logical Node, *DPVM* and it might be omitted for some systems.

6.6. Data Maps With IEC 61850-7-420 Models

In order to substantiate the operation of the modeled blocks and the operation of the proposed protection scheme, the system shown in Figure 6.16 is described over a predetermined scenario. The discussion presented is aimed at showing how the communication of various data should take place between various microgrid network elements to enable protection related decision making, e.g. adjustment of the relay protection settings.

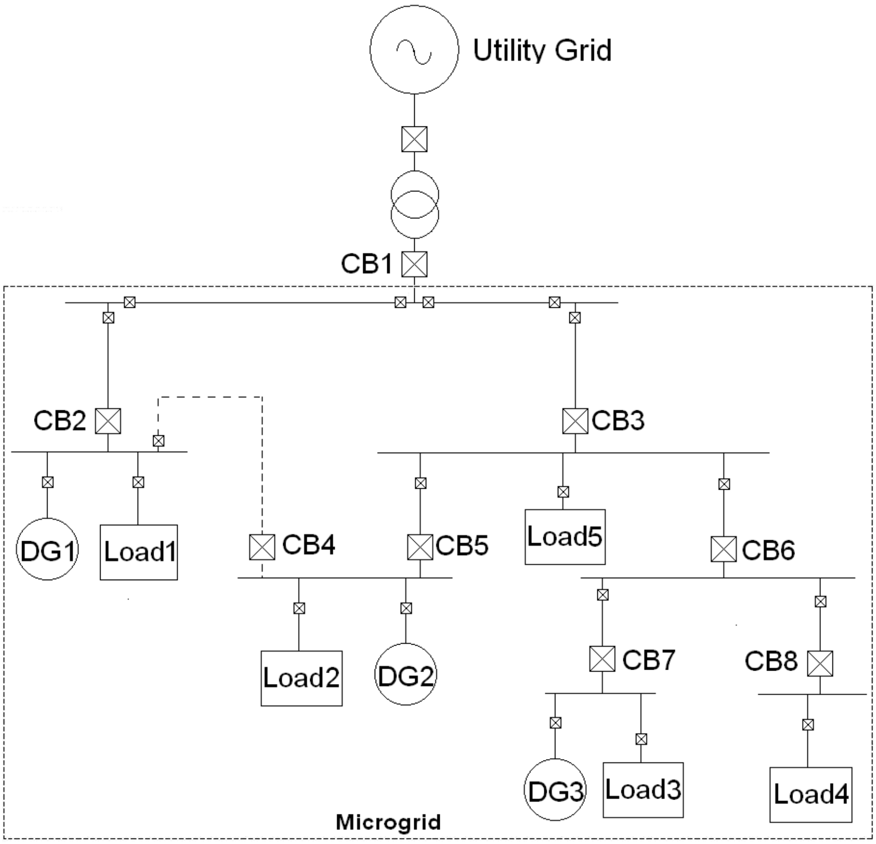

Figure 6.16. The system modeled according to IEC 61850-7-420

The system includes two inverter-interfaced DGs and a diesel generator DG which is used to set the frequency and voltage under islanded conditions. The DGs are operated under conventional droop control and share the loads in accordance with their capacities.

A specially designated scenario is applied to show different aspects of the protection scheme. The applied scenario is as follows:

1. The system starts operation with full load, all DGs are on and the MG operates in Grid-Connected Mode.
2. At t=0.2 sec a fault occurs in Load 1 (L1) and Circuit Breaker (CB) 2 opens. Due to less power demand in the system DG1 also turned off.
3. At t=0.5 sec the utility grid experiences power outage for maintenance reasons and MG becomes islanded.
4. At t=0.65 sec, while MG is operating in islanded mode another fault occurs in L4 and CB8 opens.
5. At t=0.75 sec, the connection with the utility grid is restored and MG operates in grid-connected mode.
6. At t=1 sec, the fault in L1 is cleared and it is reconnected to the system. Due to increased power demand in the network DG1 is also put into operation.
7. At t=1.25 sec, a fault occurs in Load 5 and CB3 opens. To protect the integrity of the microgrid, CB4 is closed and alternative path is used to energize right side of the microgrid.

The system shown may assume different structures depending on the status of CB4 and CB5. In the beginning CB4 is open and CB5 is connected. Therefore, the microgrid has two branches in its structure. After t=1.25 sec, CB4 closes and CB3 opens. The microgrid assumes a one-line structure. The changing selective levels of the relays are shown in the tables given below. Comparing different selective level of a particular relay for different microgrid structures shows the need for selectivity coordination. In literature, there are algorithms to ensure dynamic relay hierarchy detection [182] and they will not be discussed here.

As mentioned earlier, it is assumed that microgrid is sufficiently small and `k` is set to 1. This means that DGs supply their maximum fault current for any fault. The parameters of the network components used by the communication system are listed in Table 6.7.

TABLE 6.7. NETWORK COMPONENT PARAMETERS AT T=0 SEC

	StatusDG	**DG type**	$\mathbf{I_{fault}}$
DG1	DRCS.ModOnConn= True	DRCT.DERtyp = 4	(DRCT.MaxWLim/Voltage) * 1.5
DG2	DRCS.ModOnConn= True	DRCT.DERtyp = 3	(DRCT.MaxWLim/Voltage) * 1.5
DG3	DRCS.ModOnConn= True	DRCT.DERtyp = 2	(DRCT.MaxWLim/Voltage) * 5

	CB1	CB 2	CB 3	CB 4	CB 5	CB 6	CB 7	CB 8
XCBR.Pos	ON	ON	ON	OFF	ON	ON	ON	ON
Selective Level	1	2	2	N/A	3	3	4	4

The relay fault current value = Grid contribution + DG1 + DG2 + DG3 = IfaultGrid + (DG1.DRCT.MaxWLim/Voltage) * 1.5 + (DG2.DRCT.MaxWLim/Voltage)*1.5 +(DG3.DRCT.MaxWLim/Voltage)*5

At t=0.2 in line with the changes occurring in the microgrid, DG1 is turned off by the MCPU. This happens by setting **DG1.DRCS.ModOnConn** false and **DG1.DRCS.ModOffUnav** true. In order to achieve this, MCPU sends an IEC61850 compliant control message and asks DG1 to switch off. When DG1 switches off, the **DG1.DRCS.ModOnConn** attribute changes to FALSE and the **DG1.DRCS.ModOffUnav** attribute becomes TRUE. The change in data parameters of the DG1 model is depicted in Figure 6.17:

MCPU -> DG1.IHMI -> DG1.ITCI -> DG1.DRCS -> DG1.DRCS.ModOnConn and -> DG1.DRCS.ModOffUnav

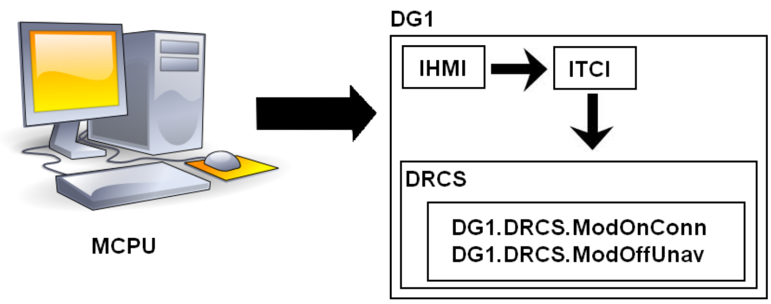

Figure 6.17. Reporting DG status through IEC 61850-7-420 Models

At t=0.5 sec, the utility grid experiences power outage so the microgrid becomes islanded. CB1 is now open. This information is extracted by the MCPU from the following scheme, as shown in Figure 6.18. Relay1 controlling CB1 would send a GOOSE message to the MCPU and the GOOSE message would contain the data attribute (**Relay1.XCBR.Pos**) beyond others. The value of the attribute "**Relay1.XCBR.Pos**" was set in the relay to OFF an indicator of the OPEN status of CB1. On receiving this GOOSE message from Relay1, MCPU would unpack the contents of the GOOSE message, read the new status of CB1, and adjust its "Network Component Parameter" table as shown in Table 6.8. Essentially, the "Network Component Parameter" table has been updated to reflect the change in the status of CB1.

MCPU -> Relay1.IHMI -> Relay1.ITCI -> Relay1.XCBR.Pos

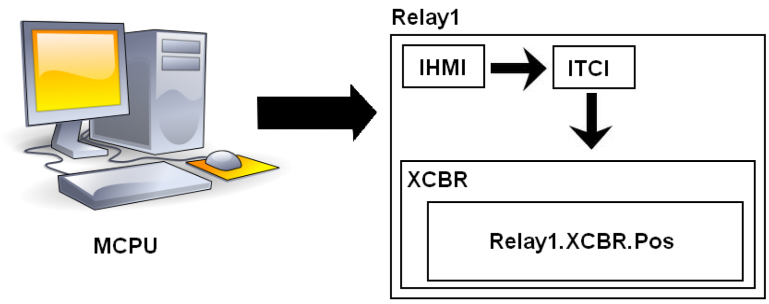

Figure 6.18. Reporting Relay status through IEC 61850-7-420 Models

At t=0.5 sec the network component parameter table is as shown in Table 6.8.

TABLE 6.8. NETWORK COMPONENT PARAMETERS AT T=0.5 SEC

	StatusDG	**DG type**	**I_{fault}**
DG1	DRCS.ModOffUnav = True	DRCT.DERtyp = 4	(DRCT.MaxWLim/Voltage) * 1.5
DG2	DRCS.ModOnConn = True	DRCT.DERtyp = 3	(DRCT.MaxWLim/Voltage) * 1.5
DG3	DRCS.ModOnConn = True	DRCT.DERtyp = 2	(DRCT.MaxWLim/Voltage) * 5

	CB1	CB 2	CB 3	CB 4	CB 5	CB 6	CB 7	CB 8
XCBR.Pos	OFF	OFF	ON	OFF	ON	ON	ON	ON
Selective Level	N/A	N/A	1	N/A	2	2	3	3

The relay fault current value = DG2 + DG3 = (DG2.DRCT.MaxWLim/Voltage)*1.5 - (DG3.DRCT.MaxWLim/Voltage)*5

At t=0.65 sec, a fault occurs in L4 and CB8 opens. In a similar fashion to Figure 6.18, MCPU receives an IEC 61850 complaint packet and extracts this information:

MCPU -> Relay8.IHMI -> Relay8.ITCI -> Relay8.XCBR.Pos

At t=0.75 sec, the connection is restored with the utility and once again, the microgrid operates in grid-connected mode. This information is extracted by the MCPU from:

MCPU -> Relay1.IHMI -> Relay1.ITCI -> Relay7.XCBR.Pos

At t = 1 sec, L1 and DG1 are connected to microgrid. These will be reported to MCPU through:

MCPU -> Relay2.IHMI -> Relay2.ITCI -> Relay2.XCBR.Pos

and

MCPU -> DG1.IHMI -> DG1.ITCI -> DG1.DRCS -> DG1.DRCS.ModOnConn and -> DG1.DRCS.ModOffUnav

Finally, at t = 1.25 sec, L5 and CB3 are disconnected from and CB4 is connected to microgrid. These will be reported to MCPU through following channels:

MCPU -> Relay3.IHMI -> Relay3.ITCI -> Relay1.XCBR.Pos
MCPU -> Relay4.IHMI -> Relay4.ITCI -> Relay4.XCBR.Pos

The final state of the network component table is as shown in Table 6.9.

TABLE 6.9. NETWORK COMPONENT PARAMETERS AT T=1.25 SEC

	StatusDG	**DG type**	**I_{fault}**
DG1	DRCS.ModOnConn = True	DRCT.DERtyp = 4	(DRCT.MaxWLim/Voltage) * 1.5
DG2	DRCS.ModOnConn = True	DRCT.DERtyp = 3	(DRCT.MaxWLim/Voltage) * 1.5
DG3	DRCS.ModOnConn = True	DRCT.DERtyp = 2	(DRCT.MaxWLim/Voltage) * 5

	CB1	**CB 2**	**CB 3**	**CB 4**	**CB 5**	**CB 6**	**CB 7**	**CB 8**
XCBR.Pos	ON	ON	OFF	ON	ON	ON	OFF	ON
Selective Level	1	2	N/A	3	3	4	5	5

The relay fault current value = Grid contribution + DG1 + DG2 + DG3 = IfaultGrid + (DG1.DRCT.MaxWLim/Voltage) * 1.5 + (DG2.DRCT.MaxWLim/Voltage)*1.5 +(DG3.DRCT.MaxWLim/Voltage)*5

For all of the changes occurring in the microgrid, MCPU re-calculates the fault current. These new values are updated in the associated relays through the communication shown in Figure 6.19. MCPU would essentially send an IEC 61850 compliant control message to the Relay. On receiving and unpacking the control message, Relay finds out that it needs to reset its ***Relay.PTOC.StrVal*** attribute to reflect the changes that have occurred**.**

MCPU -> Relay.IHMI -> Relay.ITCI -> Relay.PTOC -> Relay.PTOC.StrVal

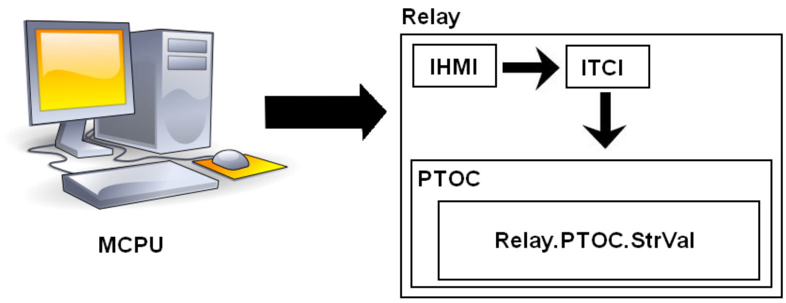

Figure 6.19. Updating Relay operating Currents through IEC 61850-7-420 Models

Over an established communication line between the components and the MCPU, the proposed protection scheme works perfectly with the models that are designed in compliance with IEC61850 and IEC 61850-7-420.

6.7. Conclusion

Microgrids have dynamic structures which change more often than the conventional large networks. In order to ensure protection under these conditions, a centralized management is required to monitor and communicate with the microgrid components and assign suitable operation parameters. The communication lines and systems inevitably utilized in microgrids require standardization so that equipment with different manufacturers or owners can work together; and new deployments can be easily done. Design of a central microgrid management system will be very much simplified if all of the components use the same communication standard. Therefore, communication standards such as IEC 61850 and the extension IEC 61850-7-420, which is aimed at modeling the information exchange for DER devices, have been published.

In the research project presented in this thesis, two important extensions have been made to IEC 61850 Standard. Due to its promising nature for future control systems, an extension has been made for FCL to facilitate its modeling. Another extension has been made for EVs since the availability of the technologies required and the higher efficiency of electric-driven cars create a genuine interest for EVs in the market. The large acceptance of EVs will definitely have impacts on electrical networks because through V2G technology, EVs not only draw power from the network but also act as distributed storage devices. With these extensions, the mentioned communication standard has been made more comprehensive.

Finally, the information models of the various network elements and their modeling as per IEC 61850 and its most recent extension, i.e. IEC61850-7-420 have been described. The presented relay and DG information models are standard and can be used for modeling the data exchange in any power system network. The universal modeling of information/data models in DGs regardless of their models and manufacturers is very important for having a universal concept for standardizing the data to be communicated within electrical networks for automation, control and data logging purposes. This is the fundamental for the implementation of plug and play concept in microgrids.

The work presented in this chapter has made a very significant contribution to knowledge by demonstrating how a microgrid protection system can be modeled in accordance with the international communication standard the IEC 61850 and its recent extension IEC 61850-7-420. Sample Data Maps are illustrated on a predetermined scenario which highlights different aspects of the developed protection scheme. The details of simulation works are given in the next chapter.

Chapter 7

Microgrid Operation and Protection Simulations

Publications pertaining to this chapter:

1) ***Taha Selim Ustun, Cagil Ozansoy, Aladin Zayegh, "Simulation of Communication Infrastructure of a Centralized Microgrid Protection System Based on IEC 61850-7-420", in Proceedings of Third IEEE International Conference on Smart Grid Communications (SmartGridComm), Tainan City, Taiwan, 5-8 Nov, 2012.***

2) ***Taha Selim Ustun, Cagil Ozansoy, Aladin Zayegh, "Investigation of Micro-Grid Behavior While Operating Under Various Network Conditions", in Proceedings of IEEE International Conference on Smart Grid Engineering (SGE'12), UOIT, Oshawa, Canada, 27-29 August, 2012***

7.1. Introduction

Preceding chapters have presented the novel microgrid protection scheme developed during the course of this research. Chapter 2 discussed the microgrid concepts and fundamentals from a number of aspects. Chapter 3 outlined how a conceptual microgrid case study was developed. Chapter 4 investigated the use of OO modeling of microgrid systems. Chapter 5 discussed the development of an adaptive relay protection parameter assignment logic. Chapter 6 explored the modeling of microgrid communications as per the IEC61850 standard. This chapter gives the details of the simulation works undertaken to validate and confirm the intellectual contributions made in the preceding Chapters.

Firstly, general microgrid simulations have been performed to investigate the microgrid behavior under various conditions. Microgrid – utility grid connection has been switched on and off to examine the differences between grid-connected and islanded operation modes. Utility grids with different sizes have been implemented to emulate the impacts of the microgrid connections within transmission and distribution networks. Furthermore, the dynamic nature of the microgrids has been reflected by changing the structure of the connections and analyzing the power flow in the system.

Due to their promising potential in the car market, EVs have also been considered in these microgrid simulations to investigate the effect of Vehicle-to-Grid (V2G) and Grid-to-Vehicle (G2V) technologies on current microgrids. The same microgrid structure has been utilized with the initial topology used for microgrid behavior investigations to be able to contrast the results.

Following these investigative simulations, the protection scheme proposed in the preceding chapters has been implemented for further verification. The individual control and communication blocks of the proposed communication-assisted protection scheme have been modeled and simulated for various microgrid events. Control signals have been named in accordance with IEC 61850 standard and its recent extension IEC 61850-7-420. The results show that the modeling, control signals and the adaptation of the protection system to the changes in the microgrid are satisfactory.

In conclusion, the simulation works have been performed over a wide range of topologies and operating conditions. The results have shown that the preliminary assumptions made during the design of this adaptive microgrid protection system were factual and the overall design successfully serves to adjust this protection system according to the events occurring in the microgrid.

7.2. Microgrid Operation Simulations

To understand the behavior of micro-grids when operated in grid connected and islanded modes, it was necessary to build a model micro-grid network and conduct in depth studies and simulations using this model to determine its operational behavior. All modeling and simulations presented in this section have been achieved through utilizing the Paladin DesignBase 4.0 software suite.

The micro-grid layouts used for the simulations are typical in nature [73, 90, 151, 153, 182]. The overall structures of the micro-grids used in simulations are depicted in Figure 7.1 and 7.2. Both systems are identical in all ways except for the bus tie that connects Bus 4 to the upstream system. The connection supply connection for BUS 4 is fed through CB5 in Figure 7.1 and CB12 in Figure 7.2.

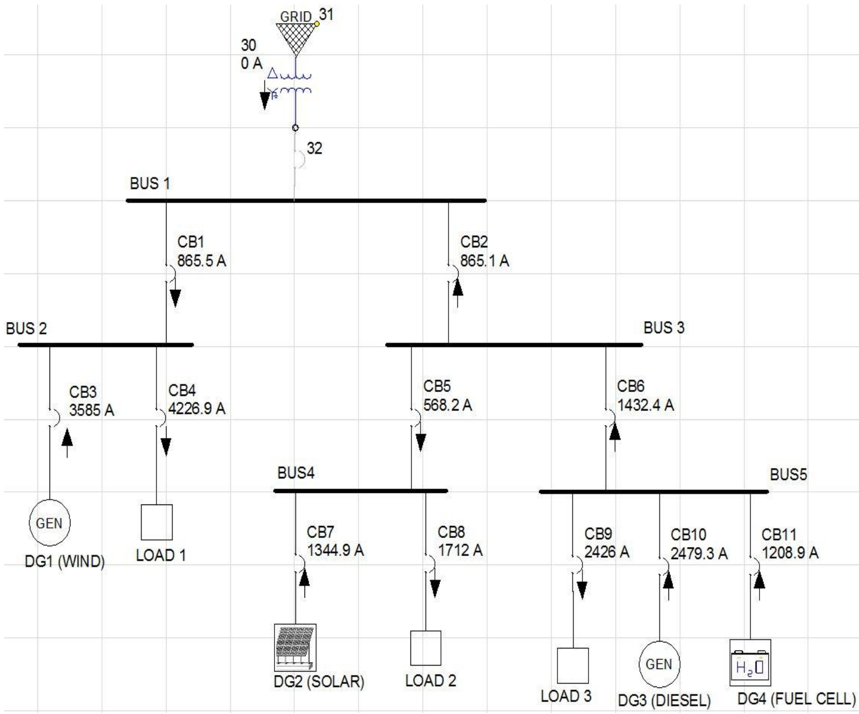

Figure 7.1. Micro-grid network structure used for investigation & simulation – when bus 4 is connected to bus 3 through CB5

The two similar yet different layouts represent a dynamic change in a micro-grid network structure and can be viewed as two possible ways of connecting BUS 4 to the micro-grid. The reason for testing and simulating two micro-grid structures is that in the event of a fault or maintenance being done to/at CB5 for example, CB12 would become the feeder supply line to BUS 4 ensuring reliability of supply. The two networks behave in different ways by altering the path which power flows to/from different areas of the network. The impact of this will be further elaborated in the following sections.

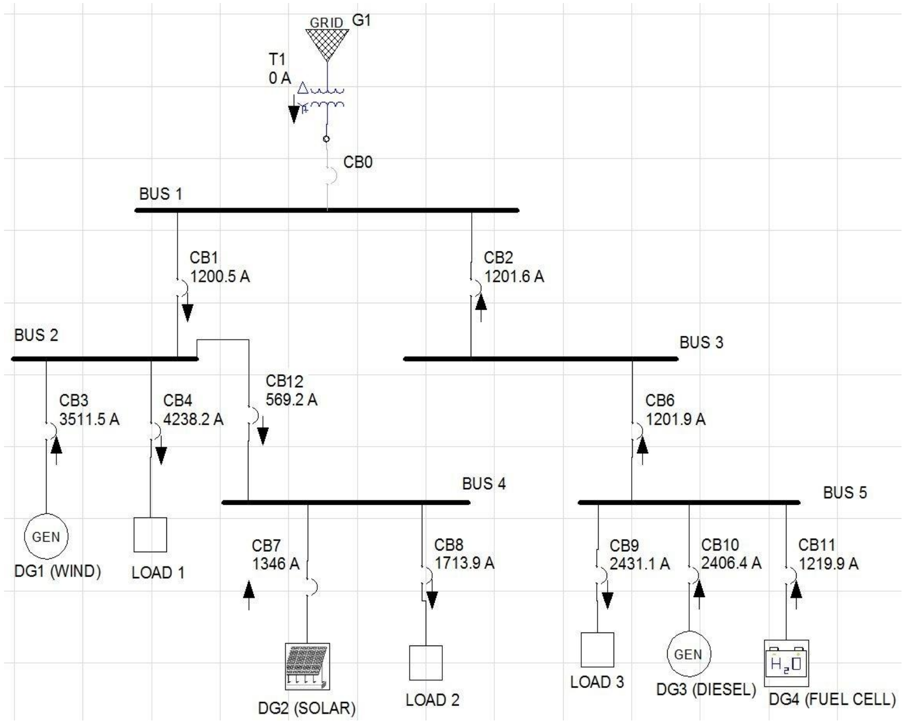

Figure 7.2. Micro-grid network structure used for investigation & simulation – when bus 4 is connected to bus 2 through CB12

The micro-grid consists of varying loads and DG sources connected to a low voltage (LV) - 480V network. The loading scheme for the networks is shown in Table 7.1.

TABLE 7.1 – MICRO-GRID LOADING MAGNITUDES

Name	Magnitude	
	MW	MVAR
Load 1	3.5	0.25
Load 2	1.4	0.25
Load 3	2	0.25

The loads within the micro-grids are placed close to the DG sources to minimize the power loss during transmission. The micro-grids consist of 2 primary radial feeders and 2 secondary feeders connected through various circuit breakers (see Figure 7.1 & 7.2). BUS 1 of the micro-grid is coupled to the main medium voltage (MV) utility grid through a transformer and a circuit breaker. This connection is elaborated on further in Section 7.2.1. This circuit breaker is operated to connect/disconnect the micro-grid to/from the utility bus, while the feeding circuit breakers CB1, CB2, CB5, CB6 and CB12 are operated to isolate a section or multiple sections within the micro-grid.

The wind generation micro-source (DG1 connected to BUS 2) has been modeled using a standard diesel generator. The reason for using a diesel generation in the model for wind generation is that wind generation uses rotating machines much like diesel generators. This provides us with although not an exact model of wind turbine generation, but a close approximation, which is sufficient enough to observe its behavior.

The final DG source (DG4) is a fuel cell which has been modeled using a PV cell source. The decision to use a PV panel model was made due to the fact that both PV panel and fuel cells are inverter interfaced-DGs (IIDG). Their behaviors under normal operation as well as fault conditions are very similar. Therefore, the used model provides a close approximation of operation of a DG fuel cell micro-source. Table 7.2 shows the full list of all the distributed generation sources of the micro-grid network and their magnitudes.

TABLE 7.2 – DISTRIBUTED GENERATION TYPE & MAGNITUDE OF POWER GENERATED

Component Name	Type of Generation	Magnitude(MW)
DG1	Wind	2.00
DG2	Solar(PV)	1.00
DG3	Diesel	2.00
DG4	Fuel Cell	1.00

7.2.1. Microgrid Simulation - Islanded Operation

Operation in Islanded mode is achieved when the Circuit Breaker 0 (CB0) is opened, disconnecting the micro-grid from the main grid. When operated in Islanded mode the micro-sources are responsible for maintaining the voltage and frequency while sharing the power supply to the loads [211]. The diesel generator, namely DG3, serves to maintain the frequency of the network in absence of the utility network. It also provides reactive power along with wind farm, DG1, which cannot be supported by IIDGs, DG2 and DG4 [14]. This fact becomes evident when it is observed that the micro-grids as a whole are very self sufficient and self reliant.

Although greater currents are present throughout the micro-grid during islanded operation, the power supply demands of the various loads of the micro-grid are met by the power supplied from distributed generation micro-sources within the network. The power supplied to the various loads is faultless and the network is stable. This enables the micro-grid to have a “plug and play” functionality which provides a solution for constant power supply demands in the case of larger/main network faults and/or disturbances.

However, though stable as a whole, the micro-grid branches connected through BUS 1 (CB1 & CB2) are closely dependent on each other to supply sufficient power and maintain stable operation when operated in islanded mode. The branches connected through BUS 3 (CB5 & CB6 – in configuration 1) are also dependant on one another. This can be traced back to the micro-grid acting as a single entity.

When the operational behaviors of the two micro grids depicted in Figure 7.1 and 7.2 are observed, it can be seen that the currents present in the two primary feeder branches (CB1 & CB2) in Figure 7.2 configurations are significantly higher than those present in that of Figure 7.1. This can be seen in the tabulated branch flow results below in Table 7.3 and Table 7.4. This difference in current flow leads to the conclusion that the primary feeder branches in Configuration 2 are much more dependent on the power supplied to/from each other than those in Configuration 1. This greater dependence makes this section more important in case of a critical fault within the micro-grid.

TABLE 7.3 – ISLANDED OPERATION: MICRO-GRID CONFIGURATION 1 - BRANCH FLOW RESULTS

Name	**To**	**Current (Amps)**	**Power (MW)**
BUS 1	BUS 2	866	0.60
	BUS 3	865	-0.60
BUS 2	LOAD 1	4227	3.50
	DG1 (WIND)	3585	-2.91
BUS 3	BUS 4	568	0.40
	BUS 5	1432	-1.00
BUS 4	DG2 (SOLAR)	1345	-1.00
	LOAD 2	1712	1.40
BUS 5	LOAD 3	2426	2.00
	DG3 (DIESEL)	2479	-2.00
	DG4 (FUEL CELL)	1209	-1.00

TABLE 7.4 – ISLANDED OPERATION: MICRO-GRID CONFIGURATION 2 - BRANCH FLOW RESULTS

Name	**To**	**Current (Amps)**	**Power (MW)**
BUS 1	BUS 2	1200	0.99
	BUS 3	1202	-1.00
BUS 2	LOAD 1	4238	3.51
	DG1 (WIND)	3511	-2.91
	BUS 4	0.40	569
BUS 3	BUS 5	1202	-1.00
BUS 4	DG2 (SOLAR)	-1.00	-1.00
	LOAD 2	1714	1.40
BUS 5	LOAD 3	2431	2.00
	DG3 (DIESEL)	2406	-2.00
	DG4 (FUEL CELL)	1220	-1.00

7.2.2. Grid-Connected Simulation: Transmission Network Connection, IEEE T14-Bus System

The decision to model and simulate the connection of the micro-grids to the T14-Bus as well as the 34-Bus system was made with the intention of observing the behavior of the microgrids when connected to different networks which operate with differing purposes, i.e. transmission and distribution. The two networks also present two different system voltage levels. The T14 Bus system has a voltage of 69kV (MV) while the 34-Bus system has a voltage of 24.9kV (LV). See Appendix – A for parameters of IEEE T14-Bus test system.

The T14 Bus system configuration is typically employed at the transmission level power supply and when either structure of the micro-grid (Figure 7.1 or 7.2) is connected to the main medium voltage (MV – 69kV) busbar of the T14 Bus system both micro-grid structures result in acting as a net load to the main network. Pictured in Figure 7.3 is the T14 bus system with the connection point for the micro-grid(s) outlined. It should be noted that this is a schematic representation of the standard T14 Bus system with an arrow indicating where the micro-grid configuration 1 is connected to it.

As mentioned previously, the loading schemes employed by both of the micro-grid Configurations 1 & 2 are the same and the amount of power export from the main grid to the micro-grid is approximately 0.9 MW. The added power provided by the grid significantly reduces the amount of power needed to be supplied by some of the DG sources within the micro-grid structure. This reduces the stress placed upon the DG micro-sources when compared with the islanded-operation of the micro-grid.

With the addition of the utility bus as another source of power to supply the micro-grid, the dependence on power to be supplied from neighboring branches within the micro-grid structure is alleviated. Furthermore, unlike islanded operation, the duty of maintaining the network frequency is fulfilled by the utility network rather than DG3. The removal of the dependence on power supplied from DG sources within the micro-grid improves the system stability and system fault response. This improvement in stability is the result of the micro-grid being able to be segmented into sections in the event of a fault.

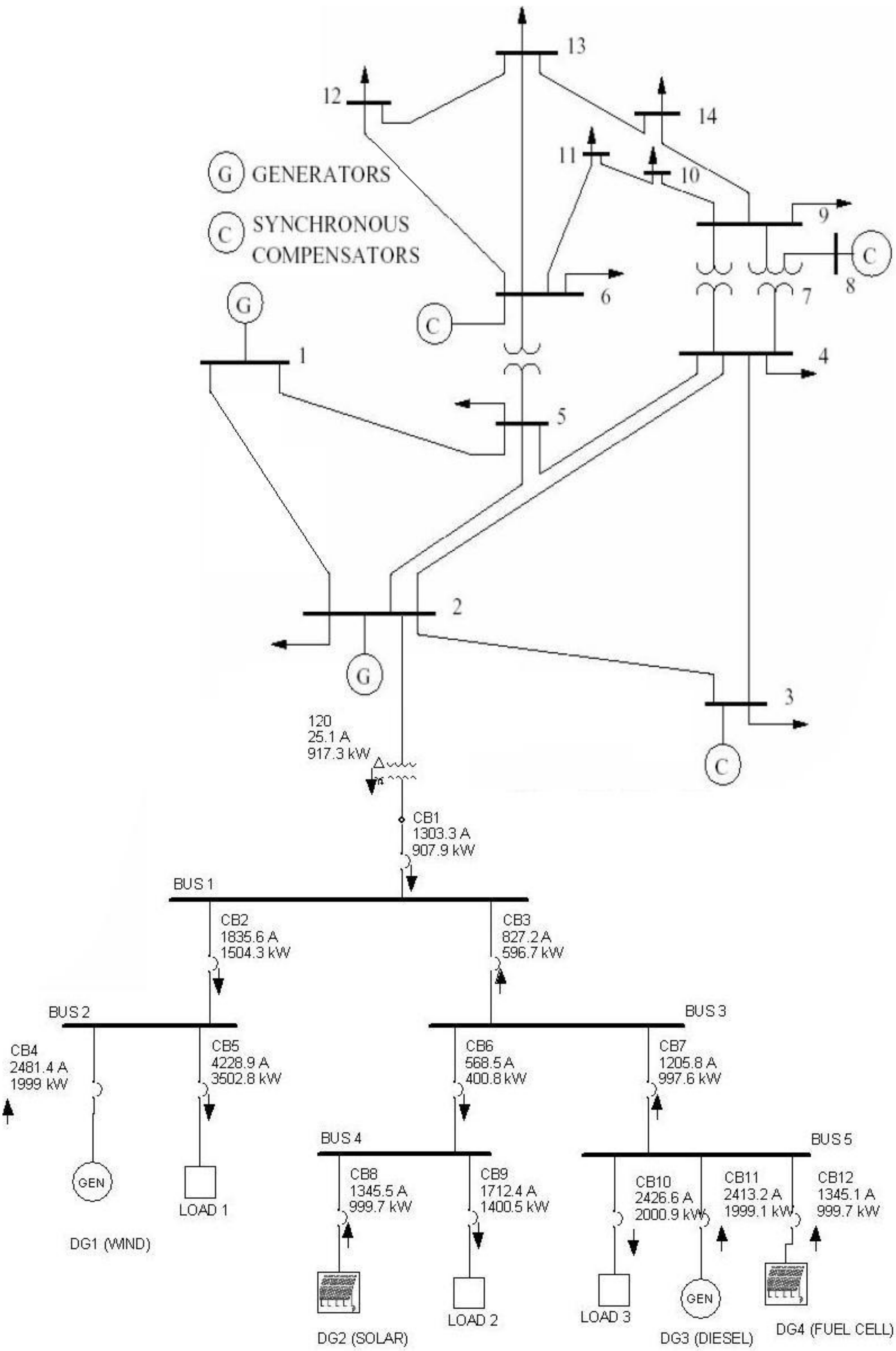

Figure 7.3. IEEE Standard T14 Bus System [212] with Microgrid Connection

The segmented area/zone is then able to supply its loading power demands load from the DG source(s) within its own area/zone. In this fashion, the micro-grid can be said to be acting as a small branching radial network which can function even after being sectionalized from a primary/key busbar within the micro-grid.

TABLE 7.5 – GRID CONNECTED OPERATION: T14 BUS SYSTEM - MICRO-GRID CONFIGURATION 1 POWER FLOW RESULTS

Name	To	Current (Amps)	Power (MW)
BUS 1	UTILITY GRID	1109	-0.91
	BUS 2	1835	1.50
	BUS 3	727	-0.60
BUS 2	LOAD 1	4228	3.50
	DG1 (WIND)	2481	-2.00
BUS 3	BUS 4	569	0.40
	BUS 5	1270	-1.00
BUS 4	DG2 (SOLAR)	1345	-1.00
	LOAD 2	1712	1.40
BUS 5	LOAD 3	2426	2.00
	DG3 (DIESEL)	2479	-2.00
	DG4 (FUEL CELL)	1298	-1.00

TABLE 7.6 – GRID CONNECTED OPERATION: T14 BUS SYSTEM - MICRO-GRID CONFIGURATION 2 POWER FLOW RESULTS

Name	To	Current (Amps)	Power (MW)
BUS 1	UTILITY GRID	1109	-0.91
	BUS 2	2371	1.91
	BUS 3	1270	-1.00
BUS 2	LOAD 1	4229	3.50
	DG1 (WIND)	2481	-2.00
	BUS 4	569	0.40
BUS 3	BUS 5	1270	-1.00
BUS 4	DG2 (SOLAR)	1346	-1.00
	LOAD 2	1713	1.40
BUS 5	LOAD 3	2426	2.00
	DG3 (DIESEL)	2479	-2.00
	DG4 (FUEL CELL)	1298	-1.00

When contrasted with the micro-grid being operated in islanded mode, there is a reduction in neighboring DG power supply dependence. This results in an increase in power flowing through some of the feeders of the network, while there is a decrease in others. This change in power flow can be directly related to the ampacity requirements of the feeder lines. When the operation of the two micro-grid configurations are separately connected the main grid and examined, it can be noted that the key difference between the two is much the same as when they are operated in islanded mode.

Through observing the tabulated branch flow currents of the two micro-grids while connected to the T14 bus system given in Table 7.5 and Table 7.6, it can be noted that the power flow through the various branches is different but the same conclusions can be drawn. The primary feeder branches in Configuration 2 are much more dependent on the power supplied to/from each other than those in 1. There is also no change in the amount of power required to be supplied from the main grid.

7.2.3. Grid-Connected Simulation: Distribution Network Connection, IEEE 34-Bus System

Similar to the case when either of the micro-grid configurations are connected to the main (LV – 24.9kV) busbar of the 34 bus system, the micro-grid networks appear as net loads to the main system. The 34 bus system, however, is employed for different purposes than the T14 bus system. The 34 bus system is typically employed at the distribution level of the electricity grid. Please see Appendix – B for parameters of IEEE 34-Bus test system.

Shown in Figure 7.4 is a schematic representation of the IEEE standard 34 Bus system with an arrow indicating where the micro-grid is connected to it. When either structure of the micro-grid is connected to the 34 bus network, the system behaves in very similar fashion to when the T14 bus system is employed as the main grid connection:

- The amount of power drawn from the main grid to supply the micro-grid is approximately 0.9MW.
- Less power supplied from DG sources is required. Less stress placed upon DG's
- The dependence on power to be supplied from neighboring branches within the micro-grid structure is alleviated

- Increased network stability in the event of fault within the micro-grid.
- The primary feeder branches in configuration 2 are much more dependent on the power supplied to/from each other than those in 1.
- There is also no change in the amount of power required to be supplied from the main grid when switching between configurations.

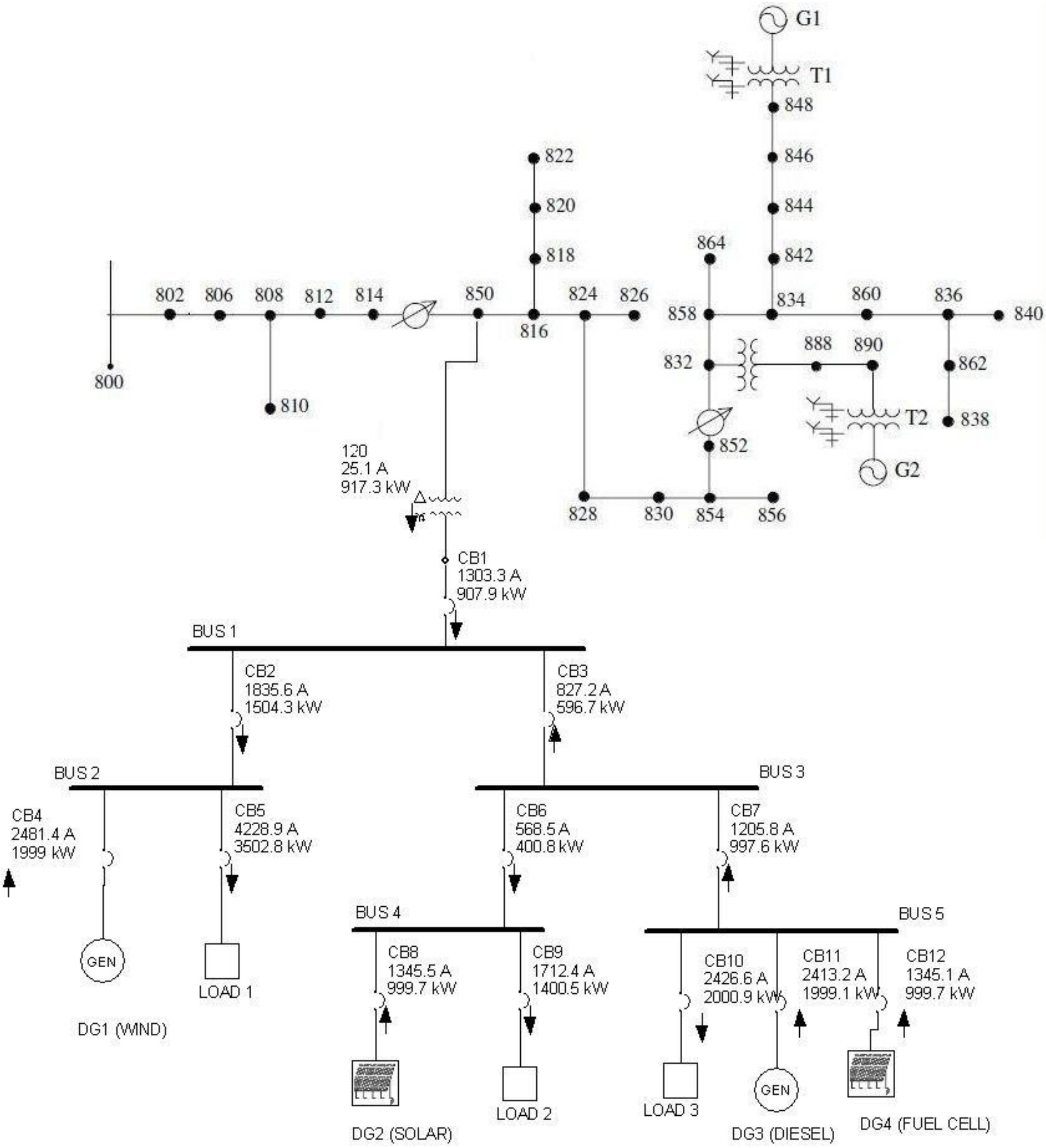

Figure 7.4. IEEE Standard 34 Bus System [213] with Microgrid Connection

This is confirmed when a comparison is made between the power flow results of the T14 bus system given in Table 7.5 & 7.6 and the 34 bus system given in Table 7.7 & 7.8.

Nevertheless, there is one minor difference between the network behaviors observed in the simulations. When either structure of the micro-grid is connected to the 34 bus system, the amount of power which is sourced from the grid is the same as the T14 bus system. However, due to the standard default setup of the bus voltages at 0.5kV in the 34 bus system and the T14 being 480V for the LV level (0.48kV) the current flowing is slightly altered in CB1 & CB3 feeders, despite the power flowing remaining the same.

TABLE 7.7 – GRID CONNECTED OPERATION: IEEE STANDARD 34 BUS SYSTEM - MICRO-GRID CONFIGURATION 1 POWER FLOW RESULTS

Name	To	Current (Amps)	Power (MW)
BUS 1	UTILITY GRID	1303	-0.91
	BUS 2	1836	1.50
	BUS 3	827	-0.60
BUS 2	LOAD 1	4229	3.50
	DG1 (WIND)	2481	-2.00
BUS 3	BUS 4	569	0.40
	BUS 5	1206	-1.00
BUS 4	DG2 (SOLAR)	1345	-1.00
	LOAD 2	1712	1.40
BUS 5	LOAD 3	2427	2.00
	DG3 (DIESEL)	2413	-2.00
	DG4 (FUEL CELL)	1345	-1.00

TABLE 7.8 – GRID CONNECTED OPERATION: IEEE STANDARD 34 BUS SYSTEM - MICRO-GRID CONFIGURATION 2 POWER FLOW RESULTS

Name	To	Current (Amps)	Power (MW)
BUS 1	UTILITY GRID	1303	-0.91
	BUS 2	2371	1.91
	BUS 3	1206	-1.00
BUS 2	LOAD 1	4230	3.50
	DG1 (WIND)	2482	-2.00
	BUS 4	569	0.40
BUS 3	BUS 5	1206	-1.00
BUS 4	DG2 (SOLAR)	1346	-1.00
	LOAD 2	1714	1.40
BUS 5	LOAD 3	2427	2.00
	DG3 (DIESEL)	2413	-2.00
	DG4 (FUEL CELL)	1345	-1.00

Again much like the T14 grid connected configuration, when the 34 bus grid connected system is contrasted with the micro-grid operating is islanded mode; there is a reduction in the neighboring DG power supply dependence. This results in an increase in power flowing through some of the feeders of the network, while there is a decrease in others. This change in power flow can be directly related to the ampacity requirements of the feeder lines.

7.2.4. Microgrid V2G-G2V Simulations for EV (Charging/Supplying)

Various simulations works have been performed to analyze the impact of possible EV migration on electrical networks. Paladin Design Base 4.0 software package was utilized to model the components as well as the networks. Considering a typical neighborhood, thirty "Chevrolet- Volt" EVs using Level 2a [134] charging option were taken as basis for simulation works.

V2G-G2V, i.e. vehicle-to-grid and grid-to-vehicle, cases are examined by modeling EVs as power sources in the prior case and as loads in the latter. For the sake of simplicity, the charging and discharging characteristics of the EV batteries are assumed to be regular. The microgrid system is connected to IEEE T14-bus system and IEEE 48 Bus system, shown above in Figure 7.3 and Figure 7.4, respectively, to investigate the behavior of the microgrid during V2G implementation.

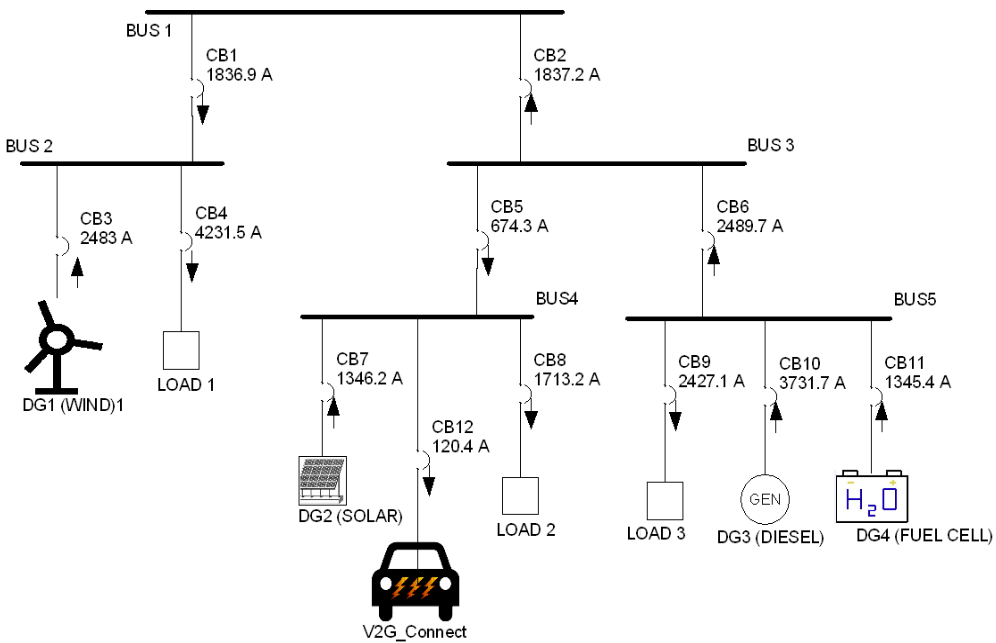

Figure 7.5. The Sample Microgrid with EV deployments (G2V mode – charging)

Figure 7.5 shows the sample microgrid utilized in earlier simulations with EV connection. In this figure, the operation mode of EV is charging, i.e. G2V. The connection has been performed in the lowest level of distribution as this will be the case in real-life implementations where EVs will be charged for the houses of the owners. Figure 7.6 shows when the EVs are used as power sources and, through V2G technology, they are supplying power to the grid.

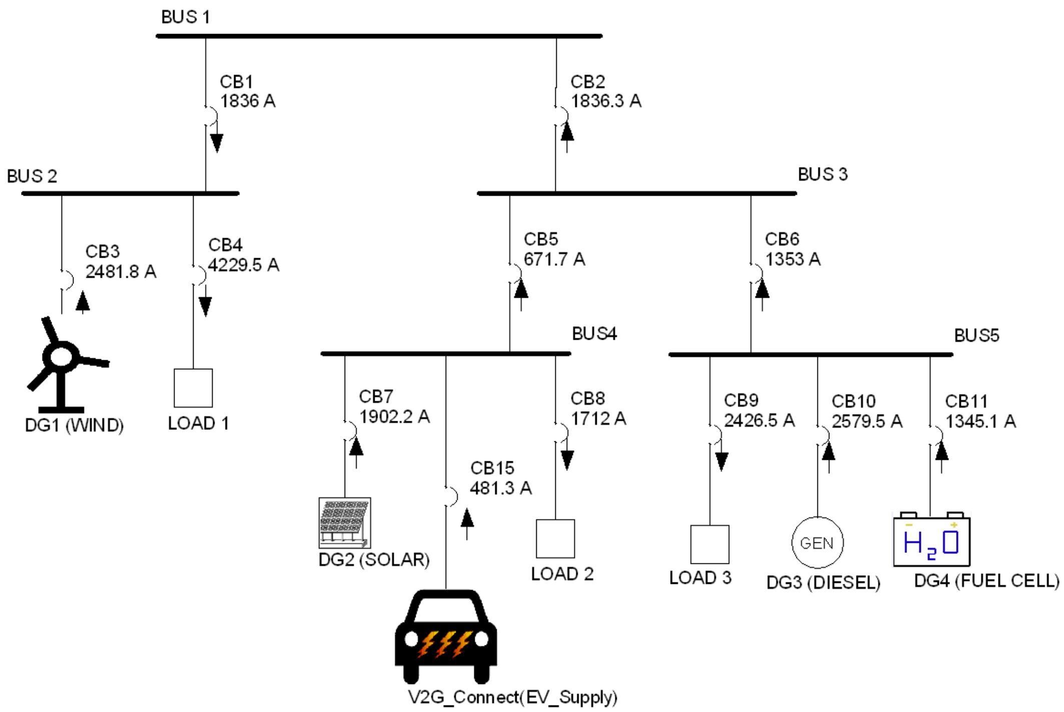

Figure 7.6. The Sample Microgrid with EVs operating in V2G mode

The simulation results are summarized in Table 7.9 below. Various parameters are tabulated under operation without any EV connection and operations under V2G (EV supplying power) and G2V (EV charging) conditions.

As mentioned in the literature [141, 143, 209], EV connection does not have any major impact in either of the Bus Systems utilized. This shows that V2G technology does not constitute a significant problem at transmission level. However, this does not hold for distribution networks. When the impact of the EVs on the sample microgrid is analyzed, it is clear that large scale mitigation to EV technology requires some developments at distribution networks, their management and protection. Once this challenge is managed, electrical networks can enjoy the benefits of new generation EVs.

TABLE 7.9 – SIMULATION RESULTS FOR TEST CASES

	Islanded Operation		**IEEE T14 Bus**		**IEEE 34 BUS**	
Control Parameter	**V2G**	**G2V**	**V2G**	**G2V**	**V2G**	**G2V**
V_{Bus1}	479.52 V	479.328 V	479.6 V	496.3V	479.6V	479.7 V
V_{Bus4}	479.76 V	479.424 V	479.8 V	496.4 V	479.8 V	479.5 V
V_{Bus5}	479.81 V	479.664 V	479.8 V	496.5 V	479.8 V	479.8 V
$I_{Bus1-Bus2}$	1836 A	1836.9 A	1835.4 A	1777.3 A	1835.4 A	1835.2 A
$I_{Bus1-Bus3}$	-1836.3 A	-1837.2 A	-1216.8 A	-1296 A	-1209.8A	-769.1
$I_{Grid-Bus1}$	N/A	N/A	4.3 A	13.23 A	14.7 A	27.8 A
I_{EV}	-481.3A	120.4 A	-481.2 A	113.67 A	-481.2 A	120.3 A
I_{DG3}	-2579.5 A	-2483 A	-1821.4A	-1833.1 A	-1805.6 A	-1808.1 A
I_{DG1}	-2481.8 A	-3731.7 A	-2481 A	-2392. A	-2481 A	-2480.8 A

Furthermore, a careful analysis yields that the presence of EVs in the electrical network changes the flowing currents in the system. During G2V mode EVs are acting as loads and drawing current from the network. Since higher operating currents are expected, relays are supposed to be programmed accordingly. In contrast, during V2G operation, the current provided by EV contributes to a possible fault and that shall be taken into account by the MCPU. In parallel with these deductions, the developed protection system is equipped with necessary infrastructure and modeling (EV modeling with IEC 61850-7-420) to provide the much required reliable and safe operation. Any other storage device can also be handled like EVs where the storage device can supply or draw power from the network.

7.3. Fault Parameter follow-up for Microgrid Operation Simulations

Fault current analyses performed for different networks, which are presented in Appendix – C, clearly show that the fault levels vary for each operation setup and, therefore, shall be monitored. In order to test the developed fault parameter adjustment procedure in relation to the changes occurring in the microgrid, the developed scheme has been modeled by using the MATLAB/Simulink computing software. The parameters which are introduced and explained in Chapter 5 have been implemented in these simulation studies. Initially, relays and distributed generators were re-modeled by equipping them with communication modules which are essential for the realization of the proposed scheme. Figure 7.7 shows the new model designed for relays whereas Figure 7.8 shows the Communication and Control Module (CCM) in detail.

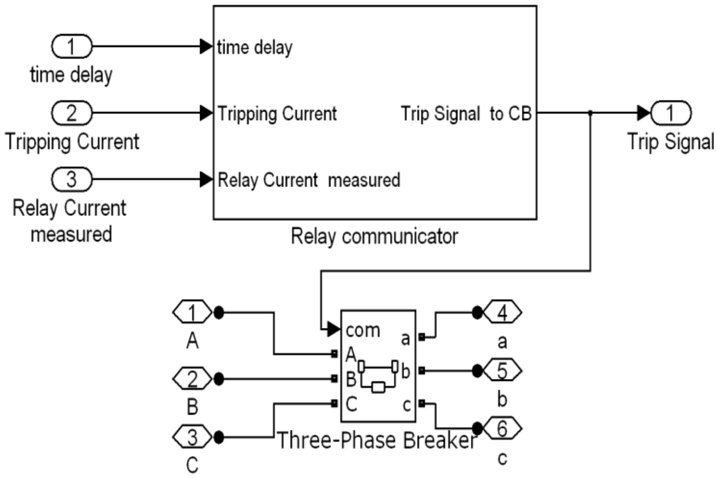

Figure 7.7. Relay model with Communication Module

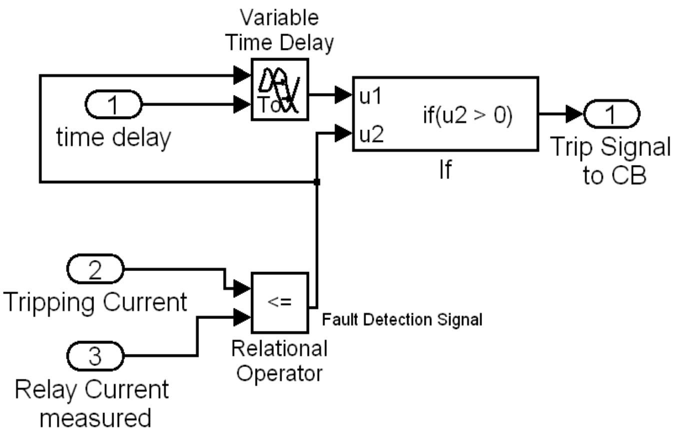

Figure 7.8. Relay Communication and Control Module

Three different signals are fed to the communication and control module:

- Time delay is the amount of delay applied for the realization of selectivity between relays.

- `Tripping Current` signal is the updated fault current signal which is calculated by the MCPU.
- Relay Current is the current which flows through the relay.

Time delay can be determined in two different ways. Firstly, depending on the microgrid structure suitable time delays for selectivity can be calculated and embedded in the CCM. Alternatively, the selectivity can also be calculated by the MCPU on the fly and fed to the relays. This feature will make the system very versatile and new connections can be performed easily. The anticipated drawback is the design and implementation of an appropriate algorithm which can analyze the current status of the network and assign incremental time delays to the relays.

The CCM compares the two current values, i.e. `Tripping Current` and `Relay Current` and sets `Fault Detection` Signal if the latter is larger. The tripping signal is delayed for the interval defined by `time delay`. If after this delay the fault has not been cleared by any other Relay (which has a higher priority), `Trip Signal` will be set to open the circuit.

For a proper communication to be achieved in the network DGs need to be equipped with a communication module which will report the parameters such as status, rated current, DG type and the coefficient k to the MCPU. For example, this can be achieved by mapping them into GOOSE and other IEC 61850 compliant messages as explained in Chapter 6. Figure 7.9 shows the new DG model with communication module.

`Status` signal indicates whether DG is in operation, `$I_{rated}$` is the rated current of the DG and `DG type` indicates whether this particular DG is an inverter interfaced DG such as a PV panel or a rotating machine such as a diesel generator. The fault current is calculated from

I_{rated} and DG type signals then in accordance with the Status signal the fault current is included in or excluded from the Tripping Current.

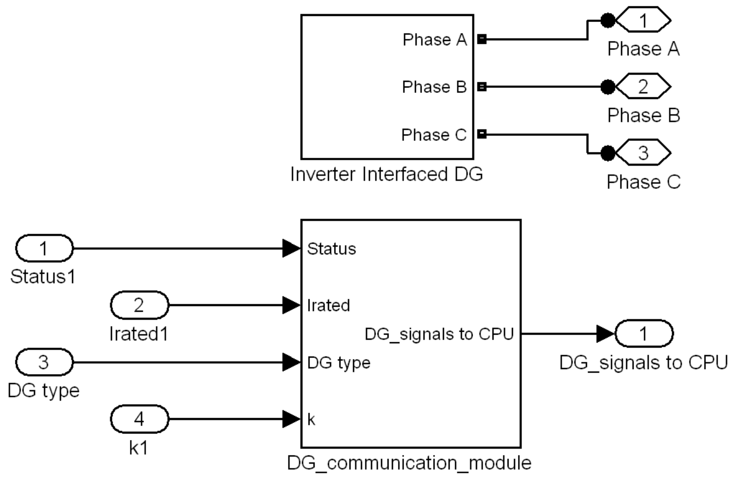

Figure 7.9. DG with Communication Module

The last signal \`k\` is a unique contribution to knowledge in this research and aimed at making the model more realistic. The signal \`k\` is the coefficient between 0 and 1 which designates the impact amount of the DG on each Relay. The DG supplies a maximum fault current of $I_{faultDG}$. However, this current may decrease if the fault occurs farther away from the DG due to cable impedance. That is to say any particular DG will have different \`k\` values for every relay in the network.

The relays closer to the DG under consideration will have higher \`k\` levels whereas those which are farther downstream or upstream will have lower coefficients. The coefficient has two indices such as \`$k_{12}$\` which means the \`the fault current coefficient of DG1 for Relay 2\`. The MCPU shall use relative \`k\` values while calculating relays' tripping currents. In this way not only the effect of distribution lines is taken into account but also a more flexible and versatile protection system is designed. This is especially desirable for growing networks with potential new deployments.

In short, DG communication module calculates the maximum fault current, $I_{faultDG}$, according to the assumption that in case of a fault inverter interfaced and rotating machine DGs supply 1.5 and 5 times their rated currents, respectively. It supplies four signals to MCPU which are Status, I_{rated}, $I_{faultDG}$ and k values. The MCPU which is responsible of calculation of tripping currents, time delays (optional) and updating of relay operating points is designed for a sample system with three DGs and five Relays.

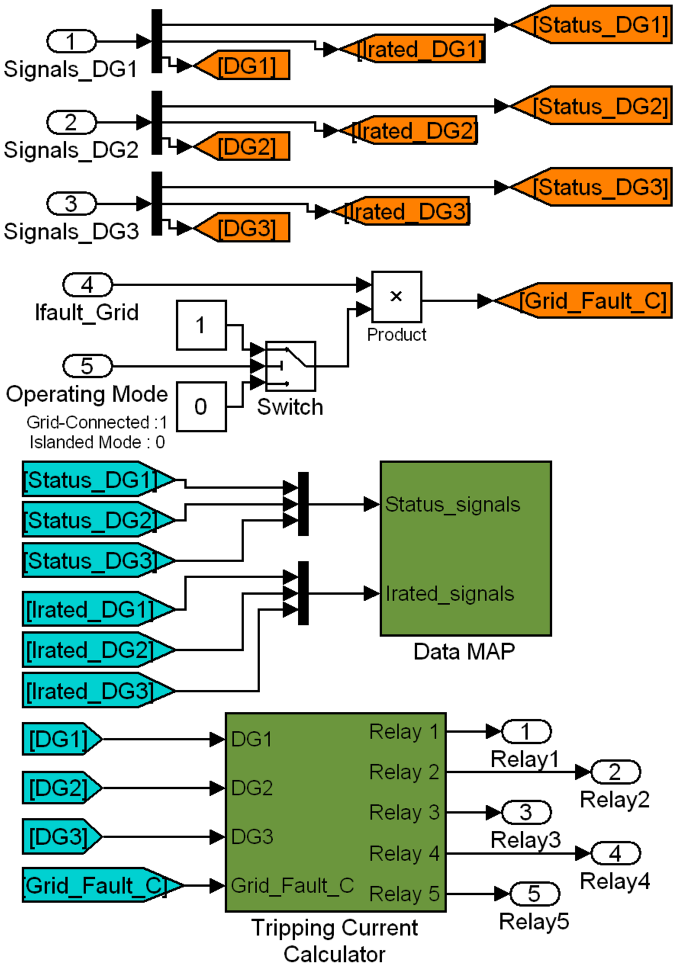

Figure 7.10. MCPU Block (inside)

In addition to incoming signals for DGs, MCPU also receives signals Grid's fault contribution ($I_{faultGRID}$) and the operating mode of the microgrid, i.e. grid-connected or islanded mode of operation. For each relay, every DG's fault contribution is calculated as explained in Chapter 5. Then the fault current levels are updated to the respective relay to ensure proper operation and sufficient protection.

The inner view of MCPU is shown in Figure 7.10. The status and rated current signals are directed to the data map block. These values are stored in a table for monitoring the current status of the network. They can also be used for further processing such as in fault isolation algorithms or for service quality enhancement in combination with the power management system.

The strength of this design is in its ability to accept new connections with very simple modifications. This is an invaluable feature since, when combined with the new relay and distributed generator designs, it introduces plug-and-play concept to electrical networks from electrical point of view. In the MCPU shown, for instance, a new connection of DG will only require an additional input to `Tripping Current Calculator` and `Data MAP` blocks. New DG's fault current contribution will be taken into account automatically. Similarly, connection of a new relay (e.g. which connects a load to the system) can be realized with an additional calculation step and an output in `Tripping Current Calculator`. Unlike the former step, this one requires an additional work to determine the coefficient `k` for each DG.

7.3.1. MATLAB Simulation Results

In order to substantiate the operation of the designed blocks and the proposed protection scheme, the microgrid model shown in Figure 7.11 has been simulated. The system includes two inverter-interfaced DGs and a diesel generator DG which is used to set the frequency and voltage under islanded conditions. The DGs are operated under conventional droop control and share the loads in accordance with their capacities.

A specially designated simulation scenario has been developed and applied to show different aspects of the protection scheme. The applied scenario is as follows:

1. The system starts operation with full load, all DGs are on and the microgrid operates in Grid-Connected Mode.
2. At t=0.2 sec Load1 turns off and R3 opens. Due to less power demand in the system DG1 also turns off.
3. At t=0.5 sec the utility grid experiences power outage for maintenance reasons and microgrid becomes islanded.
4. At t=0.65 sec, while microgrid is operating in islanded mode a fault occurs in Load4 and R7 opens.
5. At t=0.75 sec, the connection with the utility grid is restored and microgrid operates in grid-connected mode.
6. At t=1 sec, Load1 is reconnected to the system. Due to increased power demand in the network DG1 is also put into operation.

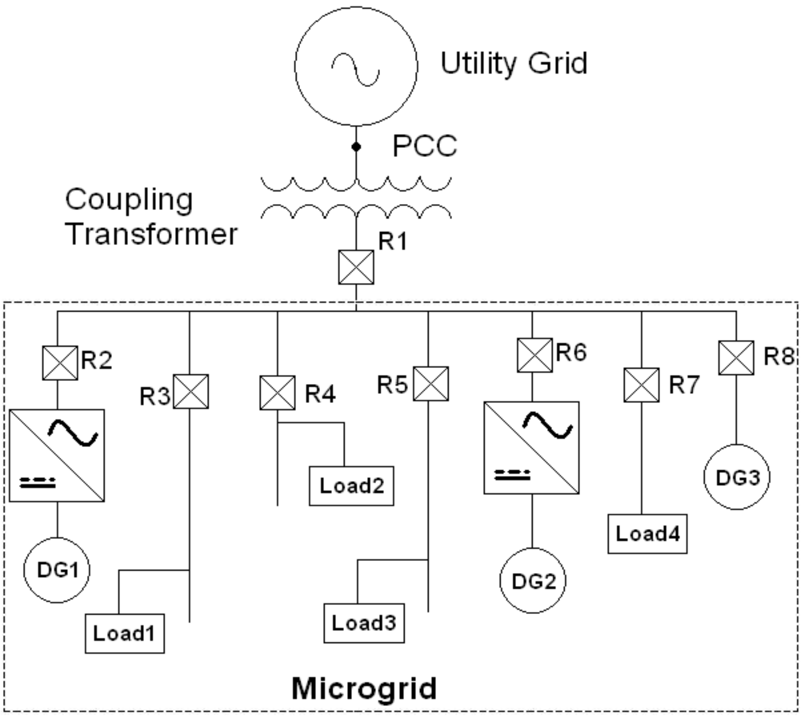

Figure 7.11. The Microgrid Model Simulated in MATLAB/Simulink

In this simulation, due to one-level hierarchy of the network, selectivity in relay operation is not an issue. Hence, zero time delay is applied in Relay CCMs. Secondly, assuming a microgrid which spans a relatively small geographical area, the coefficient `k` is set to 1 for all DGs on every relay. This means that a trivial assumption has been made that DGs supply their maximum fault current for any fault occurring in microgrid.

The parameters of the network components such as rated currents and types of DGs or Load values are given in Table 7.10. The fault current is in reality a larger value; however, in order to monitor the changes in the fault levels it is limited to this acceptable value. When the simulation was performed with the scenario explained earlier, the current waveforms given in Figure 7.12 and 7.13 were obtained for the grid and the DGs.

TABLE 7.10 – NETWORK COMPONENT PARAMETERS

	Rated current	DG type	I_{fault}/I_{rated} Ratio	k (all Relays)
DG1	100 A	Inverter Interfaced	1.5	1
DG2	100 A	Inverter Interfaced	1.5	1
DG3	200 A	Rotating Machine	5	1
	Real Power (P)		Reactive Power (Q)	
Load1	5kW		1kVAR	
Load2	50kW		1kVAR	
Load3	50kW		1kVAR	
Load4	50kW		1kVAR	
Grid Fault Contribution:	2kA			

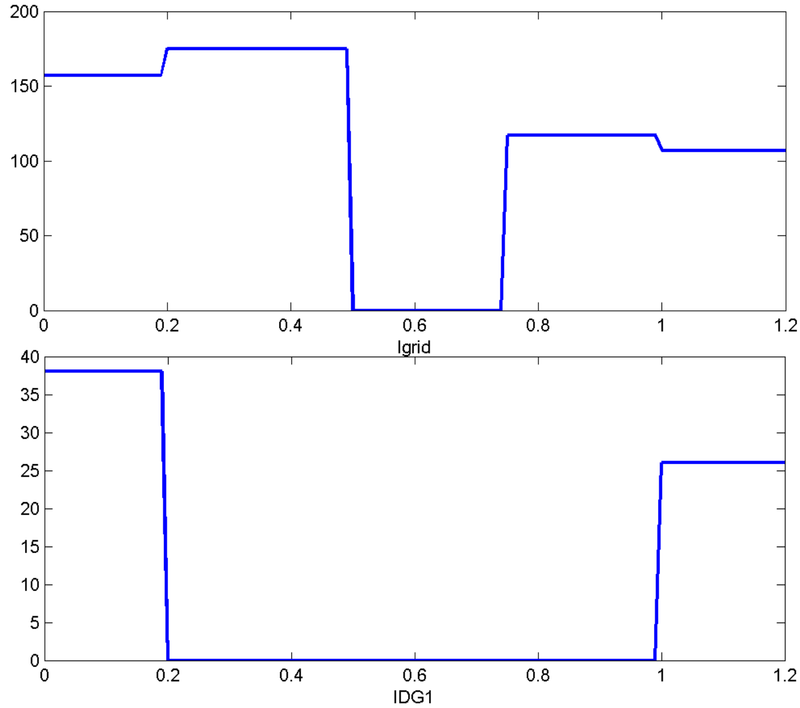

Figure 7.12. Current Waveforms for the Grid and DG1

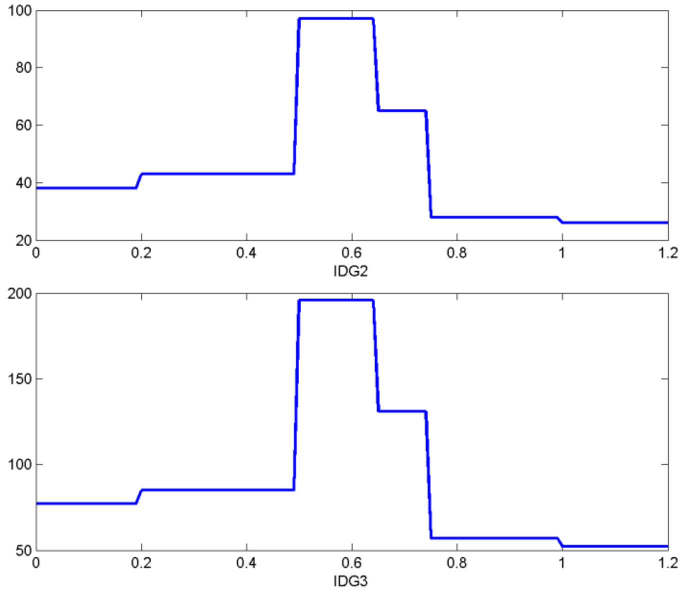

Figure 7.13. Current Waveforms for DG2 and DG3

The appropriate fault current level calculated by the MCPU and the operating mode signal are shown in Figure 7.14. The effect of various concepts such as operation of different generators, their type, operation mode of the microgrid, the power demand by the loads etc. can be seen in the tripping current updated to relays.

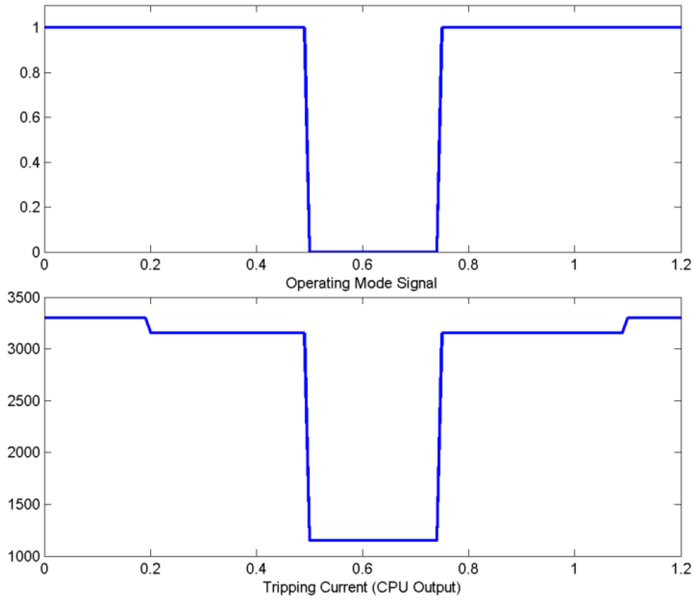

Figure 7.14. Operating Mode Signal and Tripping Current

The total current flowing through the network is shown in Figure 7.15. When compared with Figure 7.14, it is understood that the tripping current follows the total capacity connected to the system. This is aimed at preventing nuisance tripping explained earlier. This phenomenon becomes more dominant in an islanded microgrid with many DGs. The protection scheme proposed also tackles this issue by following the total capacity connected to the network.

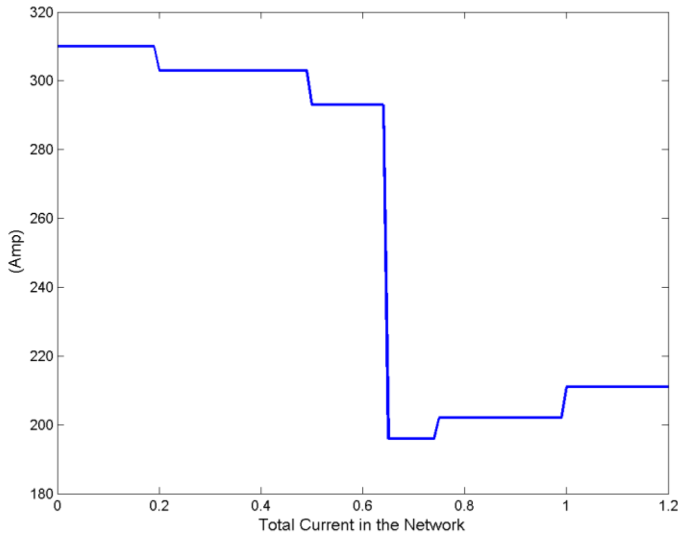

Figure 7.15. Total Current flow in the Network

7.4. Communication Interface Simulations

Following the universality approach assumed in this research, the components of the proposed microgrid system have been modeled in MATLAB/Simulink using the Logical Nodes (LNs) defined in the international communication standard IEC 61850 and its recent extension for DERs IEC 61850-7-420. Initially, relays and distributed generators have been modeled by equipping them with communication modules which are essential for the realization of the proposed scheme. Figure 7.16 shows the new model designed for relays.

In the relay model, there are two key parameters for the proper operation of relays: operating fault current I_{Relay} and the time delay for selectivity t_{relay}. The former is calculated in a unique fashion as proposed by the authors in the Chapter 5. On the other hand, time delay can be determined in two different ways. Firstly, depending on the microgrid structure suitable time delays for selectivity can be calculated and embedded in the Communication and Control module (CCM). Alternatively, the selectivity can also be calculated by the MCPU on the fly and fed to the relays as proposed in [182]. This feature will make the system very versatile and new connections can be performed easily. The anticipated drawback is the design and implementation of an appropriate algorithm which can analyze the current status of the network and assign incremental time delays to the relays.

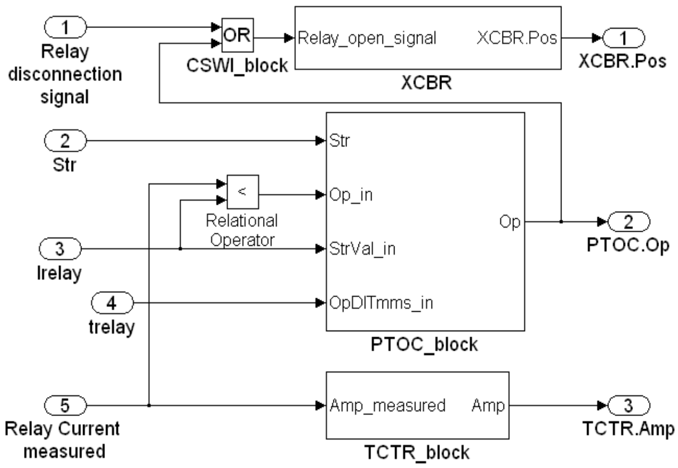

Figure 7.16. Relay Block with XCBR, PTOC and TCTR LNs

Once these parameters are calculated by the MCPU, they are sent to each individual relay and stored in PTOC which detects AC over-current flow in a predetermined direction. Therefore, the detection threshold I_{Relay} is stored in PTOC. The time delay t_{relay}, which represents the delay applied on detection signal sent to CSWI, is also stored inside PTOC. CSWI is used to send a trigger signal to the XCBR, circuit breaker, in case an over-current signal is received from PTOC. It is worthy to note here that in modeling the relay, instead of logical node PIOC, which detected instantaneous over-current or rate-of-rise, PTOC which has the capability to detect fault currents according to their directions, is utilized. This modification is required since fault currents may flow in both directions in microgrids. Furthermore, the relay model is equipped with a remote CCM to update operating fault currents and time delays calculated by the MCPU. This relay model is used for all relays regardless of their positions as load connecting, DG connecting or inter-bus relays.

For a proper communication to be achieved in the network DGs need to be modeled in accordance with IEC 61850-7-420 and equipped with a communication module which will report the parameters such as status, rated current and DG type to the MCPU. Due to their distinct features each DG type is modeled individually. Figure 7.17 shows the generic model used to represent DGs in MATLAB environment.

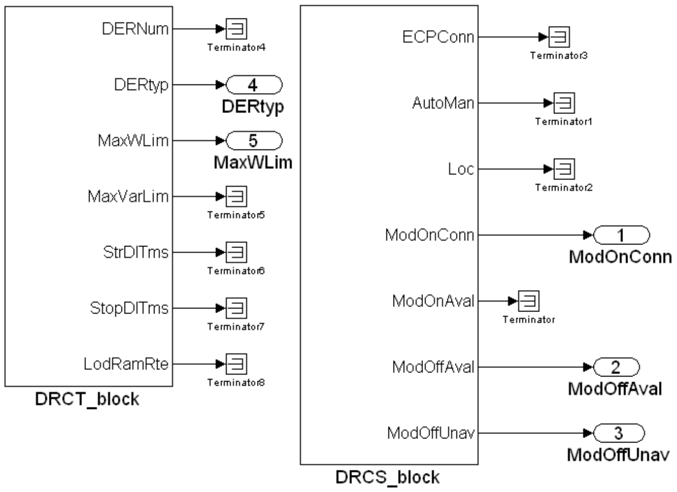

Figure 7.17. DG model with DRCT and DRCS LNs

The remote communication and control is connected to *DRCS* and *DRCT* which represent DER controller status and DER controller characteristics, respectively. In the proposed system, MCPU requires three parameters from every DG. These are DG status, DG type (i.e. inverter-interface or rotating machine) and the rated current value. The first parameter can be extracted from *DRCS*. The data **DRCS.ModOnConn** indicates whether the DG is `On and Connected`. When the DG is in operation, i.e. it is ON, and connected, then **DRCS.ModOnConn** is set `True`. The data **DRCS.ModOffAval** and **DRCS.ModOffUnav** indicate whether the DG is `OFF but available to start` or `OFF and not available to start`. In either case the DG will be OFF and will not contribute any fault current. Therefore, if **DRCS.ModOffAval** or **DRCS.ModOffUnav** is set `True` it means the D is not in operation. Following relay calculation scheme, $status_{DG}$ can be extracted from values of

DRCS.ModOnConn, **DRCS.ModOffAval** and **DRCS.ModOffUnav**. This can be represented with the logical expression given in (7.1):

$$\text{Status}_{DG} = \text{DRCS.ModOnConn} \; \& \; (\text{DRCS.ModOffAval} \vee \text{DRCS.ModOffUnav})! \tag{7.1}$$

Equation (7.1) is implemented in Simulink as in Figure 7.18:

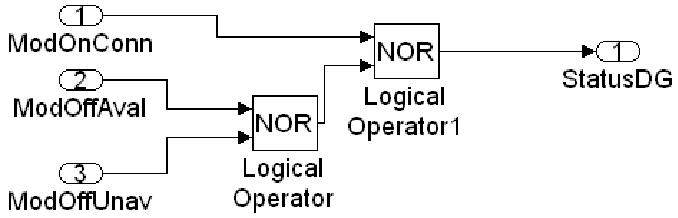

Figure 7.18. Status_{DG} module (in MCPU) to extract connection status of DGs

The DG type is required for fault current estimation and it is listed in **DRCT.DERtyp**. This parameter can be set to 2 to represent rotating machines. This will imply that a factor of 5 shall be used in estimating fault current of the DG. Alternatively, **DRCT.DERtyp** can be set to 3 or 4 to represent fuel cell or PV panel. This will imply that a factor of 1.5 shall be used in estimating fault current of the DG since these are inverter-interface DGs (IIDGs).

The rated operating current of the DG can be extracted from *DRCT*. **DRCT.MaxWLim** represents the maximum power rating of the generator. From rated current, the fault currents of a rotating machine and an inverter-interfaced DG can be extracted as in (7.2) and (7.3):

$$I_{faultDG} = (\text{DRCT.MaxWLim}/\text{Voltage}) * 5 \tag{7.2}$$

$$I_{faultDG} = (\text{DRCT.MaxWLim}/\text{Voltage}) * 1.5 \tag{7.3}$$

Equations (7.2) and (7.3) are implemented in Simulink as shown in Figure 7.19. For rotating machines, *DRAT* block might be useful in supplying the fault current of the DG. The two parameters **DRAT.FltARtg** and **DRAT.MaxFltRtg** represent the maximum fault and short circuit currents supplied by the generator and they can be directly used by MCPU. The only drawback is that these parameters are listed as `Optional` in the Logical Node, *DRAT*, and they may be omitted for some models. The other parameters used above, on the other hand, are all listed as `Mandatory` in their respective LN.

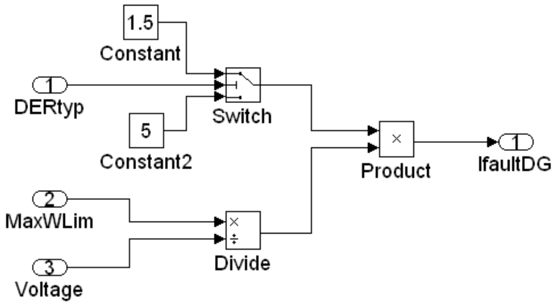

Figure 7.19. IfaultDG module (in MCPU) to extract fault contribution of DGs

Likewise, *ZINV* block might be useful in supplying the fault current of IIDGs. The parameter **ZINV.Wrtg** represents the maximum power rating of the inverter. This value can be used instead of **DRCT.MaxWLim** in (7.3). This replacement does not improve the accuracy, since the same calculation is carried out, and this parameter is listed as `Optional` in the Logical Node, *ZINV*.

7.4.1. Simulation Works and Resultant Data Maps

In order to substantiate the operation of the modeled blocks and the operation of the proposed protection scheme, the system shown in Figure 7.20 is described over a predetermined scenario.

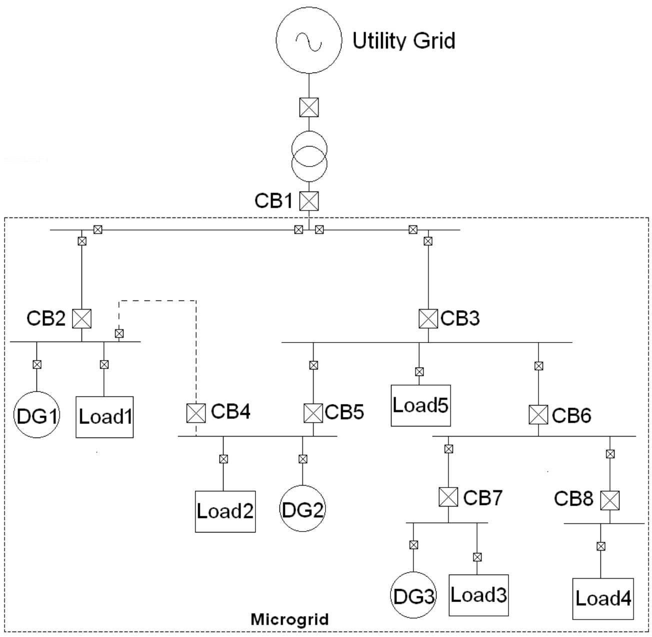

Figure 7.20. The system for which communication modeling is performed

The system includes two inverter-interfaced DGs (DG1 and DG2) and a diesel generator (DG3) which is used to set the frequency and voltage under islanded conditions. The DGs are operated under conventional droop control and share the loads in accordance with their capacities.

A specially designated scenario is applied to show different aspects of the protection scheme:

1. The system starts operation with full load, all DGs are on and the MG operates in Grid-Connected Mode.
2. At t=0.2 sec a fault occurs in Load 1 (L1) and Circuit Breaker (CB) 2 opens. Due to less power demand in the system DG1 also turned off.
3. At t=0.5 sec the utility grid experiences power outage for maintenance reasons and MG becomes islanded.
4. At t=0.65 sec, while MG is operating in islanded mode another fault occurs in L4 and CB8 opens.
5. At t=0.75 sec, the connection with the utility grid is restored and MG operates in grid-connected mode.
6. At t=1 sec, the fault in L1 is cleared and it is reconnected to the system. Due to increased power demand in the network DG1 is also put into operation.

The system shown may assume different structures depending on the status of CB4 and CB5. In the beginning CB4 is open and CB5 is connected. Therefore, the microgrid has two branches in its structure. After t=1.25 sec, CB4 closes and CB3 opens. The microgrid assumes a one-line structure. The changing selective levels of the relays are shown in the tables given below. Comparing different selective level of a particular relay for different microgrid structures shows the need for selectivity coordination. The automated operation steps mentioned in Chapter 4 fill this gap.

As mentioned earlier, it is assumed that microgrid is sufficiently small and `k` is set to 1. This means that DGs supply their maximum fault current for any fault. The parameters of the network components used by the communication system are listed in Table 7.11. At t=0.5 sec the network component parameter table is as shown in Table 7.12.

TABLE 7.11 – NETWORK COMPONENT PARAMETERS AT T=0 SEC

	$Status_{DG}$	DG type	I_{fault}
DG1	DRCS.ModOnConn= True	DRCT.DERtyp = 4	(DRCT.MaxWLim/Voltage) * 1.5
DG2	DRCS.ModOnConn= True	DRCT.DERtyp = 3	(DRCT.MaxWLim/Voltage) * 1.5
DG3	DRCS.ModOnConn= True	DRCT.DERtyp = 2	(DRCT.MaxWLim/Voltage) * 5

	CB1	CB 2	CB 3	CB 4	CB 5	CB 6	CB 7	CB 8
XCBR.Pos	ON	ON	ON	OFF	ON	ON	ON	ON
Selective Level	1	2	2	NA	3	3	4	4

The relay fault current value = Grid contribution + DG1 + DG2 + DG3
= $I_{faultGrid}$ + (DG1.DRCT.MaxWLim/Voltage) * 1.5 + (DG2.DRCT.MaxWLim/Voltage)*1.5 +(DG3.DRCT.MaxWLim/Voltage)*5

TABLE 7.12 – NETWORK COMPONENT PARAMETERS AT T=0.5 SEC

	$Status_{DG}$	DG type	I_{fault}
DG1	DRCS.ModOffUnav = True	DRCT.DERtyp = 4	(DRCT.MaxWLim/Voltage) * 1.5
DG2	DRCS.ModOnConn = True	DRCT.DERtyp = 3	(DRCT.MaxWLim/Voltage) * 1.5
DG3	DRCS.ModOnConn = True	DRCT.DERtyp = 2	(DRCT.MaxWLim/Voltage) * 5

	CB1	CB 2	CB 3	CB 4	CB 5	CB 6	CB 7	CB 8
XCBR.Pos	OFF	OFF	ON	OFF	ON	ON	ON	ON
Selective Level	N/A	N/A	1	N/A	2	2	3	3

The relay fault current value = DG2 + DG3 =

(DG2.DRCT.MaxWLim/Voltage)*1.5 + (DG3.DRCT.MaxWLim/Voltage)*5

Figure 7.21 shows the internal details of MCPU while the connections of MCPU with the DG and Relay models are given in Figure 7.22.

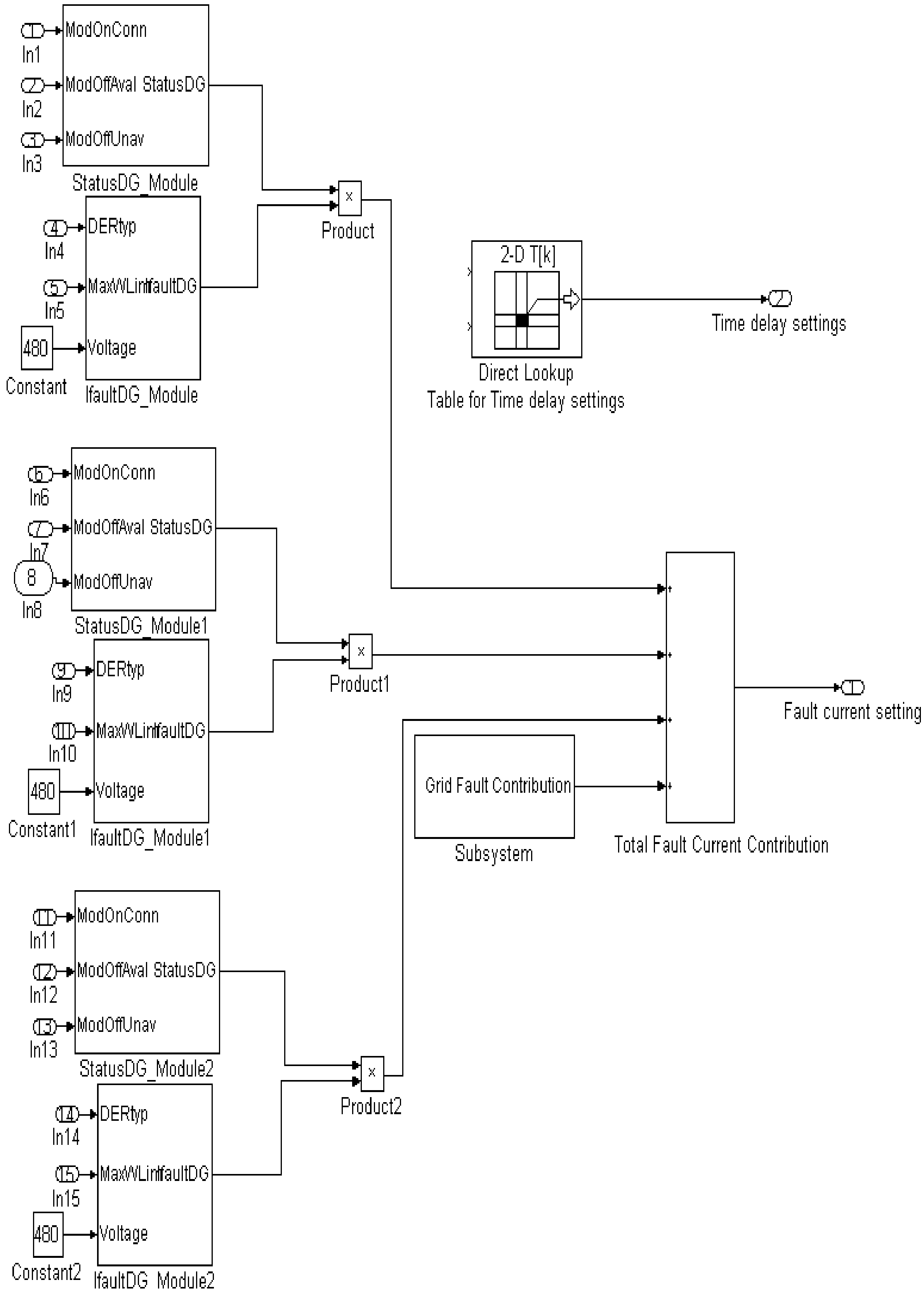

Figure 7.21. MCPU operating with modeled Relay and DG blocks

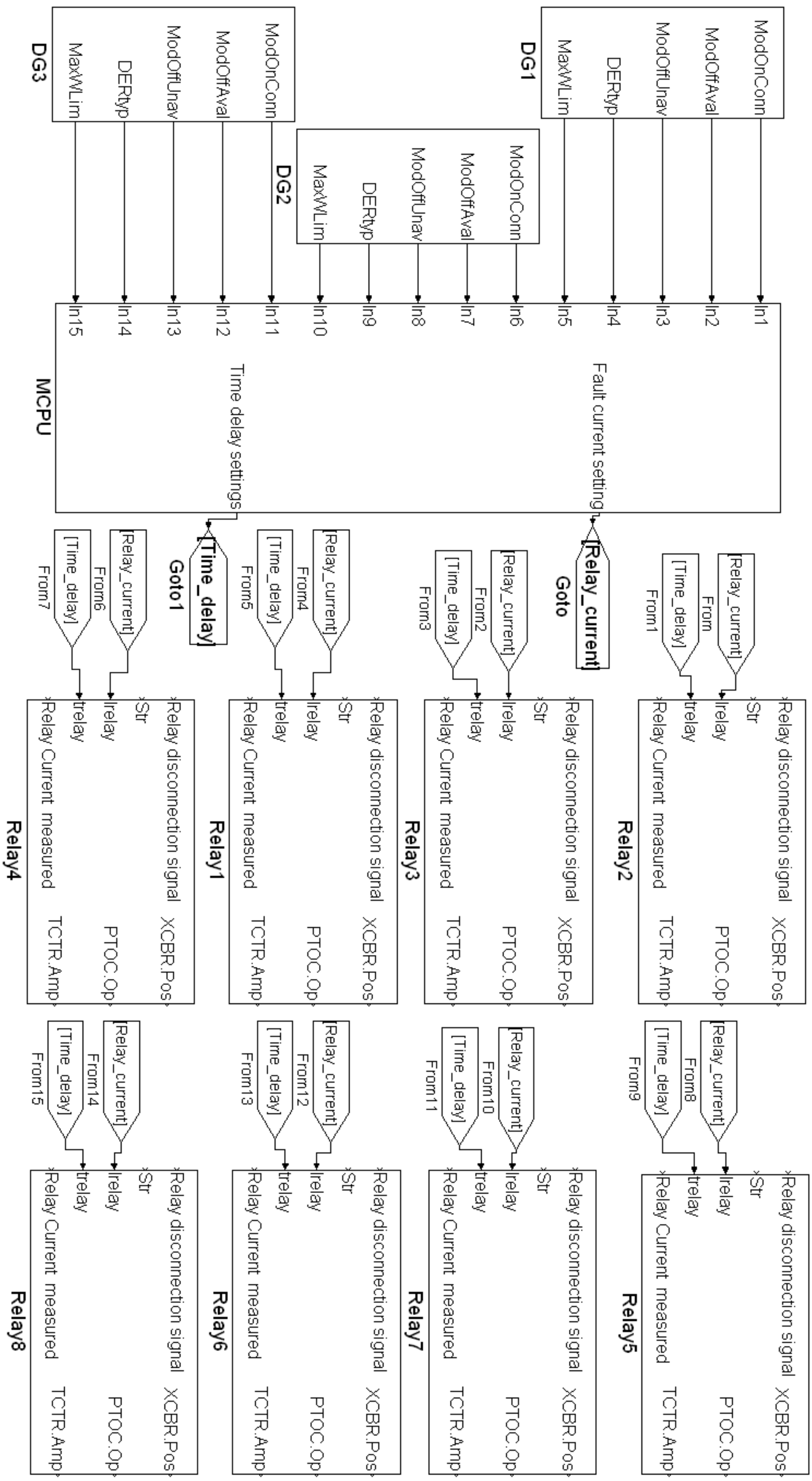

Figure 7.22. The Communication Infrastructure modeled according to IEC 61850-7-420

7.5. Conclusion

This chapter has investigated the impacts of microgrids as well as their different structures and operating conditions on the power networks. New grid components such as DGs and EVs have been utilized and the microgrid has been operated as (i) a stand-alone system, (ii) a system connected to transmission network, (iii) a system connected to distribution network. Simulation results are utilized as preliminary assumptions during the design of the novel microgrid protection system.

Secondly, the developed protection system with MCPU has been implemented in MATLAB/Simulink environment. The proposed system has been modeled in the MATLAB/Simulink environment and simulation works were carried out with a predetermined scenario which highlights different aspects of the protection scheme proposed. The new relay and DG models with communication modules along with the MCPU were modeled and tested. Obtained waveforms confirm successful operation since the protection system can adapt itself to the changes occurring in the microgrid.

For universal operation purposes, special attention must be paid to the communication protocol utilized for the communication of data within the system and a standard packet-type for the relay and distributed generator communication can be developed. If each grid component is equipped with a simple communication device to report its status, rated current and fault contribution, then a universal concept of connection can be achieved. This may prove useful for the implementation of plug and play concept in microgrids.

To this end, the communication infrastructure based on IEC 61850 and its recent extension IEC 61850-7-420 has been implemented in MATLAB/Simulink Environment. The new relay and DG models with communication modules were modeled and implemented in MATLAB/Simulink. The utilized models are very versatile and can be used in modeling different microgrids. The universal modeling of DGs regardless of their models and manufacturers is very important for having a universal concept of DG connection. Sample Data Maps are illustrated on a predetermined scenario which highlights different aspects of the protection scheme proposed. Obtained results verify the reliability and viability of the developed protection system.

Chapter 8

Operation of the Proposed Protection System under Different Protection Scenarios

Publications pertaining to this chapter:

1) ***Taha Selim Ustun, Cagil Ozansoy, Aladin Zayegh, "Differential Protection of Microgrids with Central Protection Unit Support", IEEE PES Conference on Innovative Smart Grid Technologies, Sao Paulo, Brazil, ISGT-LA 2013, 15 – 17 April, 2013 (under review).***

8.1. Introduction

Preceding chapters have explained the details of the microgrid protection system developed in this research. This chapter is the final step of this research where the interaction of the developed protection system with other protection systems is investigated. This interaction might occur in two ways. Firstly, due to the rapid extension of microgrids, more than one protection system might be implemented in a certain power network. Until all necessary adjustments have been made, several protection schemes might co-exist in the microgrid. This is particularly true, when it is considered that overall augmentation of an existing network at one instance is very rigorous and expensive. Gradual and continuous migration to a certain protection system can be the only practical solution for this problem. Consequently, for a certain period, it would be required that several protection systems operate simultaneously on the network.

Secondly, these protection systems can be used to support each other in case of need. Different protection systems have different advantages and short-comings. In future implementations, a smart microgrid central protection unit shall be able to investigate the network conditions and decide the most appropriate protection system. Furthermore, in case of a fault in the existing protection system, e.g. a communication link error in differential protection, another protection system can be used as a roll-back system for back-up protection.

As it has been expressed in various Chapters of this thesis, different protection schemes have been proposed for microgrids [84, 94, 146] and there is continuous research effort in this direction. As a strong candidate for future microgrid protection systems, differential protection is also examined [214]. Differential protection method has some inherent advantages such as immunity to voltage variations, ability to operate without prior knowledge of the fault levels and convenient acceptance of new deployments/connections [215]. This versatile nature of differential protection complies with the demanding nature of the microgrids. Consequently, this particular method is considered to be very promising for the future of microgrid protection systems.

However, there are some aspects which require to be reinforced before differential protection can be widely implemented. These include implementation of differential protection on multi-terminal elements and long power lines as well as a back-up scheme which can be used in the case of a communication failure and/or synchronization. Therefore, in this chapter, the two types of interaction schemes mentioned above, namely co-existence of different protection schemes in a microgrid and use of a protection system as a back-up, have been investigated for the developed protection system and the differential protection system. This is by no means restrictive and can be extended for other protection systems as well.

8.2. Operation with Other Microgrid Protection Systems

It is essential for future microgrid protection systems to be able to operate together on a given network. Although co-existence of several protection systems is not desirable from technical and financial point of view, some practical considerations might necessitate it. Electrical networks are operating entities and it is not possible to interrupt the power delivery for a full-fledge network upgrade. Not only that, but also such an undertaking will be toilsome and expensive. Therefore, it is expected that a gradual migration will be assumed in power networks where the new deployments shall be integrated into the desired protection system. As it is explained in Chapter 2 and 3, the unprecedented nature of microgrids requires novel protection techniques. Consequently, already existing protection system in older parts of the power network will be replaced over time. The proposed protection system has the capability to operate on dynamic microgrid structures, handle new connections/deployments, extract equipment hierarchy for changing structures and assign protection parameters on the fly. For this reason, it is appreciable that the proposed system will be selected as the novel microgrid protection implemented in the microgrids. Wherefore, it has to be able to co-operate and co-exist with other protection system during this migration period. The protection system developed in this research also has the ability to interact with other protection systems and coexist in one power network. This can be achieved by implementing Data Maps and MCPU accordingly.

Consider the system shown in Figure 8.1 where a power network has two different protection systems implemented. “Other Protection” refers to an earlier protection scheme which has already been implemented in the microgrid while "The Proposed Protection System" refers to the protection system developed in this research.

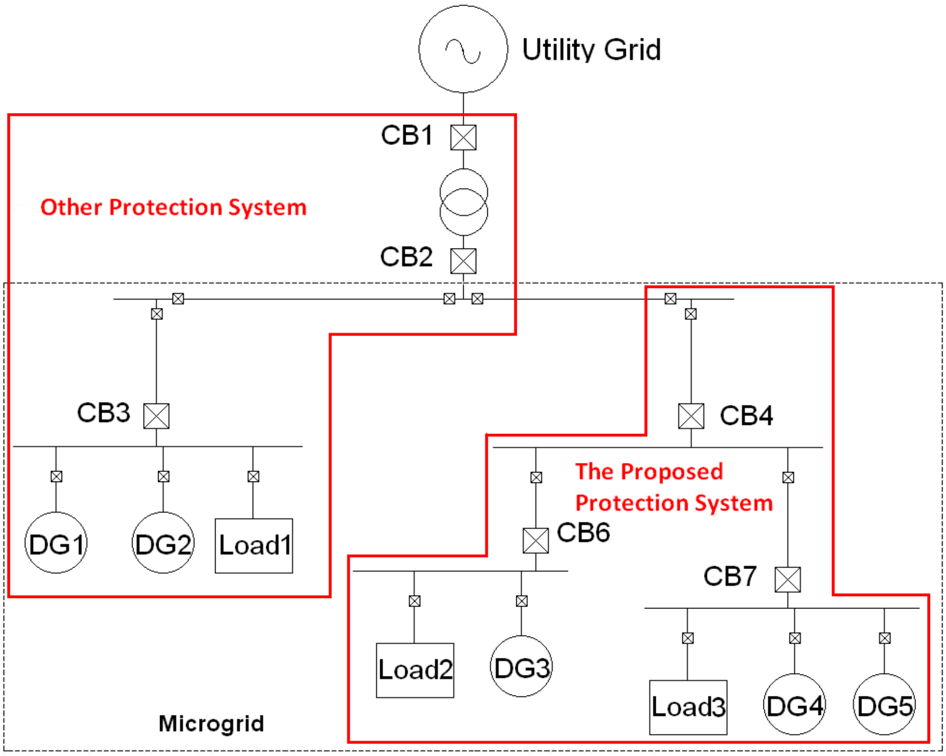

Figure 8.1. Interaction of the Proposed Protection System with Others

As shown, the previous network consists of CB1, CB2, CB3 and downstream connections of CB3, i.e. DG1, DG2 and Load1. This portion of the network has been under operation and implemented a different type of protection. The new deployments which are connected under CB4 are relatively new and for this reason, they implement a more desirable protection system which is tailor-made for microgrid operation. It is not feasible nor is it cost-effective to propose that the already-existing network be replaced at one instance. Therefore, status quo necessitates co-operation and co-existence of these protection systems.

This can be achieved by adjusting the Data Map of the Proposed Protection System as shown in Table 8.1. When the table is examined, it is observed that relays of "Other Protection System" are not listed. This is due to the fact that, these relays are not handled by MCPU of "The Proposed Protection System". Therefore, they are not accounted for. It is also worthy to note that the fault current contribution of the grid is not taken into account by the proposed protection system since the coupling transformer is included in the protection zone of the other protection system. Consequently, it is assumed that the "Other Protection System" ensures safe operation by manipulating CB1 and CB2, accordingly. As for the effect of $I_{faultGRID}$ on other relays, this can be extracted from short circuit analysis report and provided to MCPU.

TABLE 8.1. DATA MAPS FOR OPERATION WITH OTHER PROTECTION SYSTEMS

Relays	**Operating Fault Current**	**Fault Detection (1 – Y, 0 – N)**	**Time delay for Selectivity**
R4	I_{R4}	0	t_4
R6	I_{R6}	0	t_6
R7	I_{R7}	0	t_7
…			
DGs	$\mathbf{I_{rated}}$	$\mathbf{I_{faultDGx}}$	**Status (1-ON, 0-OFF)**
DG3	I_{DG3}	$I_{faultDG3}$	1
DG4	I_{DG4}	$I_{faultDG4}$	1
DG5	I_{DG5}	$I_{faultDG5}$	0

TABLE 8.2. SELECTIVITY TABLE FOR OPERATION WITH OTHER PROTECTION SYSTEMS

Relay ID	**Operating Current**	**Downstream Relay ID**	**Downstream Relay Operating Current**
R4	$Irelay_{R4}$	R6	$Irelay_{R6}$
R4	$Irelay_{R4}$	R7	$Irelay_{R7}$
R6	$Irelay_{R6}$	IR_{DG3}	$Irelay_{IRDG3}$
R6	$Irelay_{R6}$	IR_{Load2}	$Irelay_{IRLoad2}$
R7	$Irelay_{R7}$	IR_{Load3}	$Irelay_{IRLoad3}$
R7	$Irelay_{R7}$	IR_{DG4}	$Irelay_{IRDG4}$
R7	$Irelay_{R7}$	IR_{DG5}	$Irelay_{IRDG5}$

The selectivity can be assured in two ways. If there is a communication link established with CBs operating under "Other Protection System" then the selective operation explained in Chapter 5 can be implemented. If that is not the case, then the Proposed Protection System will implement selectivity in its own domain as shown in Table 8.2. Here, R4 is coupled with

R6 and R7 for selective operation while R6 and R7 are coupled with their downstream relays for 2-pair selective operation as explained in Chapter 5.

When the network operator decides to upgrade some sections of the network and integrate them into the proposed system, this can easily be performed. An example case is given in Figure 8.2 where CB1 and CB2 are integrated into the proposed system. The branch downstream of CB3 is still operating on the previous conditions. Should there be additional investment by the network operator, this branch can also be integrated. In this manner, the gradual emigration to the proposed protection system can be finalized.

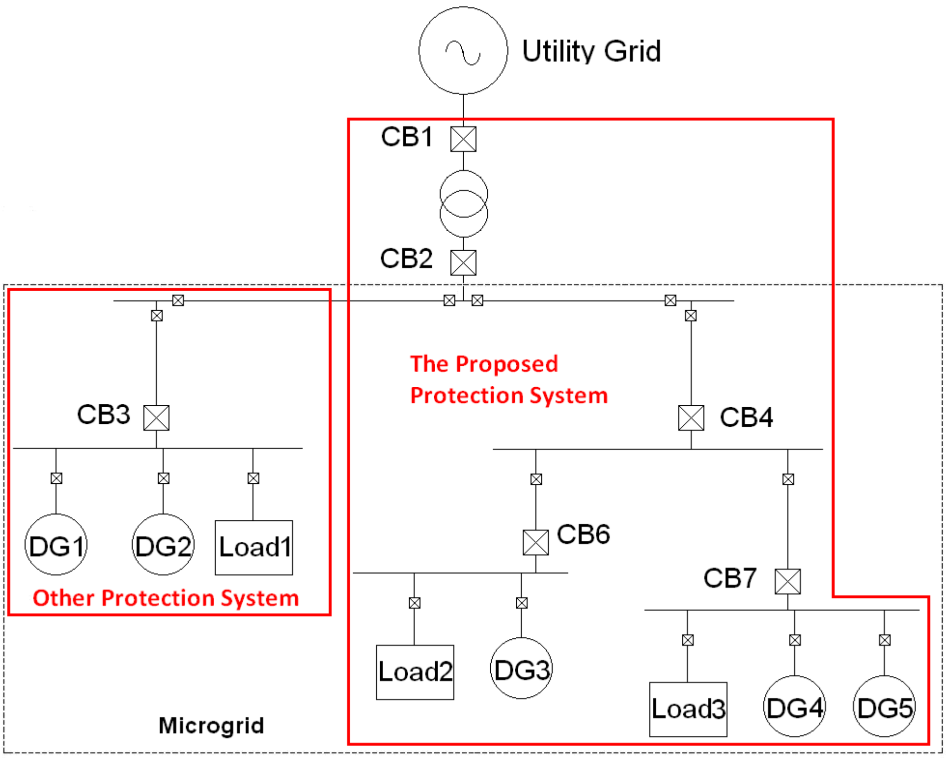

Figure 8.2. Status of the network after inclusion of CB1 and CB2 in the Proposed Protection System

Table 8.3 shows the updated Data Maps in MCPU for the new case. Since grid-connecting relays are included in the system, the fault current contribution of the utility grid is taken into account by the proposed protection system. The branch located downstream of CB3 is protected by “Other Protection System”; therefore it is assumed that necessary precautions are taken to protect DG1, DG2 and Load1.

TABLE 8.3. DATA MAPS AFTER INTEGRATION OF CB1 AND CB2

	Grid-Connected	**Islanded**	
Operating Mode	1	0	
Grid Fault Contribution	$I_{faultGRID}$		
Relays	**Operating Fault Current**	**Fault Detection (1 – Y, 0 – N)**	**Time delay for Selectivity**
R1	I_{R1}	0	t_1
R2	I_{R2}	0	t_2
R4	I_{R3}	0	t_4
R6	I_{R3}	0	t_6
R7	I_{R3}	0	t_7
DGs	$\mathbf{I_{rated}}$	$\mathbf{I_{faultDGx}}$	**Status (1-ON, 0-OFF)**
DG3	I_{DG3}	$I_{faultDG3}$	0
DG4	I_{DG4}	$I_{faultDG4}$	1
DG5	I_{DG5}	$I_{faultDG5}$	1

The selectivity pairs for the new case can be arranged as shown in Table 8.4. 1st branch incorporates all the equipment controlled by the proposed protection system. The interaction between two protection schemes occurs in the 2nd branch. R2 is paired with R3 as a back-up protection in case R3 cannot interrupt the fault current. The synchronization between these relays can be achieved through communication lines, if any, or by any other proper means.

TABLE 8.4. 2-PAIR SELECTIVITY LIST AFTER NEW INTEGRATIONS

Relay Hierarchy	**1st branch**	**Selectivity pairs**
5	R1	
4	R2	
3	R4	
4	R6	
1	R7	
	2nd branch	
2	R2	
1	R3	

The process mentioned above is vital for implementing gradual migration towards a desired microgrid protection system. This is all the more crucial, if the mentioned protection system requires special equipment and deployments. Furthermore, the flexibility of the proposed protection system, which is illustrated above, can be utilized for accepting new deployments in the microgrid. New deployments can be easily detected and integrated into the established system. Some sections in Chapter 4 have been dedicated to plug-and-play concept which serves for new deployments. This can be achieved while the proposed system is co-operating on an electrical network along with other protection systems.

The ability to implement the proposed protection system simultaneously with other schemes is also a very important and necessary feature. Having the flexibility given above, the proposed protection system is a good candidate for future microgrid protection systems.

8.3. Usage of Proposed System as a support for Differential Protection

One of the most widely used methods for power system protection is differential protection [216]. It is based on the fact that under all circumstances the sum of all the currents in the protected zone shall add up to zero except for internal faults. Since it only uses electrical current value from the power system, it does not require voltage measurements and, hence, is less sensitive to power swings, sudden load changes and voltage variations [217]. Differential protection is especially attractive if the both ends of the apparatus are close to each other [218]. Consequently, it is commonly used to protect transformers, generators, bus bars and motors. In addition, the use of differential protection on short transmission lines dates back to as early as 1930s [219].

Consider the system given in Figure 8.3 where a power system component, such as a transformer, motor, load or power line, is protected with differential protection. As shown, this protection scheme is an application of Kirchhoff's Current Law. Under normal circumstances the currents flowing on the secondary sides of Current Transformers (CTs) add up to zero and the coil would not have any energy to operate [220]. Should there be fault, this equilibrium will not hold anymore and the relay will be triggered.

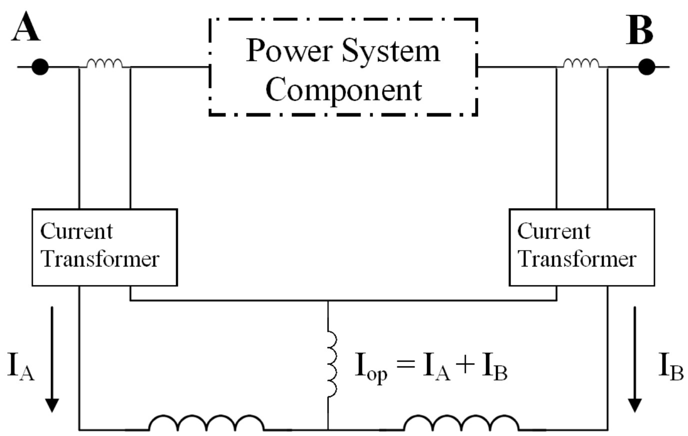

Figure 8.3. A sample differential protection topology

The application of differential protection to power lines require communication links since the two terminals of the protected component are located far away from each other [221]. As illustrated in Figure 8.4, two relays located at the either end of the power line receive local measurements and report these values to the other relay. However, in this case, the communication delay shall be taken into account and the measurements received from the communication link shall be compared with the corresponding local measurements. This requires a synchronization algorithm based on time-stamping concept where the timing of each measurement is recorded as well as the measurement value. The application extent of differential protection to power lines was highly limited with analog communication lines due to signal attenuation. Therefore, this protection scheme has been used mostly on short lines which cannot be effectively protected by distance protection. However, the latest developments in digital communication and microprocessor-based relays made this application possible on long lines [215].

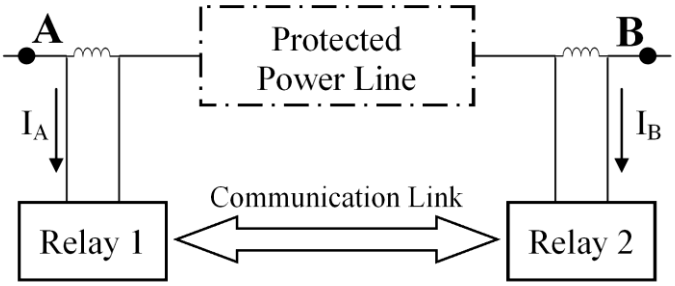

Figure 8.4. Differential Protection for power lines

Along with its advantages, differential protection has its own important drawbacks. Among these are; dependence on high communication performance when used for the protection of long feeders, the need for uninterrupted communication link, current transformer mismatch or saturation, synchronization and application to multi-terminal systems.

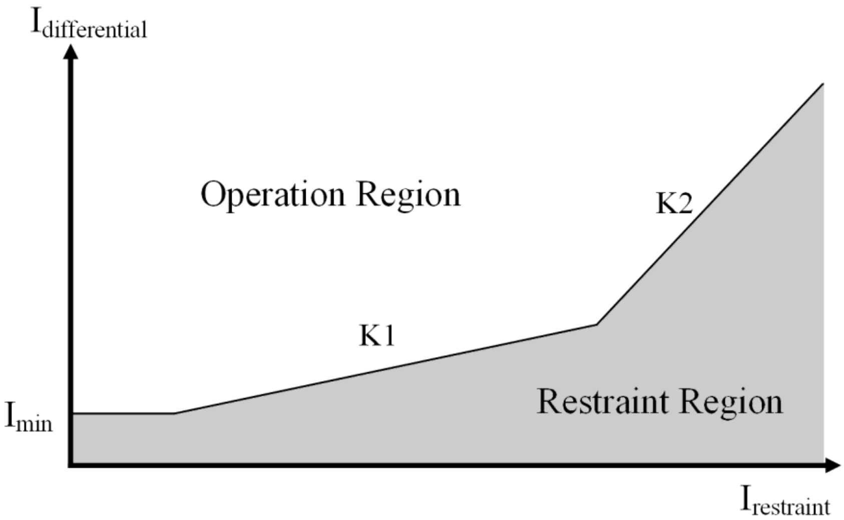

Figure 8.5. A double-slope restraint characteristic [222]

The mismatch between CTs and their saturation are major concerns since they cause relays to measure false differential currents. In order to compensate these measurements errors, a threshold is used to restrain the operation of the relays. Following this definition threshold current is called restraint current [222]. It is calculated from local parameters and increases with increasing current to match higher measurement errors at higher levels. A typical restrain characteristic is shown in Figure 8.5. The operation of the relay is controlled with an adjustable threshold, I_{min}. The restraint current increases with increasing differential current. Two different coefficients are used to control rate-of-increase where the smaller slope K1 is used to compensate CT mismatch while larger slope K2 is used to compensate CT saturation at very high current values.

The currents are calculated as follows;

$$I_{op} = I_{differential} = i_A + i_B \quad (8.1)$$

$$I_{restraint} = f\,(i_A\ ,\ i_B) \quad (8.2)$$

$$\text{If} \quad I_{differential} > g(I_{restraint}) \Rightarrow \text{Operate!} \quad (8.3)$$

where $\mathbf{i_A}$ denotes the average or the magnitude of the current, ***f*()** and **g()** denote independently adjustable functions. The former is utilized to calculate the restraint current based on measurements whereas the latter defines the operation condition based on differential and restraint currents.

Various calculation methods, i.e. definitions of ***f*()**, are reported in the literature for restraint current determination. Different methods, in (8.4), (8.5), prove to have better performance under different fault conditions [218].

$$I_{restraint} = i_A - i_B \quad (8.4)$$

$$I_{restraint} = i_A + i_B \quad (8.5)$$

$$I_{restraint} = \max\,(i_A\ ,\ i_B) \quad (8.6)$$

Consequently, the structure of the network and the possible fault conditions might be considered while selecting the proper restraint method. Moreover, adjusting the restraint current calculation method according to changes in microgrids or recently developed concepts may provide the most efficient and effective differential protection. This point is further studied in the next section where the proposed system is explained in detail.

Another challenge is the adjustment of differential protection for multi-terminal components where several inputs shall be arranged to define a protected zone, see Figure 8.6. Especially, if there are changing connections, differential protection has to be implemented with a digital setup. Otherwise, the CTs have to be manually coupled and decoupled.

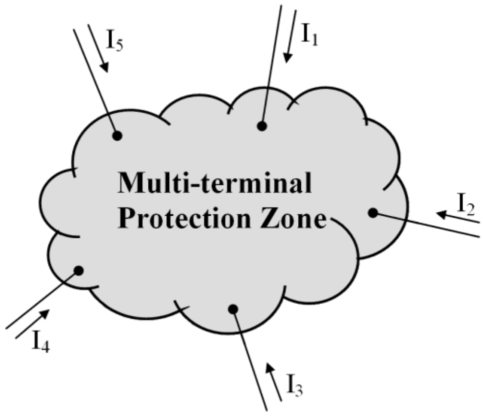

Figure 8.6. Multi-terminal protection zone with several currents

For this purpose, micro-processor based relays are used where all connections are reported to the microprocessor. Then, they are grouped according to the state of connections. That being said, it is extremely difficult to implement this concept on power lines where there are numerous components continuously connect to and disconnect from the protection zone. Therefore, as shown in the next section, a comprehensive control system might be used to support the differential protection.

The most important disadvantage is the dependence on the communication link between the relays. The measurements are reported in a continuous fashion and a possible failure in communication lines proves to be lethal for differential protection. The malfunctioning of the relays or the complete collapse of the protection is out of question. Some back-up strategies are mentioned in the literature, to be used in case of communication failure. But they are not developed as a complete system [215]. The next section explains an alternative back-up strategy which can be used in case of communication failure.

8.3.1. Differential Protection with Microgrid Central Protection Unit (MCPU)

As outlined in the previous section, the wide-scale application of differential protection to modern microgrids requires some adjustments. In this section, an MCPU is used to support these shortcomings and reinforce differential protection as the promising protection scheme of future networks. This system is designed to tackle the following issues:

- Adjustment of restraint current calculation algorithm in accordance with changing network conditions and/or Incorporating new calculations algorithms developed as a result of research in this field
- Integration of multi-terminal protection zones into differential protection
- Proposing an alternative system which can be used in a back-up strategy if there is a failure in communication links

For this purpose, the protection system developed in this research [55], shown in Figure 8.7, is utilized. This system has an MCPU to communicate with all relays and DGs in the microgrid. In this fashion the network can be effectively monitored and necessary adjustments can be made. The strength of this topology is its ability to be tailored for different applications such as fault current limiters [146] or differential protection.

MCPU communicates with every network component and each new connection/disconnection is reported to it. Therefore, MCPU has the ability to extract the current state of the network, list the connected entities and choose a proper restraint current calculation method. In order to achieve this, a comprehensive algorithm should be implemented in the MCPU. Similarly, if it is desired to upload a completely novel algorithm, then MCPU will be able to achieve this in a centralized manner. This will decrease the burden on network operators who, otherwise, would need to visit each relay individually.

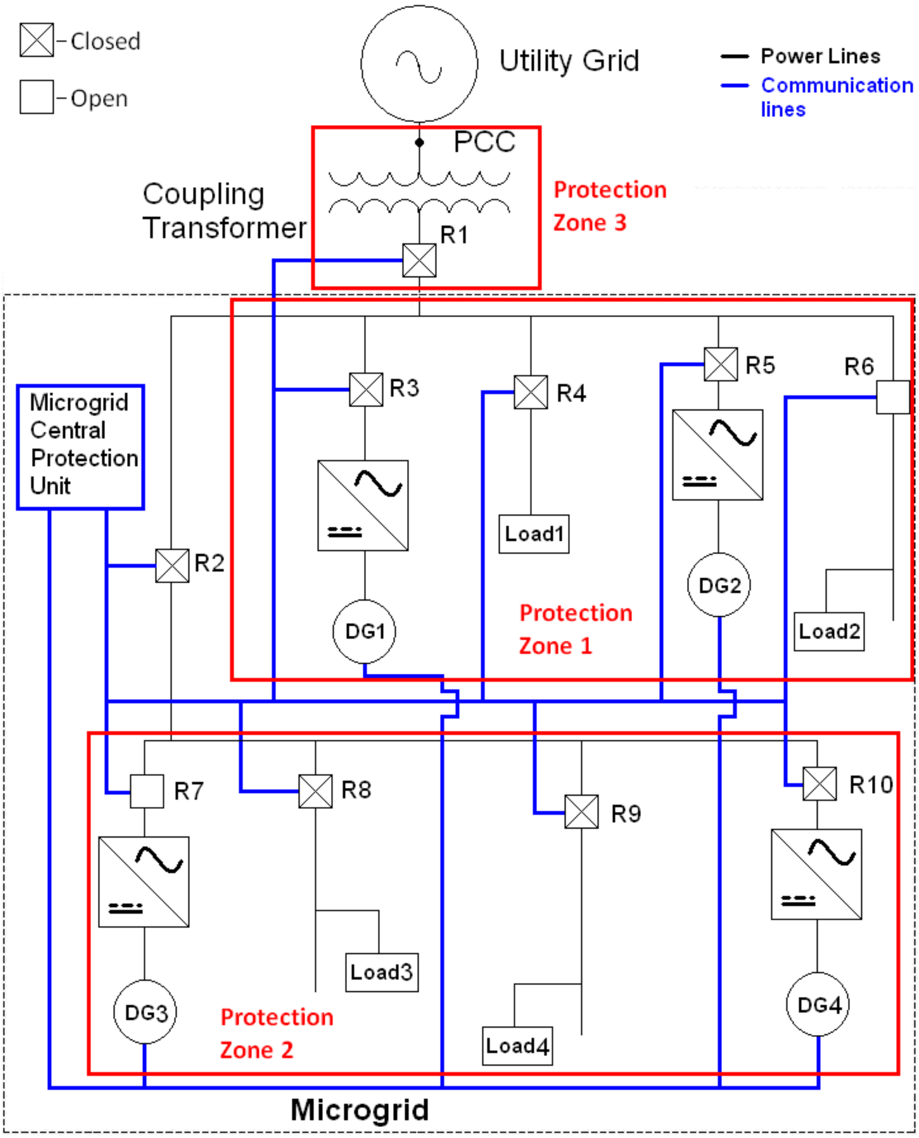

Figure 8.7. Topology of the Developed Differential Protection with MCPU

Secondly, MCPU assists multi-terminal differential protection. Multi-terminal protection can be locally implemented if all the terminals are connected to the same point, e.g. buses with more than two terminals. However, if it is required to cover a protection zone with differential protection then additional support is necessary. For example, when a power line is protected, the connections of compensators, shunt reactors etc. shall be taken into account. The initial charging currents of these components shall be added to the differential protection scheme.

Table 8.5 shows a sample multi-terminal differential protection zone implemented in Figure 8.7. Since Load 2 and DG4 are not connected to the network, their currents are not included in the protection scheme. The coupling transformer is also protected with differential protection (Zone 3) and its charging current is considered when the network is re-connects to the grid after being islanded. The changes in the microgrid are immediately reflected to the protection zones. Furthermore, new deployments can be easily inducted without the need for any physical CT or communication link installation between the relays.

TABLE 8.5. MULTI-TERMINAL DIFFERENTIAL PROTECTION ZONES

Protection Zone No.	Active Currents	Non-active Currents	Charging Currents
1	I_{DG1}, $I_{DG2,}$ I_{load1}	I_{load2}	-
2	I_{DG4}, I_{load3}, I_{load4}	I_{DG3}	-
3	I_{grid}	-	$I_{coupling\_transformer}$

The final and most important contribution of the proposed system is the back-up protection utilized in case of communication failures. The fault current estimation methodology developed in this research which is used to program over-current relays [55, 146, 182] has been presented in earlier chapters. The microgrid is continuously monitored and fault currents are estimated based on the number and type of the components connected to it. Once the fault currents are estimated and the operating currents are reported to relays, the relays operate individually without any communication process.

In other words, communication is only required when there is a change in the microgrid and fault currents need to be estimated. Since it uses local decision-making, shown in Figure 8.8, this scheme is less dependent on the communication. It is proposed to use this scheme as the back-up of differential protection. Should there be a communication and/or synchronization problem, the system can roll-back to the over-current protection presented in previous chapters. This can be easily implemented in some differential protection schemes where over current relays are already utilized for differential protection [223, 224]. In other networks where overcurrent relays are not present, digital multifunction relays can be used for both differential and overcurrent protection techniques [225-227].

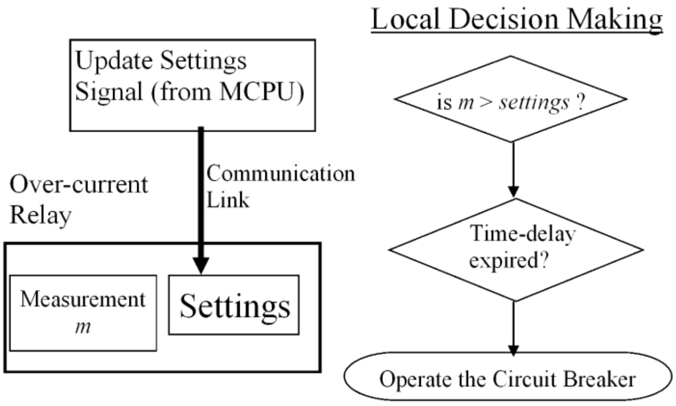

Figure 8.8. Local Decision Making without Continuous Communication

To perform its duties, MCPU employs a data map as shown in Table 8.6. Information on each component is stored with the relevant control variables. The very first variable of the central unit is the operating condition of the microgrid. Once the microgrid is islanded or re-connected to the grid, the status of the relay R1 is handled by the central controller algorithm. New operating fault currents of relays will be calculated by considering the fault contribution of the grid, i.e. $Ifault_{GRID}$ and updated.

TABLE 8.6. DATA MAPS IN THE MCPU

	Grid-Connected	**Islanded**	
Operating Mode	1	0	
Grid Fault Contribution	$Ifault_{GRID}$		
Relays	**Operating Fault Current**	**Fault Detection (1 – Y, 0 – N)**	**Time delay for Selectivity**
R1	I_{R1}	0	t_1
R2	I_{R2}	0	t_2
R3	I_{R3}	0	t_3
…			
DGs	$\mathbf{I_{faultDGx}}$	**Status (1-ON, 0-OFF)**	
DG1	$I_{faultDG1}$	1	
DG2	$I_{faultDG2}$	1	
DG3	$I_{faultDG3}$	0	

The MCPU continuously monitors the statuses of all DGs in a synchronized manner by communicating with them using a Publish/Subscribe peer-to-peer messaging (similar to IEC 61850's GOOSE) messaging system. If a DG disconnects at any time for example, the fault currents are re-calculated by considering the fault current contribution ($I_{faultDGx}$) of that particular DG. In this way, the system is ready for any fault condition before any fault, actually, occurs.

The prospective relay settings are recalculated and updated based on the DG status data. In Table 8.2, the status of DG3 (alternatively status of R7, not shown) shows that it is not in operation. This may be due to maintenance, the intermittent nature of RE resources (no sun or wind) or the excess local generation. In case the local consumption increases and DG3 is put back into operation, this is reported back to the MCPU either through DG3's or R7's status signals. The new fault current contribution IfaultDG3 is taken into account and new fault levels are updated for all the relays in the grid. Similarly, if DG2 is shut down for a certain reason, then it is reported to the MCPU through DG2's or R5's status signal. The data map will be updated and new fault current level calculations will be performed without IfaultDG2. For a particular relay, the operating fault current (the current level that causes the relay to trip) is calculated as in (8.7). The details of this calculation process have been given in Chapter 3 and Chapter 5.

$$I_{relay} = \left(I_{faultGRID} \times OperatingMode\right) + \sum_{i=1}^{m} (k_i \times I_{faultDGi} \times Status_{DGi}) \qquad (8.7)$$

The MCPU uses a simple algorithm shown in Figure 8.9. The status of R1 has been given a special consideration since it imposes the operating mode and grid fault contribution. The details of the algorithm implemented have been as presented in Chapter 3, Conceptual Design.

Once new fault currents are updated, relays operate independently. When the current flowing over the relay exceeds the operating current, relays send signals to set the fault detection bit. If the fault is not cleared by any other relay inside the delay time, that particular relay triggers the circuit breaker to isolate the fault. These time delays are set to ensure proper selectivity in the system. Obviously central relays such as R1 and R2 have larger time delays than those located in branches such as R4 and R8.

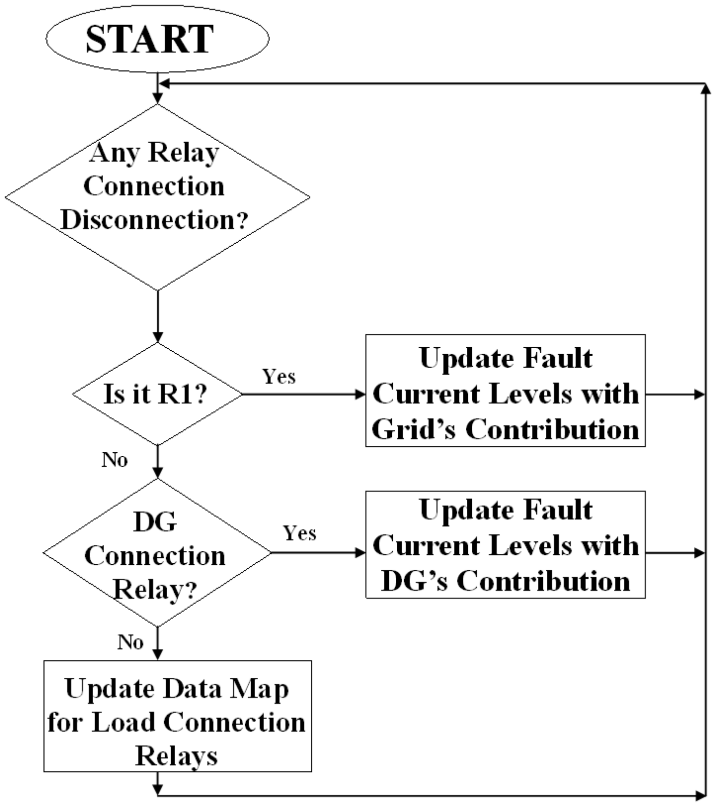

Figure 8.9. Protection Algorithm employed in MCPU.

The system shown in Figure 8.7 does not require rearrangement of time delays for different operating conditions. In a more complex system, new time delay settings should be updated in relays along with the operating fault currents. This can be performed with the automated microgrid structure detection scheme presented in Chapter 4. Furthermore, 2-pair selectivity method can also be implemented.

8.3.2. Communication Infrastructure Reliability Considerations

In addition to the above-mentioned advantages, proposed protection system is more reliable than differential protection from communication perspective. This is due to the fact that the communication used in differential protection is required to be continuous while the proposed system needs communication to update protection parameters. In recent years, different reliability assessment methods have been proposed such as Reliability Block Diagram (RBD) [185], 3RF Technique [186], and Software Reliability Allocation [187]. The failures are classified and new parameters are introduced to design a more comprehensive reliability assessment scheme [184, 188].

These systems consider issues related to relay hardware, relay software, ancillary equipment, communication units and human errors. [186, 188]. All of them consider the probability of a failure occurrence and its impact on system dependability and security as defined by IEEE standard C37.100-1992 [189]. The probability of a failure is defined by [187, 190]:

$$P[failure] = \sum component_{failure} \tag{8.8}$$

where all the individual probability components are added to find the overall value. Equation (8.8) applies to differential protection schemes, since they require all components to function perfectly for reliable operation. A failure in any component such as current transformer or a communication line failure will trigger the collapse of the whole system. The probability of a failure in differential protection is as follows:

$$P\left[failure_{diff.prot}\right] = \sum_{i=1}^{n} P\left[individual_{failure}\right] \tag{8.9}$$

Contrary to this, the proposed system implements a "last-setting-valid" approach in case of a communication failure. Therefore the probability of a failure in the proposed protection system can be expressed as in (8.10).

$$P[failure_{combined}] = \prod_{i=1}^{n} P[probability_i] \tag{8.10}$$

where n is the total number of independent events.

As shown in Figure 8.8, the operation is independent of the communication link and this ensures that relays are always set to operate, though it may not be the most desirable operation point. However, this requires two events:

1) a failure in the communication line,

2) an electrical fault in the network before the communication line is restored.

Therefore the probability of a relay operating following "last-setting-valid" method is the multiplication of the probabilities of communication link failure and electrical fault:

$$P[comm_{fault}]=P[comm] \text{ x } P[fault] \tag{8.11}$$

where P[comm] is the probability of a communication failure occurring in the microgrid while P[fault] is the probability of an electrical fault occurring in the same microgrid.

It is clearly mentioned in the literature that with the improving technology the hardware failures are less frequent [187]. Consequently, the value of probability of communication failure is very small. The values assumed for these probability values are around on the order of 10^{-2} or 10^{-3} [188, 190]. For short term analysis these values may drop as low as 10^{-5}[192]. Accordingly, replacing these characteristic figures in (8.11) yields probability of failure for the proposed protection systems:

$$P[comm_{fault}]=0.01 \text{ x } 0.001 = 10^{-5} \tag{8.12}$$

Replacing same figures in (8.9) yields the probability of failure for differential protection approach. A simple protection setup given in Figure 8.4 incorporates two relays and a communication link. Therefore the cumulative probability is:

$$P[failure_{diff.prot}]=0.01 + 0.01 + 0.001 = 0.021 \tag{8.13}$$

As a result, the developed protection system proves to be reliable in accordance with the requirements of the standards [189]. Considering the value of $P[comm_{fault}]$, it is concluded that the possibility of relays operating when there is a communication failure is very small.

Even if they are forced to operate before the communication is restored, the implementation of "last-setting-valid" method ensures that no catastrophic condition occurs. If, as an exceptional case, a fault occurs just after a Relay Setting Update process has started, then the regular communication speed is around 80 ms [193] and this ensures that relay settings will be updated. In contrast, differential protection requires all components to work perfectly and this adds to the probability of failure. Consequently, the probabilities of failure given in (8.12) and (8.13) are substantially different.

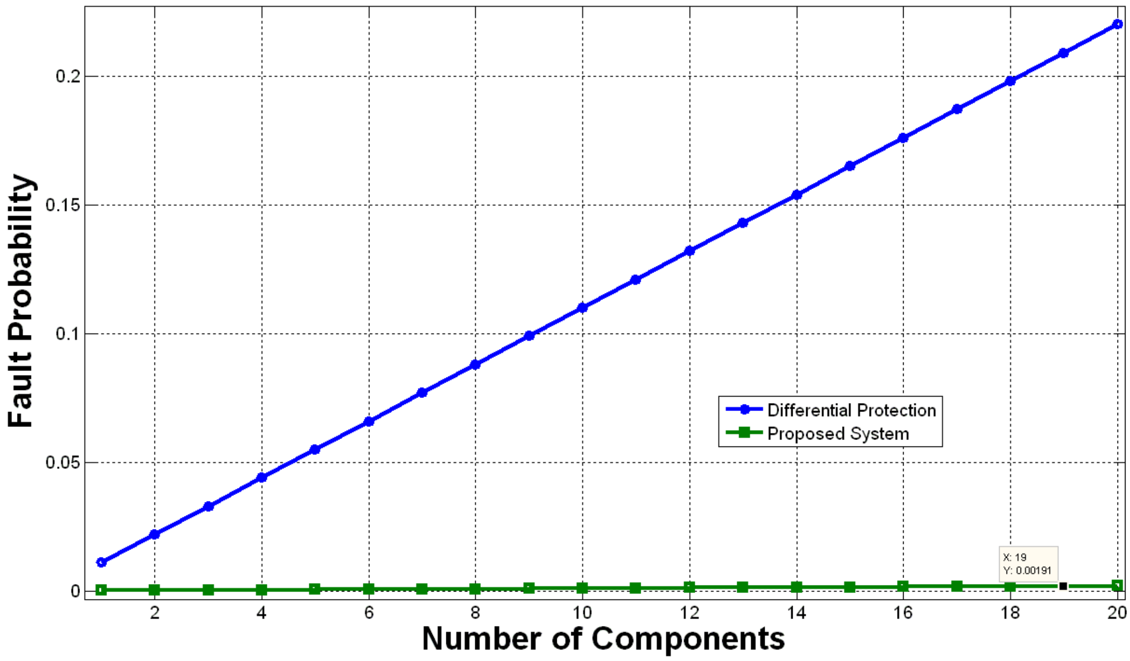

Figure 8.10. Fault Probability Distribution in a Multi-Terminal Protection Zone

As the complexity of the protection zone increases, the reliability advantage of the proposed system becomes more apparent. When there is a multi-terminal protection zone similar to Figure 8.6, the number of components increases and the difference in failure possibilities grows larger. Figure 8.10 depicts the fault probability distribution for different number of components in a multi-terminal protection zone.

Naturally, higher number of the components increases the likelihood of a fault. However, as the graph reveals, the rate of increase is much larger for differential protection. This indicates that some modifications shall be done before conventional differential protection scheme is implemented in multi-terminal zones. On the other hand, the proposed system sustains a low rate-of-increase and it is much reliable in more complex systems.

8.4. Conclusions

This chapter has presented the interaction of the protection scheme developed in this thesis with other conventional protection systems. Two different interaction types which are vital to microgrid protection have been investigated. One of them envisages the simultaneous operation of several protection systems until the complete emigration towards a certain protection system has been completed in a gradual manner. The latter interaction is required to reinforce protection systems with others wherever it is required.

In this regard, a new communication-assisted protection scheme for microgrids has been examined. This hybrid protection scheme employs differential current as the primary approach and reinforces it with MCPU. In this fashion, some of the major drawbacks of differential current protection are removed with MCPU support. The ability to monitor the entire microgrid gives the opportunity to choose different restraint current calculation algorithms and to adjust the multi-terminal zone protection according to the changes in topology. The proposed system is very versatile and more reliable than conventional differential protection approach.

Furthermore, it has been investigated how the protection system developed in this thesis can be used as a back-up protection scheme which operates under communication failures. The combinatory usage of two protection systems is feasible and yields very robust and reliable protection.

The selection of differential protection is not intended to be limiting. These interactions can be achieved with other protection systems with the help of MCPU and the flexible use of Data Maps. With the smart programming of MCPUs, future microgrid protection systems may have the luxury to select from different protection systems depending on the network conditions. Therefore, protection systems should be designed to be cooperative rather than being mutually exclusive. The developed protection system serves this purpose as well.

Chapter 9

Conclusions and Future Work

9.1. Introduction

This research presents a novel microgrid protection system which comprises a central unit, i.e. MCPU, and uses a communication network to achieve protection adaptation and synchronization. Considering the proliferation of DGs and the unprecedented protection issues appearing due to their impacts on microgrids, such a protection system is a relevant and timely contribution to the literature. Advantageously, this protection system has been developed to be versatile and flexible so as to accommodate several microgrid topologies with different set of grid components and to accept new deployments, respectively. The utilization of communication lines might seem as a drawback at first sight, however, smartgrid concept implies that every grid component shall have a communication capability in power networks. The develop system shall make use of these lines and will not require installation of separate lines.

Since it is an emerging field in power networks, microgrid concept received a lot of attention in research circles. In a short span of time, many applications have been made, several enhancements have been proposed and power engineering has evolved indelibly. However, relatively little effort has been made towards microgrid protection systems as the researchers mainly focused on RE based DGs, efficiency enhancement, load sharing, stability etc. Protection issues and considerations come into play only after necessary work has been done in other fields and microgrids have started to operate. Only after having several DGs installed in microgrids can we see their impacts on fault currents and fault levels. Therefore, the existence of this knowledge gap is not coincidental.

Nevertheless, there are some publications focusing on microgrid protection where some protection schemes are proposed. These solutions are not as comprehensive as the system proposed in this thesis from several aspects. Firstly, almost all of these solutions are tailor made for a specific microgrid with a given set of grid components. Any new deployment or any new connection which adds a new microgrid structure will render these protection schemes useless. This is a major drawback for universality and compatibility purposes.

On the other hand, some protection schemes have been kept very broad and very open-ended with the intention of including all possible microgrids with various sets of grid components. These broad schemes are not developed further and they remain as a conceptual design without any solid application framework. Consequently, the major concern about these schemes is the lack of implementation features. Furthermore, majority of these proposed protection schemes declare that communication will be an indispensible part thereof. However, there is not any research work focusing on the communication infrastructure of future microgrids and the standardization of the communication in microgrids to achieve universal protection schemes that can accommodate all types of grid components.

The research work presented in this thesis has proposed a novel microgrid protection system which has been designed to be versatile so that it can be implemented in various microgrid topologies with differing set of grid components. It has been designed to be dynamic, i.e. to follow dynamic changes occurring in the microgrid such as connection changes or new deployments, and adapt the protection scheme automatically by extracting the resulting microgrid topology and assigning new operating conditions. Furthermore, this detailed conceptual design was modeled according to IEC 61850 communication standard to make it universal and applicable on all sorts of equipment and compliant with IEC 61850 enabled relays. In order to achieve a system which is fully modeled under IEC standards, several extensions to IEC 61850 have been proposed for FCLs and EVs.

The overall protection system has been formed by compiling these individual modules in MCPU with the help of communication lines. This protection system can be used as a stand-alone system in a microgrid or it can be utilized as a roll-back strategy for other protection systems in case of a failure. Due to the design strength, proposed protection system does not require continuous communication. Communication is only required when a change occurs in the microgrid and this increases the reliability of this system largely.

9.2. Key Contributions of the Research

As mentioned in the section above, the microgrid protection system developed in this research focused on several aspects of microgrids to devise a more comprehensive system. Therefore, key contributions of the research spans over different areas which are itemized below.

- A thorough review of the microgrid evolution and the effects of new grid equipments

This research provides information on the newly emerging areas such as microgrids and new grid equipments such as FCLs and EVs. Various test cases have been explained from around the globe to reflect the differences in the understanding and interpretation of these concepts.

Special attention has been paid to microgrid protection area to highlight the knowledge gaps. Moreover, the impacts of the equipment which are connected to the grids recently have been investigated. This investigation comprises of several components such as DGs, RE based DGs, IIDGs, DGs with FCLs. Furthermore, the impact of EVs and their two-way operation, i.e. V2G and G2V, has been analyzed. Since these new grid components are bound to become more popular in the future, this research provides valuable information about their behaviors and impacts on microgrids.

- Details the design of a novel protection system based on comprehensive communication and MCPU

Most of the research work present in the literature talk about protection systems in general terms. They iterate that communication would be required between the components. However, this research designs a complete protection system with detailed analysis on the central unit, MCPU, and its interaction with other components. Special attention has been paid to discussing the type and format of communicated data, the decisions making process in the MCPU and the development and update of data maps stored for proper operation. A novel microgrid protection system has therefore been fully designed and investigated for its proper and reliable operation.

- Utilization of IEC 61850 Standard and its recent extension IEC 61850-7-420 in modeling for standardized communication of data

The detailed design of the microgrid protection system data exchange process has been implemented with international substation communication standard IEC 61850 and its recent extension for DGs IEC 61850-7-420. This is a very important contribution for achieving a universal protection system that can operate with different equipment with different models and from different vendors . This communication infrastructure shows how a standard communication interface can be used in an environment where equipment with different origin and models are utilized. It is highly recognized in the literature that future microgrid management and protection systems should be comprehensive and able to operate with all sets of components. The implementation of the data communication aspects of the developed system as per the IEC 61850 standard tackles this issue by bringing forth a universal communication interface. Instead of having a localized, custom-made protection system for a particular microgrid, this approach ensures that the proposed protection system can be utilized as a generic system and applied to microgrids worldwide.

- Advancement of IEC 61850-7-420 through necessary extensions

IEC 61850 received much attention in power engineering fields. In order to keep up with the changes occurring in microgrids, a new extension of this standard has been published for DGs, the IEC 61850-7-420. There are still some devices which are not defined in this standard. These include FCLs and EVs. Since they are bound to be used very often in future power networks, abstract information models need also be incorporated into the IEC 61850 standard. In this research, these missing links have been connected by proposing new information models for these devices. Therefore, these extensions do not only constitute a vital part of this research but also contributes to the enhancement and improvement of the IEC 61850 standard in power networks.

- Realization of plug-and-play concept with automatic microgrid structure detection

One of the fundamental differences between old interconnected systems and microgrids is the dynamic structure of microgrids. In a microgrid, several connections/disconnections may happen in a very short period of time and some new deployments are always bound to occur. These deployments need not be very high cost projects. For instance, whenever a new EV is purchased by a household or a PV panel is installed, this will appear as a new deployment from network operator's point of view. Therefore, a new approach has been taken to enable the microgrid protection system monitor the changes and extract the resulting structure. Most of the proposed microgrid protection systems in the literature are tailor-made solutions for a known structure of the microgrid. An unprecedented connection or a new deployment cannot be considered by the protection system. However, thanks to the automated approach implemented in this research with Dijkstra's algorithm, network structure is not required to be known by the protection system beforehand. The hierarchy of grid components and new deployments can be easily detected by running Dijsktra's Algorithm over the object-oriented modeling of the microgrid. Therefore, the protection system is generic and can be implemented in different types of microgrids. Moreover, easy handling of new deployments serves for plug-and-play concept.

- Supporting other protection systems and co-existence

The developed protection system can be implemented with other protection schemes used in microgrids. It is not realistic to propose full-replacement of protective devices and their operation at one instance. This will be too expensive and troublesome to manage for network operators. Rather a gradual change might be realized to lower the costs and the workload. This implies that the interaction between different protection systems is of crucial importance as they might co-exist in a microgrid for a short period of time. Therefore it is important for the protection system to be able to cooperate over a microgrid and interact in a suitable manner. Furthermore, the developed system can be used to support others wherever they are insufficient such as multi-terminal protection in differential protection systems. Alternatively, the developed system can be implemented a roll-back strategy in case of a failure of the primary protection system. All of these contributions are possible thanks to the nature of the developed system which can interact with other protection system in a proper manner.

In summary, the technique presented in this thesis addresses a large knowledge gap in the microgrid protection field. In this research, a communication-based protection system with central control and monitoring capabilities has been developed. Thanks to use of central control with communication approach, changes occurring in the electrical network can easily be incorporated into the protection system. This improves the strength and robustness of the designed system. Dijkstra's Algorithm has been implemented to extract the hierarchy of the microgrid components. In this fashion, the protection system ensures safe operation without the need for prior knowledge of the microgrid structure. The changes in the connections and new deployments are detected on the fly. The protection parameter algorithm developed in this thesis is embedded in the central control unit. Therefore, whole process is automated. Following the detection of the microgrid structure with Dijkstra's Algorithm, parameter assignment algorithm assigns protection parameters for the devices. Finally, to ensure universal operation, this microgrid protection system has been modeled with international communication standards such as IEC 61850. With standardized approach, the developed protection system can be implemented in different microgrids with different set of components.

9.3. Future Work

The research presented in this thesis is an important contribution to the knowledge in microgrid field. However, it can still be extended in several ways by removing some of the scope limitations assumed in this research or by using it as a stepping-stone to investigate other aspects of microgrid protection. Regardless of their nature, these extensions will make the proposed system much more comprehensive and reliable.

One possible research is related to the fault current coefficients of DGs. In compliance with the general assumption of the literature, the fault current coefficient of IIDGs has been taken as 1.5. It is known that inverter interfaces do not provide large fault currents and their fault contribution heavily depends on their control loops. A dedicated research can be done to model the fault current contributions of IIDGs. This modeling can be used to enhance the fault current calculations.

Another extension can be the removal of two research limitations, namely the size of the microgrid and the effects of extreme weather conditions. During the course of this research, it has been assumed that the size of the microgrid is suitable for the implementation of a centralized command and control by MCPU. Although the whole idea of microgrid is aimed towards decreasing the size of power networks, even then it shall be beneficial to investigate the impact of microgrid size on the proposed protection system and determine any boundary conditions, if any. Furthermore, the effect of extreme weather conditions on the electrical lines has not been taken into account in this research. A future work may focus on this effect to make the developed protection system more comprehensive and reliable even under extreme conditions.

Finally, the dynamic timing of network communication is an interesting topic and it might be very useful in making real-time decisions pertaining to the power networks. By performing real-time communication simulations in a suitable environment such as OPNET, solid information can be gathered about the communication times and associated delays. This information is very useful for reliable operation as well as acceptable installation as a roll-back system. Furthermore, the actual content and the size of the packages required for communication can be determined and adjusted for optimum performance.

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Appendix - A

IEEE 14 Bus Test System

Table A.1: Exciter data

Exciter no.	1	2	3	4	5
K_A	200	20	20	20	20
T_A	0.02	0.02	0.02	0.02	0.02
T_B	0.00	0.00	0.00	0.00	0.00
T_C	0.00	0.00	0.00	0.00	0.00
V_{Rmax}	7.32	4.38	4.38	6.81	6.81
V_{Rmin}	0.00	0.00	0.00	1.395	1.395
K_E	1.00	1.00	1.00	1.00	1.00
T_E	0.19	1.98	1.98	0.70	0.70
K_F	0.0012	0.001	0.001	0.001	0.001
T_F	1.0	1.0	1.0	1.0	1.0

Table A.2: Generator data

Generator bus no.	1	2	3	4	5
MVA	615	60	60	25	25
x_l (p.u.)	0.2396	0.00	0.00	0.134	0.134
r_a (p.u.)	0.00	0.0031	0.0031	0.0014	0.0041
x_d (p.u.)	0.8979	1.05	1.05	1.25	1.25
x'_d (p.u.)	0.2995	0.1850	0.1850	0.232	0.232
x''_d (p.u.)	0.23	0.13	0.13	0.12	0.12
T'_{do}	7.4	6.1	6.1	4.75	4.75
T''_{do}	0.03	0.04	0.04	0.06	0.06
x_q (p.u.)	0.646	0.98	0.98	1.22	1.22
x'_q (p.u.)	0.646	0.36	0.36	0.715	0.715
x''_q (p.u.)	0.4	0.13	0.13	0.12	0.12
T'_{qo}	0.00	0.3	0.3	1.5	1.5
T''_{qo}	0.033	0.099	0.099	0.21	0.21
H	5.148	6.54	6.54	5.06	5.06
D	2	2	2	2	2

Table A.3: Bus data

Bus No.	P Generated (p.u.)	Q Generated (p.u.)	P Load (p.u.)	Q Load (p.u.)	Bus Type*	Q Generated max. (p.u.)	Q Generated min. (p.u.)
1	2.32	0.00	0.00	0.00	2	10.0	-10.0
2	0.4	-0.424	0.2170	0.1270	1	0.5	-0.4
3	0.00	0.00	0.9420	0.1900	2	0.4	0.00
4	0.00	0.00	0.4780	0.00	3	0.00	0.00
5	0.00	0.00	0.0760	0.0160	3	0.00	0.00
6	0.00	0.00	0.1120	0.0750	2	0.24	-0.06
7	0.00	0.00	0.00	0.00	3	0.00	0.00
8	0.00	0.00	0.00	0.00	2	0.24	-0.06
9	0.00	0.00	0.2950	0.1660	3	0.00	0.00
10	0.00	0.00	0.0900	0.0580	3	0.00	0.00
11	0.00	0.00	0.0350	0.0180	3	0.00	0.00
12	0.00	0.00	0.0610	0.0160	3	0.00	0.00
13	0.00	0.00	0.1350	0.0580	3	0.00	0.00
14	0.00	0.00	0.1490	0.0500	3	0.00	0.00

*Bus Type : (1) Swing Bus, (2) Generator Bus (PV Bus) and (3) Load Bus (P-Q Bus)

Table A.4: Line data

From Bus	To Bus	Resistance (p.u.)	Reactance (p.u.)	Line Charging (p.u.)	tap ratio
1	2	0.01938	0.05917	0.0528	1
1	5	0.05403	0.22304	0.0492	1
2	3	0.04699	0.19797	0.0438	1
2	4	0.05811	0.17632	0.0374	1
2	5	0.05695	0.17388	0.034	1
3	4	0.06701	0.17103	0.0346	1
4	5	0.01335	0.04211	0.0128	1
4	7	0.00	0.20912	0.00	0.978
4	9	0.00	0.55618	0.00	0.969
5	6	0.00	0.25202	0.00	0.932
6	11	0.09498	0.1989	0.00	1
6	12	0.12291	0.25581	0.00	1
6	13	0.06615	0.13027	0.00	1
7	8	0.00	0.17615	0.00	1
7	9	0.00	0.11001	0.00	1
9	10	0.03181	0.08450	0.00	1
9	14	0.12711	0.27038	0.00	1
10	11	0.08205	0.19207	0.00	1
12	13	0.22092	0.19988	0.00	1
13	14	0.17093	0.34802	0.00	1

Appendix - B

IEEE 34 Bus Test System

(*Reference*: IEEE 34 Node Test Feeder, Distribution System Analysis Subcommittee, Power System Analysis, Computing and Economics Committee, IEEE Power Engineering Society http://ewh.ieee.org/soc/pes/dsacom/testfeeders/index.html)

Table B.1. – Line Segment Data

Node A	Node E	Length (ft)	Config
800	802	2580	300
802	806	1730	300
806	808	32230	300
808	810	5804	303
808	812	37500	300
812	814	29730	300
814	850	10	301
816	818	1710	302
816	824	10210	301
818	820	48150	302
820	822	13740	302
824	826	3030	303
824	828	840	301
828	830	20440	301
830	854	520	301
832	858	4900	301
832	888	0	XFM-1
834	860	2020	301
834	842	280	301
836	840	860	301
836	862	280	301
842	844	1350	301
844	846	3640	301
846	848	530	301
850	816	310	301
852	832	10	301
854	856	23330	303
854	852	36830	301
858	864	1620	302
858	834	5830	301
860	836	2680	301
862	838	4860	304
888	890	10560	300

Table B.2. – Overhead Line Configurations

Config.	Phasing	Phase	Neutral	Spacing ID
		ACSR	ACSR	
300	B A C N	1/0	1/0	500
301	B A C N	#2 6/1	#2 6/1	500
302	A N	#4 6/1	#4 6/1	510
303	B N	#4 6/1	#4 6/1	510
304	B N	#2 6/1	#2 6/1	510

Table B.3. – Transformer Data

	kVA	kV-high	kV-low	R - %	X - %
Substation	2500	69 – D	24.9 – Gr. W	1	8
XFM-1	500	24.9 – Gr. W	4.16 – Gr. W	1.9	4.08

Table B.4. – Spot Loads

Node	Load	Ph-1	Ph-1	Ph-2	Ph-2	Ph-3	Ph-4
	Model	kW	kVAR	kW	kVAR	kW	kVAR
860	Y-PQ	20	16	20	16	20	16
840	Y-I	9	7	9	7	9	7
844	Y-Z	135	105	135	105	135	105
848	D-PQ	20	16	20	16	20	16
890	D-I	150	75	150	75	150	75
830	D-Z	10	5	10	5	25	10
Total		344	224	344	224	359	229

Table B.5. – Distributed Loads

Node	Node	Load	Ph-1	Ph-1	Ph-2	Ph-2	Ph-3	Ph-3
A	B	Model	kW	kVAR	kW	kVAR	kW	kVAR
802	806	Y-PQ	0	0	30	15	25	14
808	810	Y-I	0	0	16	8	0	0
818	820	Y-Z	34	17	0	0	0	0
820	822	Y-PQ	135	70	0	0	0	0
816	824	D-I	0	0	5	2	0	0
824	826	Y-I	0	0	40	20	0	0
824	828	Y-PQ	0	0	0	0	4	2
828	830	Y-PQ	7	3	0	0	0	0
854	856	Y-PQ	0	0	4	2	0	0
832	858	D-Z	7	3	2	1	6	3
858	864	Y-PQ	2	1	0	0	0	0
858	834	D-PQ	4	2	15	8	13	7
834	860	D-Z	16	8	20	10	110	55
860	836	D-PQ	30	15	10	6	42	22
836	840	D-I	18	9	22	11	0	0
862	838	Y-PQ	0	0	28	14	0	0
842	844	Y-PQ	9	5	0	0	0	0
844	846	Y-PQ	0	0	25	12	20	11
846	848	Y-PQ	0	0	23	11	0	0
Total			262	133	240	120	220	114

Appendix - C

Short Circuit Analysis Results for Simulated Power Systems

C-1) Microgrid Topology a – Standalone Operation

Paladin DesignBase

3-Phase Short Circuit v6.70.00

Project No. : 1 Page : 1
Project Name: Micro-Grid 2a (Islanded) Date : 11/16/2012
Title : Time : 04:57:10 pm
Drawing No. : 4 Company : Victoria University
Revision No.: Engineer: Taha Selim USTUN
Jobfile Name: Micro-Grid 2a Check by:
Scenario : 1 : PEAK-LOAD NOPV Date :

System Summary

Base MVA	:	100.000
System Frequency (Hz)	:	50
# of Total Buses	:	12
# of Active Buses	:	12
# of Total Branches	:	11
# of Active Sources	:	4
# of Active Motors	:	0
# of Active Shunts	:	3
# of Transformers	:	0
Reference Temperature(°C)	:	20.0
Impedance Displaying Temperature(°C)	:	25.0

Calculation Options

Calculating All or Mult-Buses Fault with Fault Z = 0.00000 + j 0.00000 Ohms

Fault Phases:
Phase A for Line-Ground Fault
Phase B,C for Line-Line or Line-Line-Ground Fault

ANSI/IEEE Calculation:
Using ANSI Std. C37.010-1979 or above.
Separate R and X for X/R, Complex Z for Fault Current
The Multiplying Factors to calculate Asym and Peak are Based on Actual X/R
Peak Time Applies ATPC Equation

Transformer Phase Shift is not considered.
Generator and Motor X/R is constant.
Base Voltages : Use System Voltages
Prefault Voltages : Use System Voltages

Jobfile Name: Micro-Grid 2a Page : 2

Bus Results: 0.5 Cycle--Symmetrical

Bus Name	Pre-Flt V	3P Flt. KA	LL Flt. KA	LG Flt. KA	LLG Flt KA	Thevenin Imped. Z+(pu)	Zo(pu)	ANSI 3P X/R
BUS 1	480	0	0	0	0	3659.06	3721.79	30.188
BUS 2	480	0	0	0	0	3659.06	3721.79	30.187
BUS 3	480	0	0	0	0	3659.06	3721.79	30.188
BUS4	480	0	0	0	0	3659.07	3721.79	30.181
BUS5	480	0	0	0	0	3659.06	3721.79	30.188
DG1 (WIND)	480	0	0	0	0	3659.06	3721.79	30.187
DG2 (SOLAR)	480	0	0	0	0	3659.07	3721.80	30.174
DG3 (DIESEL)	480	0	0	0	0	3659.06	3721.79	30.188
DG4 (FUEL CELL)	480	0	0	0	0	3659.07	3721.79	30.181
LOAD 1	480	0	0	0	0	3659.07	3721.79	30.180
LOAD 2	480	0	0	0	0	3659.07	3721.80	30.174
LOAD 3	480	0	0	0	0	3659.07	3721.79	30.181

C-2) Microgrid Topology b – Standalone Operation

Paladin DesignBase

3-Phase Short Circuit v6.70.00

Project No. :	Page : 1
Project Name: Micro-Grid 2b	Date : 11/16/2012
Title :	Time : 05:00:05 pm
Drawing No. :	Company : Victoria University
Revision No.: 2	Engineer: Taha Selim USTUN
Jobfile Name: Micro-Grid 2b	Check by:
Scenario : 1 : PEAK-LOAD NOPV	Date :

System Summary

Base MVA	: 100.000
System Frequency (Hz)	: 50
# of Total Buses	: 12
# of Active Buses	: 12
# of Total Branches	: 11
# of Active Sources	: 4
# of Active Motors	: 0
# of Active Shunts	: 3
# of Transformers	: 0
Reference Temperature(°C)	: 20.0
Impedance Displaying Temperature(°C)	: 25.0

Calculation Options

Calculating All or Mult-Buses Fault with Fault Z = 0.00000 + j 0.00000 Ohms

Fault Phases:
Phase A for Line-Ground Fault
Phase B,C for Line-Line or Line-Line-Ground Fault

ANSI/IEEE Calculation:
Using ANSI Std. C37.010-1979 or above.
Separate R and X for X/R, Complex Z for Fault Current
The Multiplying Factors to calculate Asym and Peak are Based on Actual X/R
Peak Time Applies ATPC Equation

Transformer Phase Shift is not considered.
Generator and Motor X/R is constant.
Base Voltages : Use System Voltages
Prefault Voltages : Use System Voltages

Jobfile Name: Micro-Grid 2b Page : 2

Bus Results: 0.5 Cycle--Symmetrical

Bus Name	Pre-Flt V	3P Flt. KA	Thevenin Imped. Z+(pu)	Thevenin Imped. Zo(pu)	ANSI 3P X/R
BUS 1	480	0	3659.23	3721.96	30.188
BUS 2	480	0	3659.23	3721.96	30.188
BUS 3	480	0	3659.23	3721.96	30.188
BUS 4	480	0	3659.23	3721.97	30.181
BUS 5	480	0	3659.23	3721.96	30.188
DG1 (WIND)	480	0	3659.23	3721.96	30.187
DG2 (SOLAR)	480	0	3659.24	3721.97	30.173
DG3 (DIESEL)	480	0	3659.23	3721.96	30.187
DG4 (FUEL CELL)	480	0	3659.57	3722.31	30.180
LOAD 1	480	0	3659.58	3722.31	30.180
LOAD 2	480	0	3659.24	3721.97	30.173
LOAD 3	480	0	3659.58	3722.31	30.180

C-3) IEEE T14-bus test system with Microgrid Topology a

Paladin DesignBase

3-Phase Short Circuit v6.70.00

Project No. : Page : 1
Project Name: T14 Bus System + Micro-Grid 2 Date : 11/15/2012
Title : Time : 07:07:18 pm
Drawing No. : Company : Victoria University
Revision No.: 2 Engineer: Taha Selim USTUN
Jobfile Name: T14Bus with Micro-Grid 2a Check by:
Scenario : 1 : Date :

A 14-bus network with Micro-Grid 2a Attached to BUS 3

System Summary

Base MVA	:	100.000
System Frequency (Hz)	:	50
# of Total Buses	:	27
# of Active Buses	:	27
# of Total Branches	:	29
# of Active Sources	:	9
# of Active Motors	:	0
# of Active Shunts	:	9
# of Transformers	:	5
Reference Temperature(°C)	:	20.0
Impedance Displaying Temperature(°C)	:	40.0

Calculation Options

Calculating All or Mult-Buses Fault with Fault Z = 0.00000 + j 0.00000 Ohms

Fault Phases:
Phase A for Line-Ground Fault
Phase B,C for Line-Line or Line-Line-Ground Fault

ANSI/IEEE Calculation:
Using ANSI Std. C37.010-1979 or above.
Separate R and X for X/R, Complex Z for Fault Current
The Multiplying Factors to calculate Asym and Peak are Based on Actual X/R
Peak Time Applies ATPC Equation

Transformer Phase Shift is not considered.
Generator and Motor X/R is constant.
Base Voltages : Adjusted by Tap/Turn Ratio
Prefault Voltages : Use System Voltages

Jobfile Name: T14Bus with Micro-Grid 2a Page : 2

Bus Results: 0.5 Cycle--Symmetrical

Bus Name	Pre-Flt V	3P Flt. A	Thevenin Imped. Z+(pu)	Thevenin Imped. Zo(pu)	ANSI 3P X/R
BUS 1	480	18609	6.6215	6.2347	7.1684
BUS 2	480	18584	6.6304	6.2434	6.9385
BUS 3	480	18584	6.6304	6.2434	6.9387
BUS 4	480	18559	6.6395	6.2524	6.7219
BUS 5	480	18559	6.6395	6.2524	6.7234
DG1 (WIND)	480	18559	6.6395	6.2524	6.7232
DG2 (SOLAR)	480	18533	6.6487	6.2614	6.5185
DG3 (DIESEL)	480	18533	6.6486	6.2614	6.5214
DG4 (FUEL CELL)	480	18533	6.6487	6.2614	6.5200
LOAD 1	480	18559	6.6395	6.2524	6.7216
LOAD 2	480	18533	6.6487	6.2614	6.5184
LOAD 3	480	18533	6.6487	6.2614	6.5199
T14B1	69000	2702	0.3214	0.1569	6.2267
T14B2	69000	4202	0.2067	0.1568	11.900
T14B3	69000	2196	0.3895	0.1554	6.6668

T14G1	138000	1795	0.2331	0.0963	4.5578
T14G4	138000	4355	0.0961	0.0958	5.5477
T14LOAD1	138000	1341	0.3121	0.0966	4.7647
T14LOAD3	69000	1909	0.4551	0.1568	1.9716
T14LOAD5	138000	1674	0.2499	0.0963	4.4500
T14G2	138000	1323	0.3161	0.0967	5.5438
T14G3	69000	2121	0.4033	0.1553	7.0741
T14G5	138000	1441	0.2904	0.0967	4.9639
T14LOAD2	138000	1323	0.3161	0.0967	5.5390
T14LOAD4	69000	1466	0.5833	0.1553	2.3606
T14LOAD6	138000	1441	0.2903	0.0966	4.9623

C-4) IEEE T14-bus test system with Microgrid Topology b

Paladin DesignBase

3-Phase Short Circuit v6.70.00

Project No. : Page : 1
Project Name: T14 Bus System + Micro-Grid 2 Date : 11/15/2012
Title : Time : 07:12:10 pm
Drawing No. : Company : Victoria University
Revision No.: 2 Engineer: Taha Selim USTUN
Jobfile Name: T14Bus with Micro-Grid 2b Check by:
Scenario : 1 : Date :

A 14-bus network with Micro-Grid 2b Attached to BUS 3

System Summary

Base MVA : 100.000
System Frequency (Hz) : 50

\# of Total Buses : 27
\# of Active Buses : 27
\# of Total Branches : 29

\# of Active Sources : 9
\# of Active Motors : 0
\# of Active Shunts : 9
\# of Transformers : 5
Reference Temperature(°C) : 20.0
Impedance Displaying Temperature(°C) : 40.0

Calculation Options

Calculating All or Mult-Buses Fault with Fault Z = 0.00000 + j 0.00000 Ohms

Fault Phases:
Phase A for Line-Ground Fault
Phase B,C for Line-Line or Line-Line-Ground Fault

Classical Calculation:

Complex Z for X/R and Fault Current

Transformer Phase Shift is not considered.
Generator and Motor X/R is constant.
Base Voltages : Adjusted by Tap/Turn Ratio
Prefault Voltages : Use System Voltages

Jobfile Name: T14Bus with Micro-Grid 2b Page : 2

Bus Results: 0.5 Cycle--Symmetrical

	Pre-Flt	3P Flt.	Thevenin Imped. Complex		
Bus Name	V	A	Z+(pu)	Zo(pu)	3P X/R
BUS 1	480	18609	6.6215	6.2347	6.9246
BUS 2	480	18596	6.6260	6.2390	6.7045
BUS 3	480	18596	6.6260	6.2390	6.7045
BUS 4	480	18583	6.6307	6.2436	6.4976
BUS 5	480	18583	6.6307	6.2436	6.4979
DG1 (WIND)	480	18583	6.6307	6.2436	6.4979
DG2 (SOLAR)	480	18570	6.6355	6.2483	6.3031
DG3 (DIESEL)	480	18570	6.6355	6.2483	6.3037
DG4 (FUEL CELL)	480	18570	6.6355	6.2483	6.3034
LOAD 1	480	18583	6.6307	6.2436	6.4976
LOAD 2	480	18570	6.6355	6.2483	6.3031
LOAD 3	480	18570	6.6355	6.2483	6.3034
T14B1	69000	2702	0.3214	0.1569	4.1666
T14B2	69000	4202	0.2067	0.1568	8.7700
T14B3	69000	2196	0.3895	0.1554	4.4546
T14G1	138000	1795	0.2331	0.0963	3.5223
T14G4	138000	4355	0.0961	0.0958	5.1525
T14LOAD1	138000	1341	0.3121	0.0966	3.5061
T14LOAD3	69000	1909	0.4551	0.1568	1.9177
T14LOAD5	138000	1674	0.2499	0.0963	3.6662
T14G2	138000	1323	0.3161	0.0967	3.5763
T14G3	69000	2121	0.4033	0.1553	4.2852
T14G5	138000	1441	0.2904	0.0967	3.6061
T14LOAD2	138000	1323	0.3161	0.0967	3.5759
T14LOAD4	69000	1466	0.5833	0.1553	2.1403
T14LOAD6	138000	1441	0.2903	0.0966	3.6073

C-5)IEEE 34-bus test system with Microgrid Topology a

Paladin DesignBase
3-Phase Short Circuit v6.70.00
Project No. : Page : 1
Project Name: IEEE 34 Bus PV + Micro-Grid 2 Date : 11/15/2012
Title : Time : 06:48:19 pm
Drawing No. : Company : Victoria University
Revision No.: 2 Engineer: Taha Selim Ustun
Jobfile Name: IEEE-34BUS WITH MICRO-GRID 2A Check by:
Scenario : 1 : PEAK-LOAD NOPV Date :

System Summary

Base MVA	:	100.000
System Frequency (Hz)	:	50
# of Total Buses	:	61
# of Active Buses	:	61
# of Total Branches	:	60
# of Active Sources	:	8
# of Active Motors	:	0
# of Active Shunts	:	11
# of Transformers	:	6
Reference Temperature(°C)	:	20.0
Impedance Displaying Temperature(°C)	:	25.0

Calculation Options

Calculating All or Mult-Buses Fault with Fault Z = 0.00000 + j 0.00000 Ohms

Fault Phases:
Phase A for Line-Ground Fault
Phase B,C for Line-Line or Line-Line-Ground Fault

ANSI/IEEE Calculation:
Using ANSI Std. C37.010-1979 or above.
Separate R and X for X/R, Complex Z for Fault Current
The Multiplying Factors to calculate Asym and Peak are Based on Actual X/R
Peak Time Applies ATPC Equation

Transformer Phase Shift is not considered.
Generator and Motor X/R is constant.
Base Voltages : Use System Voltages
Prefault Voltages : Use System Voltages

Jobfile Name: IEEE-34BUS WITH MICRO-GRID 2A Page : 2

Bus Results: 0.5 Cycle--Symmetrical

Bus Name	Pre-Flt V	3P Flt. KA	LL Flt. KA	LG Flt. KA	LLG Flt KA	Thevenin Imped. Z+(pu)	Thevenin Imped. Zo(pu)	ANSI 3P X/R
101	24900	0	0	0	0	16.6868	15.2278	3.5623
3	69000	0	0	0	0	9.9722	10.0000	20.026
800	24900	0	0	0	0	13.1697	3.2249	14.717
816	24900	0	0	0	0	16.2989	14.0368	3.9175
822	24900	0	0	0	0	19.4141	21.9726	2.0506
826	24900	0	0	0	0	16.8145	15.5823	3.4220
830-L	24900	0	0	0	0	16.6811	15.2133	3.5656

838	24900	0	0	0	0	16.6875	15.2296	3.5619
840-L	24900	0	0	0	0	16.6868	15.2279	3.5623
844-L	24900	0	0	0	0	16.6861	15.2260	3.5627
848-L	24900	0	0	0	0	16.6868	15.2279	3.5623
856	24900	0	0	0	0	16.6825	15.2169	3.5648
860-L	24900	0	0	0	0	16.6854	15.2242	3.5631
864	24900	0	0	0	0	16.6847	15.2223	3.5635
890-L	4160	1	0	1	1	25.6407	9.0717	2.9091
BUS 1	480	5	5	7	7	21.9674	5.7457	4.4639
BUS 2	480	5	5	7	7	21.9785	5.7545	4.4378
BUS 3	480	5	5	7	7	21.9785	5.7545	4.4379
BUS 4	480	5	5	7	7	21.9896	5.7634	4.4111
BUS 5	480	5	5	7	7	21.9896	5.7634	4.4121
DG1 (WIND)	480	5	5	7	7	21.9896	5.7634	4.4119
DG2 (SOLAR)	480	5	5	7	7	22.0007	5.7724	4.3846
DG3 (DIESEL)	480	5	5	7	7	22.0007	5.7724	4.3866
DG4 (FUEL CELL)	480	5	5	7	7	22.0007	5.7724	4.3856
LOAD 1	480	5	5	7	7	21.9896	5.7634	4.4109
LOAD 2	480	5	5	7	7	22.0007	5.7724	4.3845
LOAD 3	480	5	5	7	7	22.0007	5.7724	4.3855
PV-BUS1	480	6	5	8	8	20.1039	5.7460	6.8384
PV-BUS1-L	480	6	5	8	8	20.1126	5.7546	6.7692
PV-BUS2	480	6	5	9	10	18.9581	2.2950	3.7970
PV-BUS2-L	480	6	5	9	10	18.9702	2.3038	3.7741
PV-G1	480	6	5	8	8	20.1126	5.7546	6.7692
PV-G2	480	6	5	9	10	18.9702	2.3038	3.7742
PV-G3	480	5	5	7	7	22.3905	5.7460	4.0980

C-6) IEEE 34-bus test system with Microgrid Topology b

Paladin DesignBase

3-Phase Short Circuit v6.70.00

Project No. : Page : 1
Project Name: IEEE 34 Buses PV + Micro-Grid Date : 11/15/2012
Title : Time : 06:59:27 pm
Drawing No. : Company : Victoria University
Revision No.: 1 Engineer: Taha Selim Ustun
Jobfile Name: IEEE-34Bus with Micro-Grid 2b Check by:
Scenario : 1 : PEAK-LOAD NOPV Date :

System Summary

Base MVA : 100.000
System Frequency (Hz) : 50

# of Total Buses : 62
# of Active Buses : 62
# of Total Branches : 61

# of Active Sources : 8
# of Active Motors : 0
# of Active Shunts : 11
# of Transformers : 6
Reference Temperature(°C) : 20.0
Impedance Displaying Temperature(°C) : 25.0

Calculation Options

Calculating All or Mult-Buses Fault with Fault Z = 0.00000 + j 0.00000 Ohms

Fault Phases:
Phase A for Line-Ground Fault
Phase B,C for Line-Line or Line-Line-Ground Fault

Classical Calculation:
Complex Z for X/R and Fault Current

Transformer Phase Shift is not considered.
Generator and Motor X/R is constant.
Base Voltages : Use System Voltages
Prefault Voltages : Use System Voltages

Jobfile Name: IEEE-34Bus with Micro-Grid 2b Page : 2

Bus Results: 0.5 Cycle--Symmetrical

	Pre-Flt	3P Flt.	LL Flt.	LG Flt.	LLG Flt	Thevenin Imped. Complex		
Bus Name	V	KA	KA	KA	KA	Z+(pu)	Zo(pu)	3P X/R
101	24900	0	0	0	0	16.6868	15.2278	3.4793
3	69000	0	0	0	0	9.9722	10.0000	20.011
800	24900	0	0	0	0	13.1697	3.2249	14.686
816	24900	0	0	0	0	16.2989	14.0368	3.8164
822	24900	0	0	0	0	19.4141	21.9726	2.0254
826	24900	0	0	0	0	16.8145	15.5823	3.3457
830-L	24900	0	0	0	0	16.6811	15.2133	3.4825
838	24900	0	0	0	0	16.6875	15.2296	3.4789
840-L	24900	0	0	0	0	16.6868	15.2279	3.4793
844-L	24900	0	0	0	0	16.6861	15.2260	3.4797
848-L	24900	0	0	0	0	16.6875	15.2297	3.4789
856	24900	0	0	0	0	16.6825	15.2169	3.4817
860-L	24900	0	0	0	0	16.6854	15.2242	3.4801
864	24900	0	0	0	0	16.6847	15.2223	3.4805
890-L	4160	1	0	1	1	25.6407	9.0717	2.8721
BUS 1	480	5	5	7	7	21.9632	5.7415	4.3311
BUS 2	480	5	5	7	7	21.9701	5.7459	4.3048
BUS 3	480	5	5	7	7	21.9701	5.7459	4.3048
BUS 4	480	5	5	7	7	21.9770	5.7505	4.2786
BUS 5	480	5	5	7	7	21.9770	5.7505	4.2788
DG1 (WIND)	480	5	5	7	7	21.9770	5.7505	4.2788
DG2 (SOLAR)	480	5	5	7	7	21.9839	5.7553	4.2528
DG3 (DIESEL)	480	5	5	7	7	21.9839	5.7553	4.2531
DG4 (FUEL CELL)	480	5	5	7	7	21.9839	5.7553	4.2530
LOAD 1	480	5	5	7	7	21.9770	5.7505	4.2786
LOAD 2	480	5	5	7	7	21.9839	5.7553	4.2528
LOAD 3	480	5	5	7	7	21.9839	5.7553	4.2530
PV-BUS1	480	6	5	8	8	20.1039	5.7460	6.7910
PV-BUS1-L	480	6	5	8	8	20.1084	5.7503	6.7213
PV-BUS2	480	6	5	9	10	18.9581	2.2950	3.7138
PV-BUS2-L	480	6	5	9	10	18.9661	2.2995	3.6910
PV-G1	480	6	5	8	8	20.1084	5.7503	6.7213
PV-G2	480	6	5	9	10	18.9661	2.2995	3.6910
PV-G3	480	5	5	7	7	22.3905	5.7460	4.0164

Appendix - D

IEC 61850-7-420 Modeling Details for Various DERs

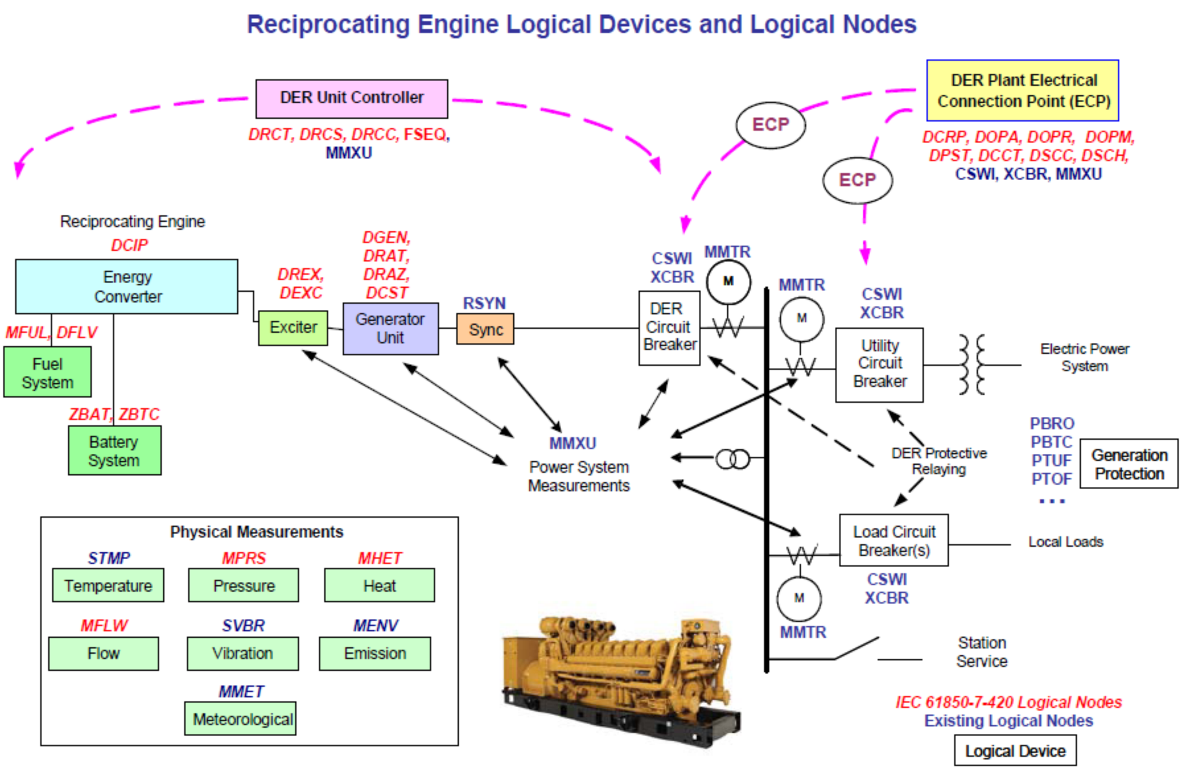
(*Reference*: IEC TC57 WG17, "Introduction to IEC 61850-7-420: Distributed Energy Resources (DER) Object Modeling," *White Paper*, vol. Ver 2., July 31, 2009.

Further Reading for LDs and LNs:

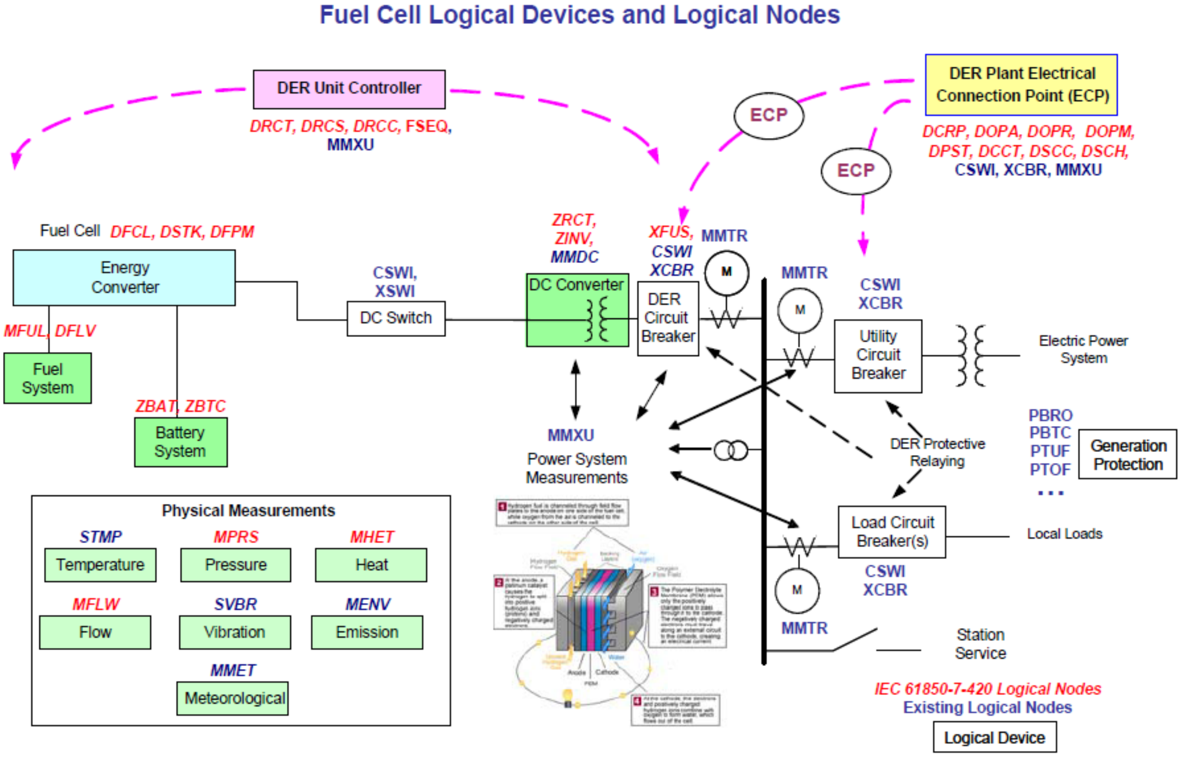
IEC TC-57, "Communication networks and systems in substations – Part 7-4: Basic communication structure for substation and feeder equipment – Compatible Logical Node Classes and Data Classes. International Electrotechnical Commission, Geneva, Switzerland, Standard 61850-7-4, IEC 2001."

IEC TC-57, "Communication networks and systems in substations – Part 7-420: Basic communication structure - Distributed energy resources logical nodes. IEC Standard IEC/TR 61850-7-420, Edition 1.0, 2009. .")

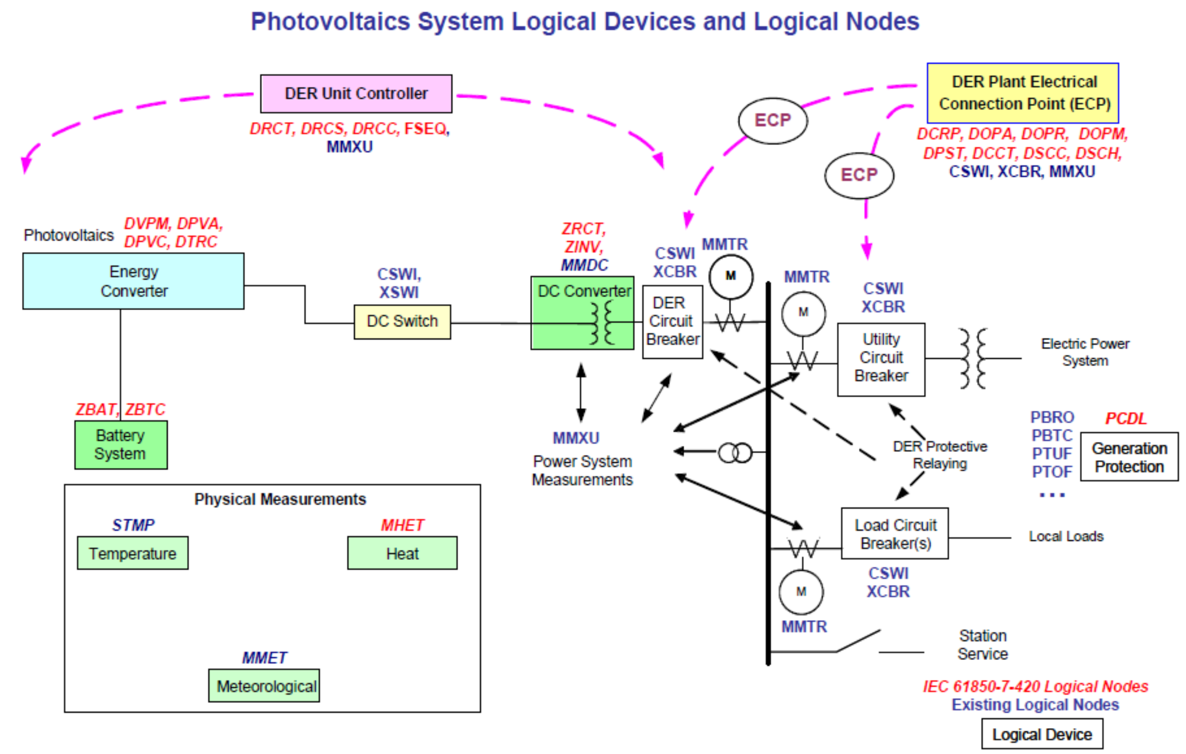
D-1) Reciprocating Engine Modeling (e.g. Diesel Generators)



D-2) Fuel Cell Modeling



D-3) PV System Modeling



D-4)Combined Hear And Power (CHP) System Modeling