Impacts of Distributed Generation on Smart Grid

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Abstract

In the twenty-first century the most critical and important issues with regards to the global climate change problem are Smart Grid and Renewable Energy technologies. The evolution of current centralised generation in the form of distributed generation and Smart Grids provides a great opportunity to eradicate several issues associated with energy efficiency, energy security, power quality and the drawback of aging power system infrastructures.

In order to meet the rising electrical power demand and increase service quality as well as reduce pollution, the existing power grid infrastructure should be developed into a Smart Grid that has the flexibility to allow interconnection with the distributed generation. However, integrating distributed generation to power systems causes several technical issues, especially system stability. Therefore, to fully address the issue, current existing power systems should be up-graded to Smart Grid. To make the power grid become 'smarter', particularly in terms of stability and flexibility, Flexible AC Transmission System (FACTS) devices, especially Static VAR Compensators (SVC) are used.

With the concept of Smart Grid, there are high possibilities that the interconnection of distributed generation issues can be solved and minimised. This thesis discusses the impacts of distributed generation on Smart Grid technology, in particular it identifies and determines whether the system remains stable or not after installing distributed generation into Smart Grid systems. This was done by examining the primary stability parameters of the system such as power angle, frequency and voltage. The simulation

result shows that the SVC makes the grid become smarter. This is achieved because SVC has the ability to improve the system stability through voltage enhancement, either by injecting or absorbing reactive power during integration of distributed generation. The result was validated by simulations for specified scenarios in DIG-SILENT Power Factory Software V13.2.

Student Declaration

'I, Nur Asyik Hidayatullah, declare that the Master by Research thesis entitled "Impact of Distributed Generation on Smart Grid" is no more than 60,000 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: [redacted] Date: 25 / FEB / 2011

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List of Publications and Awards

Journals

[1]. Hidayatullah, N.A., Stojcevsky, B. and Kalam A., ‘Analysis of distributed generation systems, smart grid technologies and future motivators influencing change in the electricity sector’, *Smart Grid and Renewable Energy Journal* 2011, available from http://www.SciRP.org/journal/sgre *[Accepted for Publication]*

[2]. Hidayatullah N.A., Paracha Z.J. and Kalam A., ‘Impact of distributed generation on smart grid transient stability’, *Smart Grid and Renewable Energy Journal* 2011, available from http://www.SciRP.org/journal/sgre *[Published]*

Conference Papers

[1]. Hidayatullah, N.A., Paracha, Z.J. and Kalam, A., ‘Impacts of distributed generation on smart grid’, *International Conference of Electrical Energy and Industrial Electronic System* (EEIES), Malaysia 7–8 Dec. 2009.

Awards

[1]. Australian Development Scholarship (ADS) 2008

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List of Abbreviations

ADMS	Advanced Distribution Management System
AMI	Advance Metering Infrastructure
ARRA	American Recovery and Reinvestment Act
AVR	Auto Voltage Regulator
CO_2	Carbon dioxide
DEO	Department of Energy Office of Electricity Delivery
DFIG	Doubly Feed Induction Generator
DG	Distributed Generation
DNP3	Distribution Network Protocol 3
DPF	Distribution Power Flow
DRM	Demand Response Management
DS	Distribution System
EISA	Energy Independent and Security Act
EMS	Energy Management System
EPRI	Electric Power Research Institute
ESI	Energy Service Infrastructure
FACTS	Flexible Alternating Current Transmission System
FC	Fuel Cells
FCL	Fault Current Limiter
FDIR	Fault Detection, Isolation and Restoration
GHG	Greenhouse Gases
HVDC	High Voltage Direct Current
ICT	Information and Communication Technology

IEC	International Electro-technical Commission
IEEE	Institute of Electrical and Electronics Engineers
IRM	Interface Reference Model
LAN	Local-Area Network
LM	Load Modelling
MPPT	Maximum Power Point Tracking
MT	Micro Turbine
MVA	Megavolt Ampere
NIST	National Institute of Standards and Technology
OLTP	On-Line Transaction Processing
PCC	Point of Common Coupling
PMU	Phasor Measurement Unit
PQM	Power Quality Monitoring
PQRAS	Power Quality, Reliability, Availability and Security
PV	Photovoltaic
RES	Renewable Energy Sources
RTO	Regional Transmission Operator
SCADA	Supervisory Control and Data Acquisition
SRA	Strategic Research Agenda
SSSC	Static Synchronous Series Compensator
STATCOM	Static Synchronous Compensator
STC	Superconducting Transmission Cable
SVC	Static VAR Compensator
TCR	Thyristor-Controlled Reactor
TCSC	Thyristor-Controlled Series Compensator
TCSR	Thyristor-Controlled Series Reactor
TSC	Thyristor-Switched Capacitor

TSSR	Thyristor-Switched Series Reactor
VAR	Voltage Ampere Reactive
VSI	Voltage Source Inverter
WAN	Wide-Area Network

Chapter 1: Introduction

1.1 Introduction

Currently, the main source of electrical power generation is fossil fuel producing carbon dioxide (CO_2) emission and other gases, which leads to global warming. Due to environmental issues in reducing greenhouse gases (GHG), the utilisation of renewable energy sources (RES) is now growing rapidly and is being widely accepted as an alternative power supply. An important phenomenon in this regard for further future electric power generation is distributed generation, which is also known as embedded generation, dispersed generation or decentralised generation [1].

The development of Smart Grid Systems is another effort to address the issue of global warming. The Smart Grid will be able to rapidly detect, analyse and respond to various perturbations by integrating intelligent devices, advance control methods and digital telecommunications on electrical networks [2]. This concept is the outcome of advanced technology and regulation from various stakeholders who are concerned with demand-side management, energy storage and increased usage of RES. Smart Grid development is underway and is expected to be dynamic, reliable, flexible, diverse and fully controllable. This new scenario will enable power operators to maximise energy efficiency, such as in loss management, demand reduction and data communication [3]. Further, Smart Grid meets environmental targets and enables the power system to become more flexible to support plug-in distributed generation.

In order to meet the rising electrical power demand and increasing service quality demands, as well as reduce pollution, the existing power grid infrastructure should be developed into a Smart Grid that is flexible for interconnectivity with distributed generation, such as wind turbines and solar power [4]. However, integrating this concept of distributed generation into Smart Grid systems will increase many complex issues on real time operation. Previous research [5] shows that distributed generation has an immediate impact when it is connected into distribution systems (DS), such as on power flow direction, protection, voltage profile, power quality and stability. Therefore, more research needs to be performed systematically in order to analyse and minimise the impact of distributed generation on power systems; not only on distribution systems but also on Smart Grid. Moreover, it is expected in the near future that the utilisation of distributed generation will increase and currently Smart Grid is regarded as vital infrastructure for the development of industrial and business nations worldwide.

This section presents an introduction to distributed generation and Smart Grid. Section 1.2 provides motivation behind the research and requirements for Smart Grid. Research methodologies and techniques are presented in Section 1.3. Section 1.4 emphasises the original contribution of the thesis and finally the thesis organisation is presented in Section 1.5.

1.2 Motivation

Smart Grid and renewable energy technologies are an important issue in regard to the global climate change problem and energy security for the twenty-first century. The evolution of current conventional or centralised generation in the form of distributed generation and Smart Power Grids has great potential to eradicate several issues associated with green energy, energy efficiency, energy security and the drawback of aging power system infrastructures. These phenomena also become major options to fulfil current high power demands and create flexible power system networks where both customer and power operator can mutually interact on a real time basis.

Current available power system networks are very complex, large scale, centralised and far from the point of utilisation. Increasing power demands and a promising energy market have led to the existing aging power system operation becoming more challenging from security, reliability, efficiency and quality of the electric power supply points of view. It also requires that the energy supply to all consumers must be continuously stable and reliable. Therefore, demand cannot exceed the generator capacity, in order to avoid overloads. Integrated distributed generation and current power systems are capable of supporting energy security, such as during peak demand or power shortages.

Integrating distributed generation to power systems causes several technical issues, such as power system stability and power quality. However, with the presence of Smart Grid concepts, there are high possibilities that these issues can be solved and minimised. For this reason, to make the power grid become 'smarter', particularly in terms of stability and flexibility, a Flexible AC Transmission System (FACTS) device such as a Static VAR Compensator (SVC) is used [6]. The SVC is a shunt-connected VAR generator or absorber whose output is adjusted to exchange capacitive or inductive current to maintain or control specific parameters of the electrical power system [7]. This device is suitable for voltage stability control in power systems and is able to maintain voltage drops or fluctuations caused by distributed generation such as wind generation [8].

Recent trends in developing Smart Grid with various frameworks have provided a motivation for examining the impacts of distributed generation on Smart Grid. Although there is no perfect Smart Grid system, as it is a relatively new concept that needs wider interdisciplinary research for its development, this research effort obviously will contribute to the knowledge of science and engineering, particularly in the area of Smart Grid technology. Up until recently, little research has been carried out to investigate this issue. Overall, research scenarios in the past have investigated the technical impact of distributed generation on distribution systems, where almost of them are coupled to the medium and low voltage levels. Moreover, none of the research scenarios dealt with the issues from Smart Grid perspectives. Hence, further investigation is required to analyse the impact of distributed generation on Smart Grid.

1.3 Research Methodologies and Techniques

This research aims to find out the performance of Smart Grid when distributed generation is connected. The primary aims are to examine Smart Grid stability when distributed generation is coupled to the networks and after several disturbances or faults have occurred in the system. The research was done by designing a simple configuration of Smart Grid and simulated using Dig-SILENT Power Factory Software V13.2. The details of proposed methods and techniques to investigate the impact of distributed generation on Smart Grids are as follows:

- **Study of the DG impact on power system network:** This highlights the initial stage for the research project, which involves searching state of the art technology in distributed generation and its impact on power systems. This part of the study was intended to collect information and review distributed generation applications on power system networks, such as in terms of interconnection, as well as the methodologies for assessing system impacts.
- **Reviewing and developing state of the art of Smart Grid:** In this part of the project, the current concept of Smart Grid from IEEE papers was reviewed and developed with the help of existing software for analysis. Dig-SILENT Power

Factory Software V13.2 was used for steady state analysis in order to evaluate the network voltage profile and load flow calculation on Smart Grid. In addition, the dynamic behaviour or the stability of Smart Grid was examined using this software, as well as through sudden changes in load or element faults in the system.

- **Distributed generation and Smart Grid system configuration:** Based on the literature review, the distributed generation and Smart Grid system configuration was developed through the use of SVC as part of Smart Grid control devices. The system simulation work allows measurement of the primary grid parameters and analysis of the system's behaviour at particular points in normal and perturbed conditions, especially before and after distributed generation is connected to Smart Grid.
- **Performance analysis, testing and data validation:** The final system configuration was performed to obtain results. The simulation results were validated by several case studies through the following scenarios:
    - Load flow analysis (pre-fault conditions), which is used to investigate the potential impact of new distributed generation units on network performance, particularly to check the voltage pattern, possible over-loading problems and demonstrate pre-fault conditions at all points on the system.
    - Smart Grid stability analysis to identify and determine whether the system remains stable or not after new distributed generation installation. This was done by examining sudden changes in load or faults in the system.

1.4 Original Contribution of the Thesis

This research will contribute to the knowledge in distributed generation and Smart Grid areas, as it addresses major concerns in Smart Grid stability. The simulation analysis using Dig-SILENT Power Factory Software V 13.2 is one of the original contributions to Smart Grid system technology.

This research will contribute to knowledge in the following particular areas:

1. Identifying the framework for analysing the impact of distributed generation on Smart Grid. The proposed research will be greatly valuable to the Smart Grid development process, given that it further improves the understanding of distributed generation and Smart Grid technology.
2. Conducting research through case studies simulation, to evaluate the performance of SVC as a Smart Grid device and examining the key issues behind the framework of Smart Grid.
3. The proposed research is important since it develops the framework of Smart Grid through Dig-SILENT Power Factory Software V13.2, which will be helpful for future research and development of Smart Grid.
4. Further, this research will contribute to knowledge since Smart Grid has become a leading concern in the field of power systems, in particular with its development in industrial nations worldwide.

1.5 Organisation of the Thesis

Chapter 1 contains the primary introduction of the research, as well as the impacts of distributed generation on Smart Grid. This chapter also contains research methodologies and techniques, motivation behind the research and original contribution to the knowledge of engineering, science and Smart Grid.

Chapter 2 presents a literature review on distributed generation technologies uses and impacts, as well as recent efforts for Smart Grid development. Further, it presents the state of the art of Smart Grid technology and its framework. This chapter also includes some basics of transient stability analysis.

An overview on FACTS as Smart Grid devices has been presented in Chapter 3. It also gives a basic description of SVC and its function. Chapter 4 provides detail on Smart Grid experimental setup and experimental procedures. Case studies, results of simulation and discussions on the above work have also been included. Conclusions and scope for future work are discussed in Chapter 5.

Chapter 2: Literature Review

2.1 Introduction

The main purpose of this chapter is to provide the essential background of distributed generation and recent developments in Smart Grid technologies, including concepts as well as some basics of transient stability analysis. This chapter also reviews the previous research done on the impact of distributed generation on power systems.

The current electric power industry is facing major challenges in converting from centralised generation into decentralised generation, as a result of advancements in power system technology. These advances in technology have created rapid growth in the utilisation of distributed generation, which leads to the energy market becoming more attractive and competitive. Moreover, due to electricity deregulation, environmental issues and government incentives, this technology has created a high level of interest in further development among industrial countries throughout the globe. This issue also introduces the Smart Grid platform to end the traditional vertically-integrated electric power industry, which has in the past resulted in higher energy costs.

Nowadays, most aging and large, remote power system stations with central dispatch suffer from disturbances due to a lack of intelligent interoperability utilities. The system also becomes vulnerable when utility abnormalities are present, for example on protection or failures of control coordination and human operation errors. Therefore, there is a need to transform this model into Smart Grid that enhances power quality and fully integrates with advanced grid elements, such as intelligent sensing and digital metering.

Smart Grid is recognised as the platform for the future of the power industry. The rapid rise of this issue is also leading to the fast growth of distributed generation technology markets, such as in fuel cells (FC), photovoltaic (PV) and wind turbine (WT). This trend will have a profound impact on future electricity technology, which allows information and communication technologies (ICT) and advanced power electronic devices to be installed and embedded throughout the networks. This is the challenge where current bulk generation and distributed generation will co-exist with higher power reliability and quality in the form of Smart Grid.

To emphasise these, this chapter provides a fundamental understanding of distributed generation issues and the framework of Smart Grid. Section 2.2 presents a definition, benefits and a model of distributed generation. A wider literature review on distributed generation is discussed in Section 2.3, which covers common distributed generation technologies used and power quality. Section 2.4 discusses distributed generation and its technical impacts on power systems from previous research done. Section 2.5 discuses the definition of Smart Grid and its benefits, recent research in the on-going effort for Smart Grid development and the concept of Smart Grid. Further concepts and the framework for Smart Grid are discussed in Section 2.6. Smart Grid transient stability analysis discussion has been presented in Section 2.7. Concluding remarks are given in Section 2.8.

2.2 Distributed Generation

For the last five years, a number of power customers have been installing stand alone distributed generation for their needs in small units. This trend indicates that distributed generation applications have gained more interest, due to the continued advancement of distributed generation technologies and their effectiveness as a local power source, where generation is in close proximity to the load or consumer. Distributed generation provides power from a few watts (W) to ten megawatts (MW) and offers several benefits compared to conventional power generation. Society's awareness of green energy utilisation also leads to the increase of distributed generation installation and operation. Moreover, constraints on new construction of bulk power generation and transmission or distribution lines have created the conditions for utilising this small-scale generation coupled to local transmission or distribution networks.

Distributed Generation is a concept of small-scale electric power generation that is operated and installed near to the customer's site. Usually, it is connected via power electronic converter or other power electronic devices to the distribution system. Most distributed generation systems are currently powered by renewable energy, including photovoltaic, wind turbines, fuel cells and micro turbines. These environmentally friendly technologies are more effective in utilising RES, which is abundantly available in nature, pollution-free and a sustainable form of energy.

2.2.1 Definition of Distributed Generation

Distributed generation is a relatively new trend in the energy market and electricity industry. Until recently, there were various definitions used to describe distributed generation terminologies, and it is called by different names in different countries throughout the globe. In South America, countries use the term 'embedded generation' whereas 'dispersed generation' is used in North America, and Asian countries and Europe use the term 'decentralised generation'. Driesen and Belmans define distributed generation as a small-scale electric power generation, which is located near the consumer load, typically having a rating of <10 MW and is not included as a major power plant [9]. Meanwhile, the Electric Power Research Institute (EPRI) defines distributed generation as generation from ‘a few kilowatts up to 50 MW’. The Gas Research Institute defines it as ‘generation which is typically between 20 to 25 MW’ [10]. However, this definition is not compulsory as there are no universal agreements on the distributed generation definition. Thus, each country and power-working group has different views on defining distributed generation; some countries describe this technology in terms of voltage level, whilst others base it on the generation capacity, interconnection and location [9]. The main objective of distributed generation is getting the electricity from point of generation close to the point of consumer.

2.2.2 Distributed Generation Benefits

Increasing power system reliability expectations have evolved into the growth of distributed generation. The main drivers of that growth can be divided into three categories, which are environmental concerns, commercial policies and energy policies. These factors have been contributing to the high interest and penetration of distributed generation utilisation. Issues related to the operation and interconnection of distributed generation into power system networks, such as power quality, reliability, stability and protections have been the focus of stakeholders, including power operators, designers, policy makers, engineers and consumers [11]. However, in spite of triggering these issues, distributed generation also offers several advantages.

The major benefits of distributed generation can be divided into two categories: economic and operational [12]. From an economic point of view, distributed generation provides power support when load increases during peak demand periods, thus reducing interruption that may lead to system outages. It also reduces the peril of investment, due to the flexibility of its capacity and installation placement. Distributed generation cuts operational costs when installed close to the customer load because it avoids upgrading or setting up a new transmission and distribution network, thereby providing a cost saving. From the operational point of view, distributed generation warranties the reliability and stability of supply and reduces power losses. In addition, this technology also plays a critical role in reducing GHGs, given that renewable energy is its main source and almost no gases are emitted during its operation, compared to fossil fuel power generation. The use of local renewable energy sources (RES) will help to reduce dependence on imported fossil fuels and decrease internationally escalating energy prices.

2.2.3 Distributed Generation Models

From a technical point of view, the presence of distributed generation in power systems leads to changes in the power flow. Moreover, most current power systems topology is radial. Therefore, before solving load flow problems, there are four limitation variables in power flow that should be known; to name of view: voltage angle, voltage magnitude, the real (P) and the reactive (Q) powers. These variables can determine the characteristic of buses whether as PQ bus or PV bus. In PQ bus there is no power generation source and these typically are load buses where the net P and Q powers are specified, with the unknown being the angle and voltage magnitudes. Meanwhile, PV buses are generator buses, where the active power P output of the generator and the voltage magnitude are known, while the reactive power Q and the angles are unknown. These buses are normally controlled by the auto voltage regulator (AVR), which keeps the voltage magnitude at a constant level by adjusting the field current of the generator and its reactive power output. A distributed generation can be modelled as a PQ or PV bus. It can also be modelled as a negative load, where the P and Q are injected into the power systems.

2.3 Distributed Generation Technology

The liberalisation of electricity markets and environmental policy has increased the use of distributed generation units for a range of applications, such as stand alone, peak load shaving and remote applications. These units can be classified into two different categories:

- Distributed generation based generation, including micro turbines, photovoltaic, fuel cells, wind turbines and biomass.
- Distributed generation based storage, including flywheels, battery, super capacitor and superconducting coil system.

All of these technologies are currently being used and are gaining popularity. Some of the different types of distributed generation are discussed in the subsequent section.

2.3.1 Wind Turbine

In recent years, wind turbine generation has developed rapidly as a competitive and effective source of distributed generation. Wind turbines use wind energy to generate electricity and have various ratings from a few kW to a few MW [13]. To produce electric power, WT can be operated at variable or constant speeds and is coupled to induction generators. Nowadays, induction generators are widely used in WT and a variable speed generator is the preferred option in newer WT installations. Through rectifier and inverter, a squirrel induction generator could be coupled to the AC grid as shown in Figure 2.1.

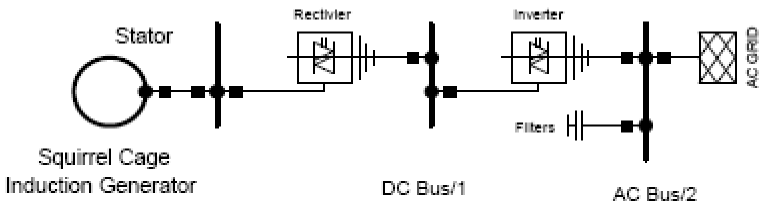

Figure 2.1: Variable speed induction generators

In addition, another method of operating induction generators is by connecting the stator directly to the AC grid and connecting the rotor through a power electronic device, thus wound rotor induction machine can be used as a doubly fed induction generator (DFIG) as illustrated in Figure 2.2.

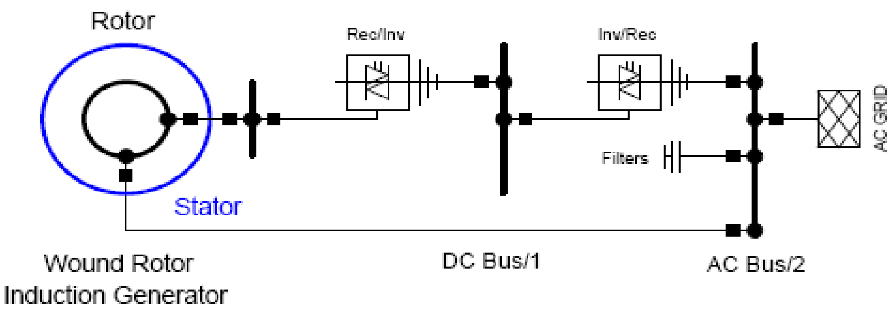

Figure 2.2: Doubly fed variable speed induction generator

In recent years, doubly fed induction generators seem to be the major option in new wind farm installation, since it supports power system stability and reliability during peak load or disturbances. The WT with DFIG also requires smaller power electronic devices, thus control of the WT by DFIG becomes more flexible, where the active and reactive power can be controlled independently.

2.3.2 Micro Turbine

Gas-fired turbines can be mass-produced with low cost in the range from 25 to100 kW. These technologies are designed to combine the reliability of on-board commercial aircraft generators with low cost automotive turbo chargers. These micro turbine systems are high frequency generators, equipped with air-foil bearings and run at high speeds (50,000–90,000 RPM). They cannot be coupled directly to the power system, thus a power electronics device is used [14]. Before injecting the voltage into the AC grid, the generated voltage must be rectified first using a diode rectifier and linked into a DC-AC inverter to synchronise with the grid as shown in Figure 2.3.

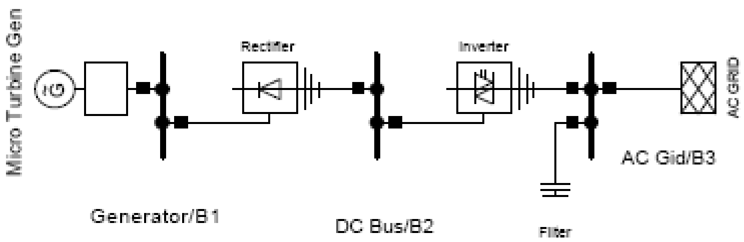

Figure 2.3: Micro turbine electrical system

2.3.3 Photovoltaic

The Photovoltaic module is an unregulated DC power source that uses semiconductor cells. It generates direct voltage and current from sunlight that falls on the cells. In order to interface the array to the power systems, it has to be conditioned first and a DC/AC inverter has to be used. In addition, for maximum power point tracking (MPPT) purposes a DC/DC converter is used at the array output as shown in Figure 2.4. It is intended to extract the maximum available power at a given insulation level, which means maintaining the voltage level as close as possible to the maximum power point

[14]. PV systems have no moving parts, and thus require less maintenance and generate electricity without producing CO_2.

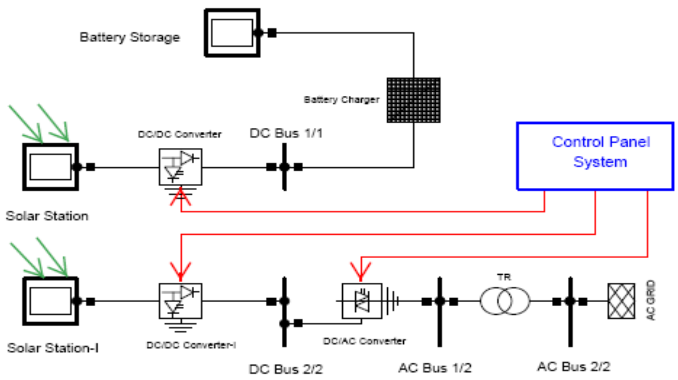

Figure 2.4: PV operation and grid connection system

2.3.4 Fuel Cells

Fuel cells are electrochemical devices that convert fuel (hydrogen) and air directly to electric power and provide thermal energy through electrochemical processes. FC does not burn hydrogen and there are no moving parts during operations, thus fewer losses and low emissions. Unlike other distributed generation, FC efficiency is higher than 60 per cent, which is considered to be double that of conventional power generations [12].

As shown in Figure 2.5, FC consists of three parts, which are anode catalyst, polymer electrolyte membrane and cathode catalyst. Hydrogen, as a fuel, passes through the anode catalyst and oxygen, as an oxidant, passes through the cathode catalyst. To produce electric power both are reformulated through electrochemical processes that result in the release of electrons. This process occurs in the polymer electrolyte membrane, which separates the ions and electrons. The electrons create DC voltage that can be used as high quality electricity and it requires an inverter to convert to AC voltage.

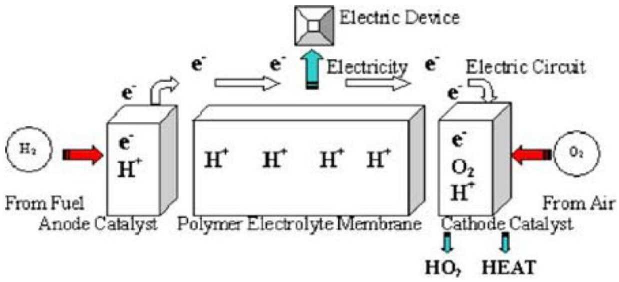

Figure 2.5: Fuel cells electrolyte membrane components [12]

2.3.5 Distributed Generation and Power Quality

The term 'power quality' can be associated with the reliability of power supply. However, engineers and power providers define it differently according to the parameter characteristic being measured, such as voltage, current or frequency.

Adding distributed generation to power systems generally increases system reliability and power quality, for instance as a voltage support. In this case, distributed generation assists the central generation when overload occurs on the system, consequently avoiding voltage drop and accordingly improving the system voltage profile. However, there is a possibility of unexpected events that influence the system's power quality, such as power reactive absorptions, over injection of the current and the variability of renewable distributed generation source. Power quality related issues are very important and should not become a major obstacle against distributed generation deployment and RES utilisation. However, it should be a challenge for novel approaches in power quality management and monitoring. Particularly with the co-existence of advanced power system utilities and information technologies, it can establish new techniques to address this case.

2.4 Distributed Generation and its Technical Impacts

The majority of power systems topology is taken for granted as a radial system, which means power flows from source to load or from generation to consumers. However, with the presence of distributed generation technology, this paradigm has changed and the power source is not only from centralised sources but also from another source such as distributed generation. Distributed generation can be operated as a power source or as a load or neither; it relies on the particular setting circumstances, thus the power flows from the central source to the distributed generation or vice versa.

The integration of distributed generation to electricity networks always has technical issues in power system operation. Therefore, analysing and determining the impact of distributed generation into power systems during interconnection and operation is a critical issue. It also involves intensive research, depending on the parameters that are required to be evaluated. In operational level for instance, the effect can be analysed on generation, transmission and distribution perspectives, whereas on the system operation level the impact evaluation can be done in the areas of steady-state analysis, dynamic analysis, power quality, reliability and protection [15].

For the last decade, much research has been done in the area of distributed generation. Moreover, the presence of distributed generation can have both positive and negative impacts on power system networks. Previous research shows that the insertion of distributed generation into distribution or transmission systems will change the direction of power flows, which has a serious impact on the operation of the system

[16–18]. Prata [19] presents that coupling distributed generation to distribution networks has a significant contribution to improving system reliability, preventing under voltage drops and maintaining voltage levels in acceptable ranges during peak load periods. However, due to the integration of distributed generation, voltage variation and violation can still happen. Therefore, the limit of power injection to the system must be verified before installing distributed generation on the system. In addition, voltage variation levels should also be considered and should not vary more than ±5 per cent (PU) [20].

In contrast, due to distributed generation connection, short-circuit or fault level on the network tends to increase and it may damage system components, therefore proper protection must be considered [21]. This protection can be identified in several aspects, such as protection on generation equipment that is used to prevent internal faults, protection on the distribution system from fault current as a result of distributed generation interconnection and anti-islanding. All of these aspects are extremely important and need to be addressed in order to determine the impact of distributed generation integration on the system.

From a power quality perspective, the presence of distributed generation technology will definitely influence the transient voltage variation and harmonic distortion of the system voltage during connection and disconnection [15]. However, it is interesting to note that in some cases distributed generation has also improved power quality. For example, when voltage drops occur or with a high load demand level, it can be used as back-up generation, thus providing voltage support. In addition, distributed generation systems can also reduce line losses, if installed close to the loads or placed at optimal locations along the feeders.

Distributed generation will also affect the network transient stability. Kumar *et al.* investigated the positive impact of distributed generation on DS during faults period [22]. The result shows that rotor angle deviation and voltage drop are found to decrease. This means that the transient stability of the system is improved with an increased penetration level of distributed generation. However, voltage drop and voltage fluctuations along distribution feeders may still occur, therefore voltage control is necessary to keep the voltage level of the network within the allowed range.

As the penetration level of distributed generation into distribution or transmission systems increases, it is obvious that all of the issues discussed above will become apparent and can no longer be neglected. Unfortunately, from the literature review it can be seen that, overall, the objectives of recently completed or current and ongoing research are to analyse the impact of distributed generation on distribution systems. However, no effort has been made regarding analysis of the impact of distributed generation on Smart Grid systems. Therefore, it is important to investigate these issues in relation to Smart Grid as well.

2.5 Smart Grid

Electric power systems are the backbone of human society's development and of industrial countries throughout the globe. Rising electricity demands, following the increase of energy efficiency concern, result in the power system facing numerous challenges, including GHG reduction, demand response management (DRM), energy conservation and power quality, reliability, availability and security (PQRAS). It is apparent that such critical issues cannot be neglected.

Characteristically, about ten per cent of the energy produced by present existing grids is wasted, which contributes to increasing energy prices, production costs and global warming. In the United States (US) for instance, more than half of the electricity produced is lost as a result of inefficiencies on power generation, transmission and distribution lines [23]. In addition, due to the conventional topology of its utilities, limited control and manual restoration and other issues, the existing power system suffers from perturbations and catastrophic failures that may lead to black outs. It is a fact that in the coming years the current power grid will require further development to meet society's expectations for high PQRAS.

To address these challenges, the next electrical power generation must co-exist with digital information technologies and advanced grid devices. This scheme will shift the paradigm of passive power systems, where most utilities have limited interoperability access, to flexible and active electrical networks. Figure 2.6 shows the vision of a future grid that integrates communication in power system networks with distributed sensors and advanced power devices.

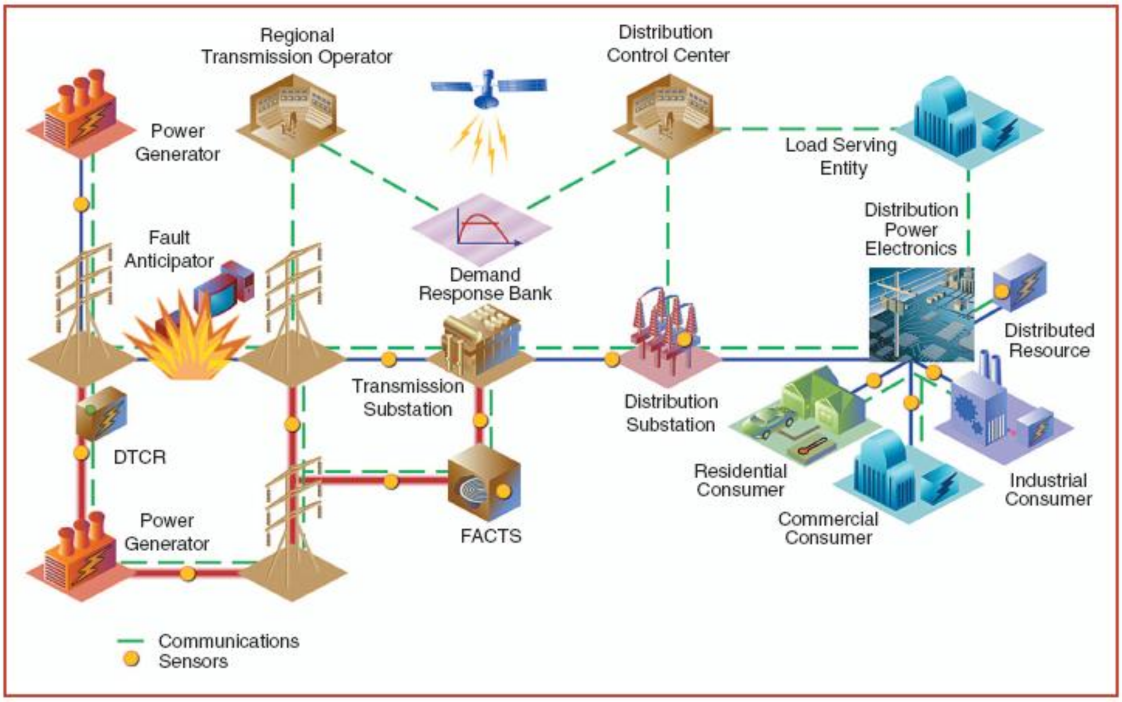

Figure 2.6: Architecture of integrated communication in power system [24]

2.5.1 Definition and Benefits of Smart Grid

Smart Grid is a complex electric power system and involves broad knowledge and advanced technologies for its operation and implementation. The term 'Smart Grid', also called 'Intelligent Grid', is a relatively new term in the power system area. There are many definitions of Smart Grid and different people have different views on defining it. The brief definition of Smart Grid, as proposed by the European Technology Platform, is: 'A Smart Grid is an electricity network that can intelligently integrate the action of all users connected to it—generators, consumers and those that do both—in order to efficiently deliver sustainable, economic and secure electricity supplies' [25]. Another definition of Smart Grid, proposed by the Distribution Energitice Intelligente, Segure of Eficiente (DENISE) project, is 'The Smart Grid integrates electricity and communications in an electric network that supports the new generation of interactive energy and communication services and supplies digital quality electricity for the final customer. In this sense, the electric network must be always available, live, interactive, interconnected and tightly coupled with the communications in a complex energy and information real-time network.' [26]. However, due to the complexity of the system, the precise meaning of Smart Grid has yet to be clearly defined; moreover, the standard and its scenario is in progress for development.

Smart Grid is the vision of future electric power system delivery, the electricity industry and markets. The fast growing concern on this topic is an effect of rapid economic development that causes the existing power system to be under pressure in order to fulfil consumer expectations. Smart Grid implementation offers a solution and can deliver various potential key benefits to society, not only for security and quality of the power supply, but also to achieve sustainable energy development. The main beneficiaries using Smart Grid can be either the utility or customer. The benefits for utilities are to:

- reduce power system perturbations and outages;
- possibly reduce power losses, brownouts and blackouts;
- improve energy efficiency;
- enable micro-grid application and energy management system (EMS);
- enable peak demand reduction and DRM;
- increase large-scale renewable energy and distributed generation integration;
- increase PQRAS;
- accelerate green and clean power generation;
- environmental benefits and reduction of GHG;
- drive economic growth through clean power markets; and
- reduce maintenance and operations cost.

From the customers' point of view, Smart Grid implementation also offers benefits such as:

- enabling electricity consumption management;
- cost-saving through EMS;
- enabling consumers to be energy producers through distributed generation; and
- enhancing consumer services.

These promising benefits will obviously have a positive impact on society. Further, it will stimulate more innovation in new power system networks associated with information technology, as well as encouraging multiple engineers from various backgrounds to conduct further research that will accelerate Smart Grid implementation.

2.5.2 Recent On-Going Efforts for Smart Grid Development

Electric power system networks, as the most critical infrastructure, have provided the critical support for industrial development for many years. The primary architecture of this network was not designed from a grand plan but rather to meet the needs of consumers, where fossil fuels are the main source of power generation and located far from the point of demand. With emerging concern for low-GHG power generation technologies and energy efficiency, modern power systems for the twenty-first century have moved to transform from the current grid into the new concept of the future grid, referred to as 'Smart Grid'.

The vision of Smart Grid has been driving developed countries to conduct more research and develop advanced power electronic devices and information technologies applied to the Smart Grid. United States and European platforms for Smart Grid have developed rapidly from five years ago and are now well established. An overview of some of the research currently being undertaken is given in the subsequence paragraph.

Initially, the US interest in developing intelligent power technologies that improve grid reliability, security and economics started in George W. Bush's government era. It was highlighted by the Department of Energy Office of Electricity Delivery (DEO) that power outages and transmission-distribution disturbances in US power systems cost the US economy billion of dollars yearly. Addressing this issue for better US energy security that is environmentally friendly and efficient, DEO held a workshop in 2003 resulting in a platform for modernising and transforming the national electricity grid by 2030 [27].

To achieve this goal and improve US energy efficiency and reliability, in 2009 the American Recovery and Reinvestment Act (ARRA) included $10 billion for Smart Grid technologies and other investments to modernise, upgrade and enhance national existing power system infrastructures. [28]. Several collaborative research programs and organisations were established as well, to demonstrate the benefits of Smart Grid. The Gridwise Alliance is an organisation that works in coordination with US DEO and Energy Reliability. [29]. The Gridwise Alliance has a focus program, such as in the Smart Grid communication, architectures, standards, simulation, new regulatory and market frameworks.

The Gridwise Architecture Council [30] was formed by DOE to lead, promote and develop innovative Smart Grid technologies. It aims at shaping the Smart Grid architectures and standards that enable interoperability for intelligent, interactive US power systems. Smart Grid technology in the US has been acknowledged in the Energy Independence and Security Act of 2007, (EISA). In addition, under this act, the National Institute of Standards and Technology (NIST) was appointed to supervise the development of Smart Grid interoperability standards [28]. The US commitment to develop intelligent power grids clearly states that, to ensure power reliability and security, the national grid should have Smart Grid features, such as increased use of digital information and control technology in order to improve reliability, security and efficiency of the electric grid [31].

Other efforts toward Smart Grid development in the US are undertaken by the Electric Power Research Institute (EPRI) through Intelligent Grid Initiative projects [32]. It is mainly concerned with technical frameworks and architectures for Smart Power Grids that provide methodologies, tools and recommendations for standards to facilitate in planning, specifying and procuring IT based systems. These systems include advanced metering infrastructures, distribution automation, demand response management and wide-area measurement or monitoring.

Meanwhile, the European technology platform on Smart Grid initially began in 2005 to meet the new challenges and opportunities that provide benefits for users, operators and power companies across Europe. To achieve this, it is expected that in the next 30 years the EU member states will spend some 750 billion euro in power system infrastructure. The Smart Grid vision [33] for Europe's electricity network must be:

- Flexible: fulfilling customers needs whilst responding to changes and challenges ahead.
- Accessible: granting connection access to all network users, particularly for renewable power sources and high efficiency local generation with zero or low carbon emissions.
- Reliable: assuring and improving security and quality of supply, consistent with the demands of the digital age towards being resilient to hazards and uncertainties.

- Economic: providing the best value through innovation, energy efficient management and 'level playing field' competition and regulation.

Following these visions and its key activities, the EU has published a Strategic Research Agenda (SRA) in 2007 [34]. It proposes a framework for future research themes and tasks that aims to ensure that Europe’s electricity networks are developed in a way that enhances Europe’s competitive position, without damaging environmental objectives and a commitment to sustainability. In addition, the SRA also focus on delivering *Catalyst Projects* that address and anticipate potential barriers, such as regulatory frameworks or technical standards. In contrast, the *Lighthouse Projects* seek to facilitate and validate experimental or demonstration innovative projects.

Overall, the European and American efforts and visions toward Smart Grid development are nearly the same. They both have high requirements and standards for power quality, reliability, efficiency and security, leading to research on how to boost the deployment of Smart Grid technology; that is, intelligently integrating consumers, operators and power system networks in a real time basis. In contrast, the most common path for power grid development in both countries is through integration or utilisation of distributed renewable energy resources as new power generators. Conversely, they have different concerns on Smart Grid agenda. The USA prioritises more on upgrading and modernising the existing power grid infrastructures, whereas the EU is more concerned with system innovation and integration of renewable energy and distributed generation into European power networks.

2.5.3 Concept of Smart Grid

The reliability of power generation is a vital parameter for power delivery and economic development. Today, power system operation is limited in interoperability across applications. The information in these areas is usually provided for local networks only and not in real time basis. Thus, the implications of this result in a new challenge for high PQRAS.

With the emergence of the Smart Grid paradigm, large numbers of sensors, power electronic devices, distributed generations and communications appliances will be added to the network to address the challenge as shown in Figure 2.7. Therefore, the system becomes smarter and more complex, which requires integration of information and data processes across the system [26].

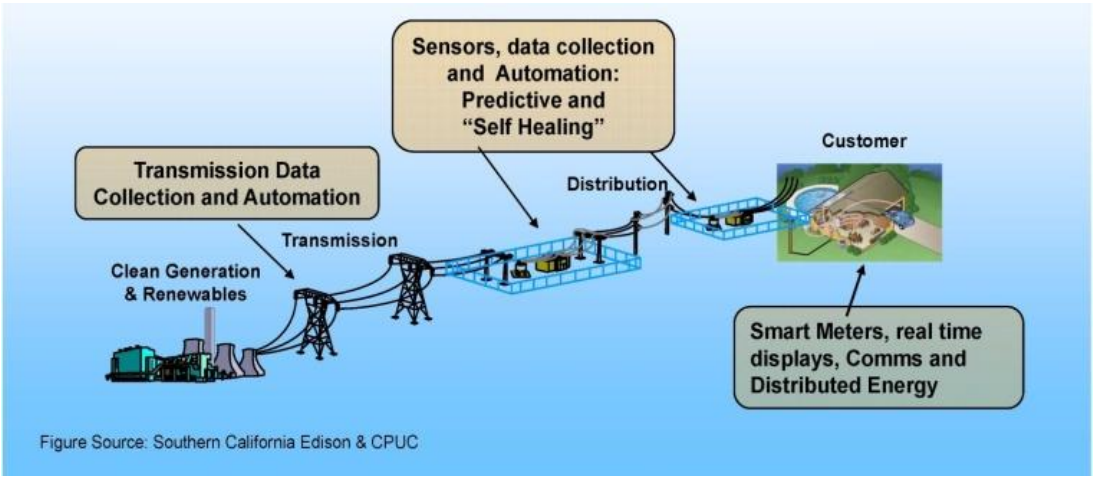

Figure 2.7: Element of Smart Grid systems [35]

Smart Grid is a new model for power systems that involves sophisticated communication and advanced control technologies for implementation. Smart Grid key characteristics and technology include [26]:

- self-healing;

- incorporates and empower the user;
- tolerates security attack;
- offers power quality enhancement;
- accommodates various generation sources;
- fully supports energy market; and
- optimises asset utilisation and reduces the expenses for system operations and maintenance.

The technology that is involved in the Smart Grid concept includes:

- Advanced control methods that aim to provide, monitor and analyse data from all essential network devices. If perturbation occurs for instance, it is able to take proper action and offer solutions to human operators. Advanced control methodologies would support various applications such as substation automation (IEC 61850), energy pricing management and DRM.
- Digital sensors, metering and measurement using two-way communications, in which various signals such as real time energy usage, peak season tariff and power quality are communicated between consumers, operator and generator.
- Advanced grid utilities —enables the production of strong, fully controllable, flexible and reliable power system operation as well as enhancing performance. These technologies include FACTS, high voltage direct current devices (HVDC), superconducting transmission cables (STC) and fault current limiters (FCL). The installation of these technologies will be the key role to transforming current power system grids into Smart Grids.

2.6 Frameworks and State of the Art of Smart Grid Technology

Smart Grid is a diverse collection of technologies, concepts and architectures. It has many elements, such as smart meters, advanced metering infrastructure (AMI), data management systems, two-way communication networks, FACTS, SCADA, digital sensing and distributed automation (DA). Smart Grid will be able to integrate all aspects of power system infrastructure, thus empowering the consumer to interact with operators or energy management systems to manage and control their energy usage through two-way communications, or so called 'end-to-end' facility. Further, Smart Grid will provide high PQRAS of an electric power supply.

The standard of Smart Grid, how all elements connect each other and how the communication or energy flow works still remains the major concern for enabling Smart Grid implementation. The National Institute of Standard and Technology (NIST) [36], reveals that there are seven important Smart Grid areas that need to be addressed to make the grid 'Smarter':

- bulk generation;
- transmission;
- distribution;
- customers;
- operation;
- markets; and
- service provider.

Each of these areas is comprised of many applications, including software programs, advanced devices or operator groups in order to make decisions and exchange data within the whole system. These areas have been elaborated and highlight the key features under the Smart Grid paradigm.

2.6.1 Bulk Generation

Figure 2.8 depicts the bulk generation site that generates power from renewable and non-renewable energy sources in bulk capacity. Electrically, it is connected to the transmission systems.

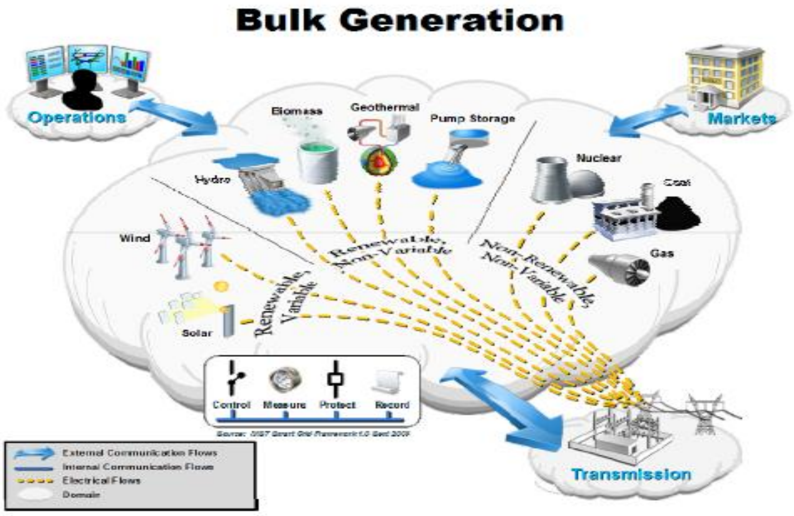

Figure 2.8: Bulk generations [36]

From the perspective of smart grid [36], bulk generation communication with transmission systems is the most crucial element to communicate, share and exchange key information performances with the operations and market domains. Typical applications include:

- Control: managing system power flow and reliability, such as using phase angle regulator.

- Measurement: providing data collection or digital measurement for all systems performances through SCADA system for control centre in the operation domain.
- Protection: maintaining a high quality of supply and providing fast response to faults that might cause power disruption.
- Asset management: identifying and recording major equipment details, such as due date for maintenance, operation history or working life expectancy.
- Record: recording data for evaluation and forecast purposes.

In order to enable these applications, it requires an intelligent and powerful device that is field-proven such as SEL Mirrored Bits™ Communication Technology [37], where advanced protection, control and monitoring applications can be communicated through fibre optic, microwave, audio and radio communication paths. Such a device will use the energy more efficiently so that power losses or power outages, for example, can be tracked faster.

2.6.2 Transmission

Transmission systems have played a critical role in delivering electrical power from generation to distribution systems through long distance high voltage power lines and substations. Thus, they have the ability to maintain power stability across the transmission lines. Moreover, transmission system stability has received much attention in meeting high demand, power quality, reliability and security of supply for the twenty-first century.

Meeting these challenges requires advanced power technologies, measurement and control centres for transition into a smart transmission network. As shown in Figure 2.9, the major elements for smart transmission domains are real-time measurement and control devices that are used for data recording, protecting and optimising system operation [36]. These applications can be used for such control as local or wide-area control along the network. In addition, smart transmission systems also require advanced communication with operations and market domain that enables energy management systems to analyse the system reliably, such as for power storage or dispersed generation to be integrated in the transmission system in case of power shortage through substation.

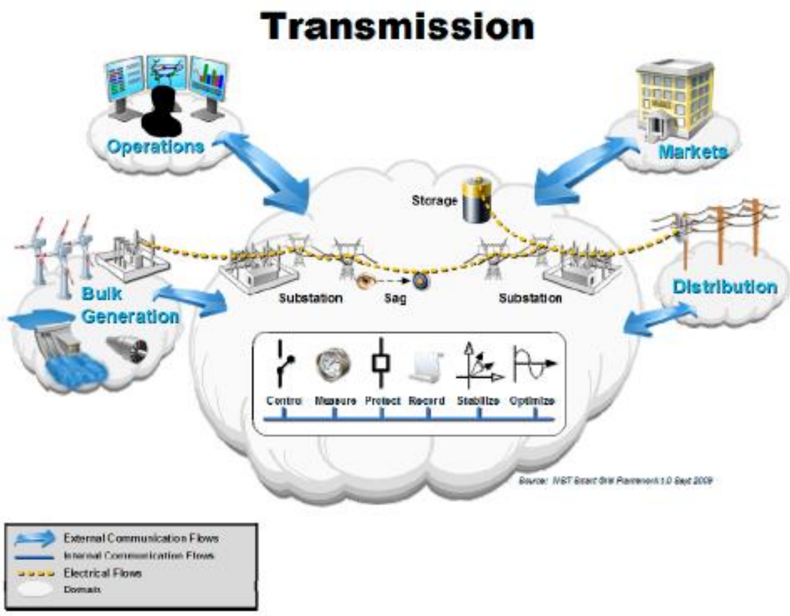

Figure 2.9: Transmission networks [36]

An example of mature technology application in smart transmission grids is phasor measurement units (PMUs). It has full power system monitoring capability, such as power system protection, islanding detection and enhancing state estimation [38]. This means that the PMUs installation in the transmission network can facilitate the regional transmission operator (RTO) in taking rapid action and precise analysis after faults or disturbances occur. Moreover, current research also shows that PMUs have been effectively proven to be used for smart islanding and anti-islanding devices to integrate distributed generation such as photovoltaic or wind turbine [39]. However, the implementation of advanced devices like PMUs will not result in more benefit unless the communication based local-area network (LAN) or wide-area network (WAN) also integrates and installs in the system, for example within each substation along the transmission network. This concept helps to collect data accurately for the control centre. In addition, it allows the analyst to determine the event sequences precisely as well as identifying the exact cause of system malfunction that may lead to catastrophic system failure such as in the 2006 US blackouts [38].

Another mature technology for smart transmission grids is power electronic based FACTS devices such as STATCOM and SVC. This device provides several possibilities to enhance power system performance, power quality, improve operational capabilities and fast control to maintain voltage stability, particularly in transmission and distribution systems [40]. Moreover, SVC can be connected directly to the grid for dynamic voltage control without the need of a step-down transformer [41]. It obviously offers benefits for distributed generation, such as wind power integration to the network, where the current trend is distributed generation utilisation in the power grid.

2.6.3 Distribution

The main objective of a distribution system is delivering power from bulk generation to customer. To do this, distribution substations receive power from transmission lines and step-down voltage transformers; it is then consumed by the end-user. Nowadays, most distribution networks are radial and nearly all the internal or external communications interfaces are unidirectional and controlled by humans [36]. It also relies on paper reporting only. Thus, if a fault occurs on the distribution system, operators obviously could not take quick action for power restoration unless the customers report the problem. This approach will no longer be accepted as demand continues to rise steadily.

Figure 2.10 is a topology of a distribution system under the Smart Grid architecture. In this domain, all types of measurement and control devices for protecting and optimising the system are equally important, as in the transmission systems. However, there is more focus on the ability of the distribution system to communicate in real time with the operations and market domain, or vice versa, in terms of managing the power flow that relates to power generation and consumption [36]. Thus, it allows and supports the integration of new applications to the system more easily, such as dispersed generation, distributed storage or micro-grids. This schema can be achieved through upgrading current distribution management system (DMS) applications such as fault detection, isolation and service restoration (FDIR), load modelling (LM) or distribution power flow (DPF) into advanced distribution management systems (ADMS) [42].

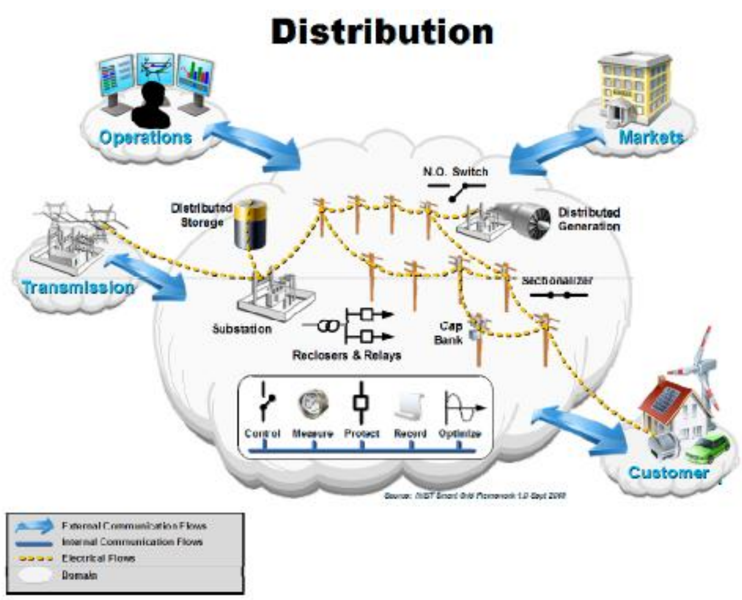

Figure 2.10: Distribution networks [36]

Transforming current DMS into ADMS requires communication based protocol between distribution networks, operations and market domains. It is essential to enable data exchange from the market domains, which deal with meter data, billing and energy trading, to operation domains where major tasks are controlling and monitoring the networks. The DNP3 is an example that is currently used as communication protocol in the transmission and distribution systems. However, it is not fully supported for all SG functions and must be expanded following the IEC 61850 standards [36].

In addition, to accommodate two-way data communication in the distribution or transmission network infrastructures with the market and operation domains, fibre optic technology could be used as an alternative option for underground conduits. It supports speed data transfer up to gigabits per second, is able to carry different data or channels in cable, is ideal for long distance distribution and transmission lines, has no electromagnetic interference and is more secure [43]. Thus, it is possible for massive data exchanges on Smart Grid networks instead of converting over-head power lines to underground cables.

2.6.4 Customer

Electricity customers are typically divided into commercial, industrial and residential areas. These areas consume electricity in different manners and essentially it contributes to energy efficiency and environmental sustainability. In recent years, most end-users are passive and unable to interact with energy management or operators to control their energy usage. It is evident that present grids are only one-way communication and suffer from energy management system issues.

Figure 2.11 presents the core functionalities of the smart customer domain, where customer utilities are linked to energy service infrastructure (ESI) via AMI, through which electricity usage is recorded, measured and communicated. As the primary bridge between end-users and energy management systems (EMS), ESI provides a secure web portal for customer to interact with EMS, such as monitoring and controlling distributed generation, remote load control, on-line customer energy usage and billing [36].

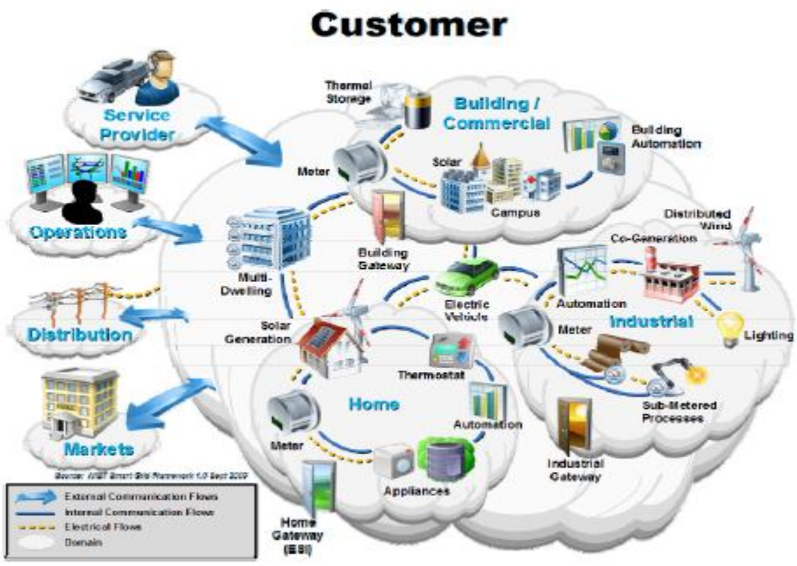

Figure 2.11: Customers domain [36]

This framework requires several major elements of EMS [44] such as:

- smart appliances and control panel;
- smart meters;
- AMI;
- meter data hubs;
- on-line transaction processing (OLTP) for power companies;
- interface between meter data hub and OLTP;
- interface between SCADA and OLTP; and
- interface between OLTP and AMI.

All these elements are integrated based on the following architecture in Figure 2.12.

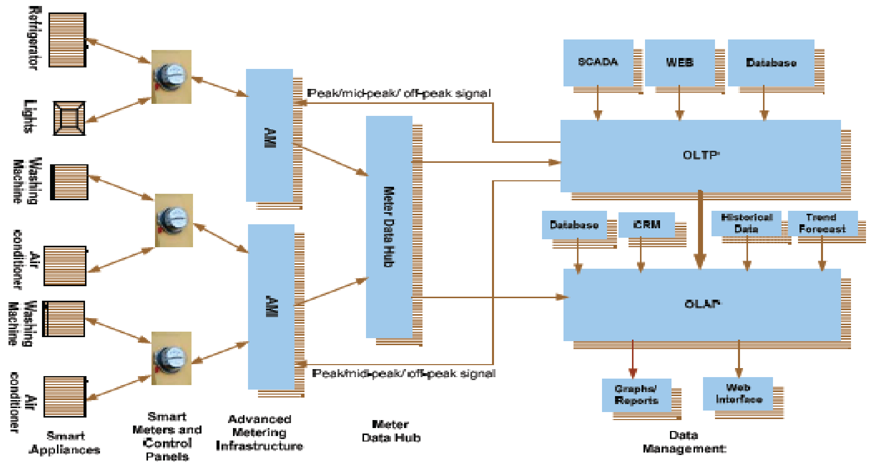

Figure 2.12: Framework of real time energy management system [44]

From the customer's point of view, this real time energy management system enables end-users to receive understandable and valuable information on their electricity usage, such as current energy consumption or history and billing. Thus, the consumer can make informed decisions to manage their electricity. However, the framework cannot be implemented unless a telecommunication infrastructure that is flexible, open and secure is available. Therefore, two-way communication in the consumer domain is fundamental to supporting demand response and real time energy management systems under the Smart Grid paradigm. The technology that could be considered for the customer domain is Zig-Bee mesh wireless technology, based on the IEEE 802.15.4 standard [45].

2.6.5 Operations

The energy management system (EMS) plays a crucial role in the transmission and distribution systems. Its major task is to ensure that the system remains reliable and efficient at all times. Typically, the EMS collects real time data from points of generation to consumers, or vice versa. The operations domain mostly deals with the entire grid management that requires all domain communication.

Figure 2.13 presents a typical functionality of operation domains for Smart Grid systems. The characteristic applications in this domain are available in the IEC 61968-1 Interface Reference Model (IRM) [36], such as:

- network operation monitoring;
- local or wide area control and fault management;
- reporting and statistics;
- calculations and analysis;
- records and assets management; and
- maintenance, construction and operation planning.

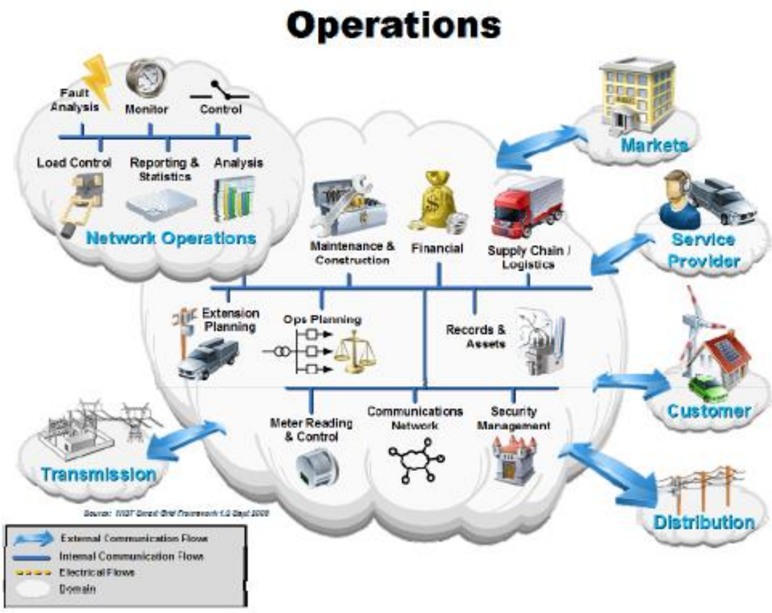

Figure 2.13: Operations domain [36]

Technically, all of those applications and infrastructures are coordinated with other domains. However, due to similarities in typical applications and devices, their networks' functionalities may not be much different. Therefore, establishing the operation domain relies upon the readiness for addressing and implementing major concerns on transmission, distribution and consumer domains, namely information and communication technology (ICT), intelligent and powerful electricity devices.

2.6.6 Markets

It is expected that the cost of electricity could be doubled in the next five to ten years due to the highly competitive energy market, increased power demand and government regulations. However, with the presence of the market domain under the Smart Grid paradigm, the power cost could be minimised. The market domain will help the energy supplier to analyse and fit their energy production to consumption, where most of the deregulated electricity market has a price gap among other electricity providers.

Figure 2.14 presents the markets domain, which is mainly responsible for managing all aspects of electricity markets, such as simplification of market rules, managing the regulation and growth of trading, retailing and wholesaling and evolving electricity prices or energy characteristics throughout the market and consumer domains [36]. This allows for load shedding management that ultimately ensures the power security of supply, despite large fluctuations of end-user demand, and offers a sophisticated energy pricing structure.

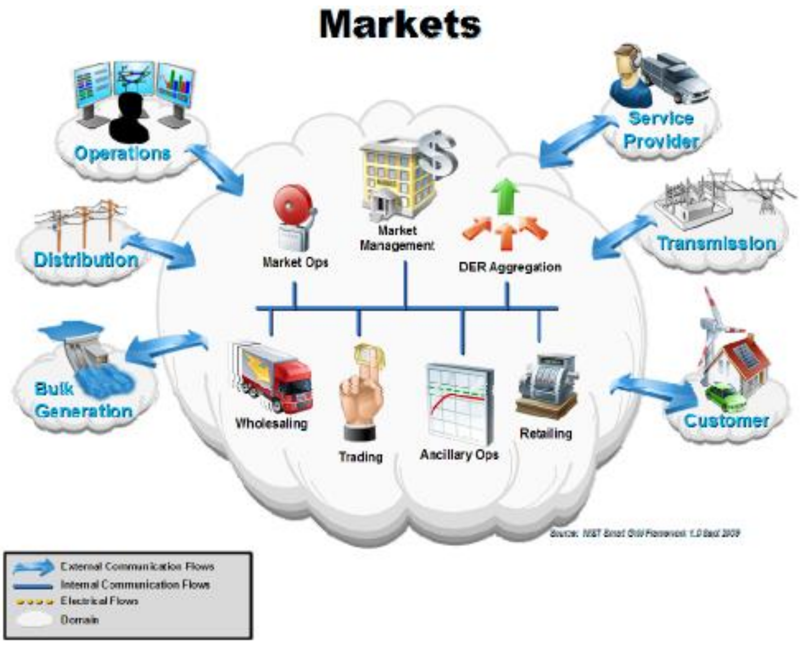

Figure 2.14: Markets domain [36]

2.6.7 Service Provider

As shown in Figure 2.15, the service provider domain consists of three distinct domains—operations, customers and markets domains. These domains are linked to each other with extremely secure interfaces to maintain cyber security, reliability, stability and integrity when delivering the services. Typical applications of the domain are managing the customer, installation, billing and accounts [36].

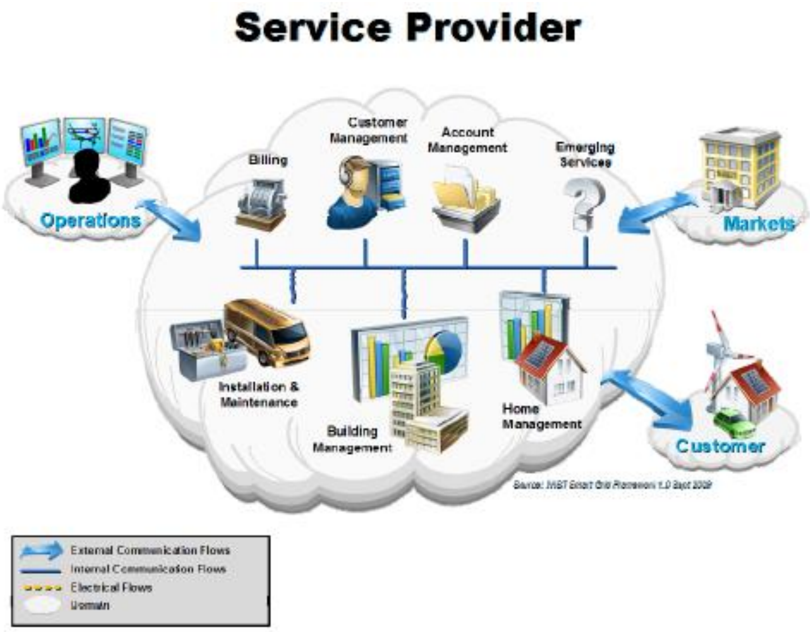

Figure 2.15: Service provider domains [36]

In addition, the service provider is expected to be more innovative to the end-user through new service offers, for example pre-paid electricity. This model allows customers to control their energy consumption more efficiently according to their pre-paid balance after they have inserted a several-digit number code to the pre-paid advanced metering infrastructure, which converts the amount of the electricity voucher into kWh. In the case of Smart Grid, pre-paid electricity allows the customer an insight into their daily energy usage.

From the preceding review it is obvious that a Smart Grid is an integrated system that involves complex co-ordination of strategy for implementation. Further, Smart Grid technology consists of broad knowledge and requires advanced technology to make the grid an ideal 'Smart Grid'. However, developing the concept of Smart Grid requires several years, takes gradual stages for Smart Grid device installation and further research studies in multiple years. Therefore, addressing one or more issues in electrical networks that make the grid become 'smarter' and enhance grid operational capability and power quality is absolutely essential.

2.6.8 Obstacles to Smart Grid

The Smart Grid concept and framework offers great promise for enhancing PQRAS, environmental compliance and supporting energy efficiency. However, the Smart Grid scheme is still under development despite many trusted available advanced power technologies that are ready to be used. The transition of current power systems through integration of intelligent advanced devices to the future Smart Grid might be the major obstacle. Therefore, it requires further profound analysis or research to overcome these barriers and vulnerabilities [24]. Generally, there are three possibilities of key obstacles for Smart Grid implementation, including but not limited to technical barriers, regulatory barriers and economic barriers.

Technical barriers: Principally, technical barriers deal with the integration issue related to automation, measurement utilities, sensors, advanced power electronic devices, ICT and standard operations. Most of the current existing power systems are not fully supported and compatible for those device installations and operations. Thus, it requires comprehensive investigation to ensure the interoperability of the system. Interoperability is the ability to share information and to use the information that has been exchanged between two or more systems and utilities across domains [46]. From a Smart Grid point of view, these systems may involve EMS, power quality monitoring (PQM), wide area measurement systems (WAMS), SCADA and various intelligent controls and sensors, which have not yet been designed in the current systems. As a consequence, when new utilities are integrated in the current system and it has no interoperability capability, the technical barrier becomes apparent and is the largest impediment.

Regulatory barriers: Due to the lack of international standards, Smart Grid frameworks and interoperability methods are different from place to place. Many parts of the utilities are currently regulating their power system operational standard, rates or policy based on local territory. These conditions can slow Smart Grid development and further increase costs for new integration of smart grid devices. In addition, upgrading current power systems into Smart Grids will require consumer, service provider and operator to share the benefits collectively. However, due to multi-dimensional benefits to customers, service providers and utilities, the usefulness of Smart Grid is difficult to measure from financial and market points of view alone. Therefore, as Smart Grid allows complex interconnectivity between users and systems, regulators may have to address the case of operational standard and regulatory frameworks based on wholesale market liberalisation.

Economic barriers: Smart Grid technology offers various benefits for utilities and consumers to wisely manage their energy consumptions. Smart Grid also provides flexibility for new integration of distributed generation. However, the implementation of Smart Grid will require huge investment to upgrade the existing power system infrastructures. Moreover, many advanced devices are still expensive and far from real applications due to incompatibilities, thus it requires further research and additional investment. In addition, Smart Grid applications will require market mechanisms that are economically efficient and are able to sell small amounts of energy in a liberalised market.

2.7 Smart Grid Stability Analysis

Stability analysis in Smart Grid is absolutely important during planning, design and operation. Usually, it evaluates the performance of the system under particular circumstances, such as before and after sudden changes in generation, loads, faults or outages in elements. The robustness parameter of Smart Grid can be defined by the ability of the system to maintain stability under normal or perturbed conditions and provide fast restoration after faults. Therefore, it is vital to study the dynamic behaviour of Smart Grid to ensure that the system remains stable and does not suffer loss of synchronisation, for example during interconnection of distributed generation.

Since the 1920s, power system stability has been recognised as a critical issue for secure power system operation [47]. Various perturbations and instability on power systems can result in loss of generator synchronism, which also leads to system outage and black-outs. This occurrence indicates the significance of power system stability, where most power providers are truly concerned in this particular case. With the fast growth of power demand and distributed generation integrations on Smart Grid, which involves many control and advanced power devices, system stability becomes of greater concern.

According to Kundur *et al*., 'power system stability is the ability of an electric power system, for a given initial operation condition, to regain state operating equilibrium after being subjected to physical disturbance, with most system variables bounded so that practically the entire system remains intact' [47]. However, in general system stability describes the ability of power systems to maintain synchronicity and steadiness at any given key parameter setting. In this regard, there are three classifications that are often associated with power system stability: rotor or power angle stability, frequency stability and voltage stability. Figure 2.16 shows overall power system stability classification [47].

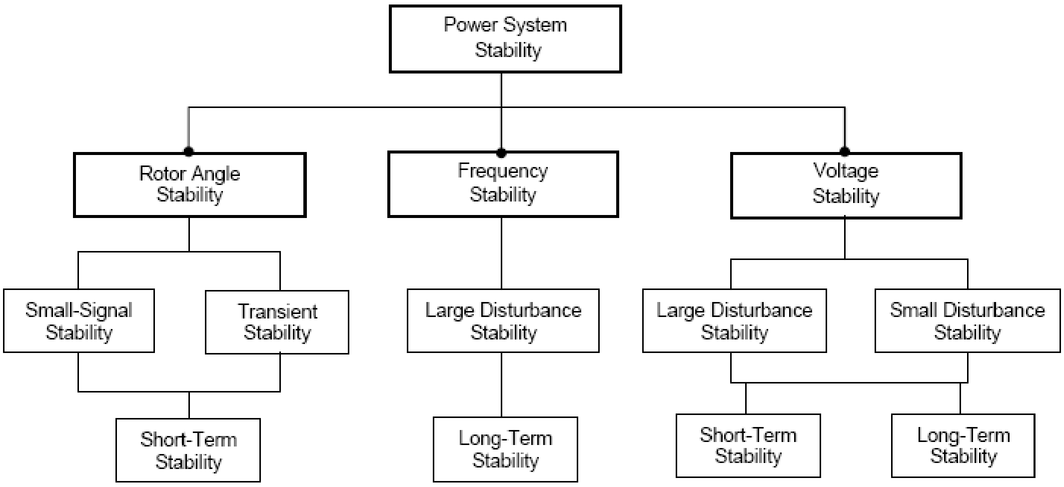

Figure 2.16: Classification of power system stability

The following are brief explanations of major power system stability phenomena [47]. This fundamental theory has been applied to Smart Grid stability analysis.

2.7.1 Rotor Angle Stability

Rotor angle or power angle stability means the ability of synchronous generators to regain in synchronism or return to normal conditions after having been subjected to physical perturbations. The rotor angle stability problem requires the study of electromechanical oscillation in power systems. A crucial issue in this case is the behaviour in which the power output of synchronous machines fluctuates as their rotor angle changes. In a steady state situation, the speed remains constant and the input of mechanical torque and electrical torque of each machine is balanced. If perturbation occurs in the system, it takes the system away from equilibrium, which results in the rotor of the machines speeding up or slowing down. If one machine is momentarily spinning faster than another, the spinning rates of all machines do not match each other, resulting in angular differences in position. This tends to alternately inject or absorb power from the fast machine to the slow machine. In addition, if angular separation is increased subsequently the power transfer is decreased or a decrease in bus voltage occurs, which leads to instability. An unstable system could lead to system failure and cascading outages for major components of the power system. Rotor angle or power angle stability problems can be categorised into two distinct areas:

- Small signal rotor angle (steady state) stability is the ability of the power system to maintain synchronism under small perturbations. The usual problems may cause small stability disturbances, such as HVDC control, FACTS controller, inter-area oscillation mode and load changes. The time frame for small signal stability problems is ten to twenty seconds following perturbations.
- Large signal rotor angle stability (transient stability) is the ability of the power system to maintain synchronism after having been subjected to severe perturbation, such as short-circuit and switching operation. The time frame for large signal stability problem is three to five seconds following perturbation.

2.7.2 Frequency Stability

Frequency stability refers to the ability of power systems to maintain steady frequency within a permissible range following a severe system perturbation. Unstable frequency results in a considerable imbalance between generation and load, consequently it affects large excursions of frequency, voltage, power flows and other system parameters. Frequency stability problems are usually caused by inadequacy of the system utilities to respond to disturbances, lack of control coordination and advanced protection devices. The time frame for frequency stability problems is extended from one second to minutes depending on the control and device response.

2.7.3 Voltage Stability

Voltage stability is the ability of power systems to maintain steady voltage within permissible ranges at all buses in normal conditions and after having been subjected to a severe system perturbation. Voltage instability may result in significant rise or fall of voltages on some buses. The key contributing factor to voltage instability is voltage drop that occurs when active and reactive power flows through inductive reactance in transmission lines. Consequently, it limits the capability of the transmission system for voltage support and power transfer. In addition, dynamic loads also contribute to the voltage instability when disturbance occurs. The load tends to respond by restoring the consumed power, which can increase reactive power consumption and the stress of high voltage network causes more voltage reduction.

Voltage stability can be classified into two distinct sub-system categories:

- Large disturbance voltage stability refers to the ability of power systems to maintain and control voltages following large perturbations, such as loss of generation or system faults.
- Small disturbance stability refers to the ability of power systems to maintain and control voltages following small perturbations, such as incremental change in loads.

Meanwhile, the duration time for voltage stability problems may vary from a few seconds to tens of minutes. Therefore, the extent of voltage stability could be a short-term or long-term phenomenon.

2.8 Conclusion

This chapter reviews previous work done on distributed generation technology and its impact on power systems. It shows that distributed generation has both positive and negative impacts on power systems, such as improving system reliability, preventing under-voltage drop, influencing transient stability and harmonic distortion during connection or disconnection. In addition, this chapter provides comprehensive analysis of Smart Grid concepts, frameworks and the state of the art of Smart Grid technology as well as some basics of Smart Grid stability. Smart Grid as a new concept for future power system generation involves broadening knowledge and technologies, which requires standard and interoperability features for operation and implementation. The realisation of Smart Grid frameworks will take gradual stages and possibly many years. The next chapter provides an overview of FACTS technology, especially SVC as a Smart Grid device controller.

Chapter 3: Overview of Flexible AC Transmission Systems (Facts) as Smart Grid Devices

3.1 Introduction

For the last ten years, power demand has increased steadily. This has resulted in widespread development and use of distributed generation technology to meet the increased load. The increased usage of distributed generation connected to the grid will result in further instability of the system. This is the real challenge, where utilities have to find appropriate technical solutions to overcome this problem. The answer seems to lie in transforming current power systems into Smart Grids. Future Smart Grids will be more flexible and fully controllable with distributed generations. Enabling this concept, Zhang discusses a framework for operation and control of Smart Grids with distributed generation [48]. With the distributed generation participation in power systems, network reliability can be enhanced by proper control of the system transient stability and voltage stability through the use of FACTS devices such as static VAR compensators (SVC) [48]. The use of power electronic devices like SVC will make current power systems 'smarter', particularly in terms of system stability in the presence of distributed generation technology. This chapter discusses the fundamental of FACTS technology as Smart Grid devices.

3.2 Fundamentals of Power Compensation for System Stability

Figure 3.1(a) presents the simplified model of a power flow diagram in a transmission system. Two power generators are integrated by a transmission line, which may be interconnecting points or may have load. It is assumed that the transmission line is lossless and represented by the reactance *X*. $E_1\angle\delta_1$ and $E_2\angle\delta_2$ represent the buses' voltage magnitudes with angle $\delta = \delta_1 - \delta_2$. The corresponding phasor diagram is shown in Figure 3.1(b).

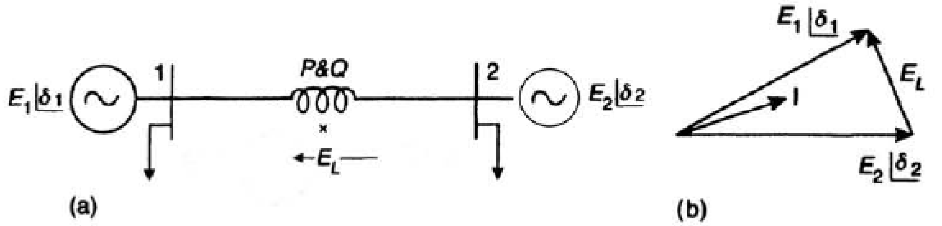

Figure 3.1: AC power transmission systems (a) simple two generator model (b) phasor diagram [7]

The current magnitude in the transmission line is given by:

$$I = \frac{E_L}{X} = \frac{|E_1\angle\delta_1 - E_2\angle\delta_2|}{X} \quad (3.1)$$

The active component of the current flow at bus 1 is given by:

$$I_{p1} = \frac{(E_2 \, Sin \; \delta)}{X} \quad (3.2)$$

The reactive component of the current flow at bus 1 is given by:

$$I_{q_1} = \frac{E_1 - E_2 Cos\,\delta}{X} \quad (3.3)$$

Thus, the active and reactive powers at bus 1 are given by:

$$I_{p1} = \frac{E_1\,(E_2 \, Sin\,\delta)}{X} \quad (3.4)$$

$$Q_1 = \frac{E_1\,(E_1 - E_2 \, Cos\,\delta)}{X} \quad (3.5)$$

Similarly, the active component of the current flow at bus 2 is given by:

$$I_{p2} = \frac{(E_1 \, Sin \; \delta)}{X} \quad (3.6)$$

and the reactive component of the current flow at bus 2 is:

$$I_{q2} = \frac{(E_2 - E_1 Cos\,\delta)}{X} \quad (3.7)$$

Thus, the active and reactive powers at bus 2 ends are given by:

$$P_2 = \frac{E_2(E_1 Sin\,\delta)}{X} \quad (3.8)$$

$$Q_2 = \frac{E_2(E_2 - E_1 Cos\,\delta)}{X} \quad (3.9)$$

From equations (3.1) to (3.9) it can be seen that the current flow or the active and reactive power can be controlled by regulating the voltage, phase angles and line impedance of the transmission line. From the power angle curve in Figure 3.2(a), it is seen that when the phase angle δ is 90' the active power will reach the maximum value. Voltage magnitude regulation in the transmission network is more related to the reactive power flow compensation. As can be seen from Figure 3.2(b), the change of voltage magnitude E_1 does not modify the magnitude of E_L, however the current phase angle is correspondingly varied. Usually, there are two models of power compensation in transmission line i.e. series compensation and shunt compensation.

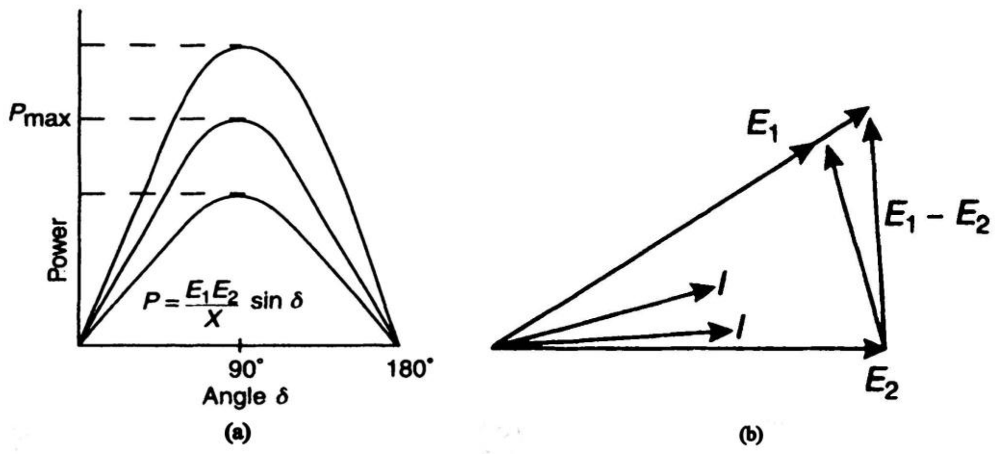

Figure 3.2: Power angle curve (a) and regulating voltage magnitude diagram (b) [7]

3.2.1 Series Compensation Model

One of the main objectives of series capacitor compensation is to control series impedance in the transmission line. Referring to equations (3.1) through (3.9), the power flow in the transmission network is mainly limited by the series reactive impedance of the transmission line.

The use of series compensation in the transmission line is illustrated in Figure 3.3 (a). It is assumed that the bus voltage magnitudes of V_s, V_m and V_r are equal, as V and the phase angle between them is δ . The transmission line is also assumed lossless and represented by the reactance X. At the mid-point of the transmission line, a series capacitor compensation controller is connected. The phasor diagram is shown in Figure 3.3 (b).

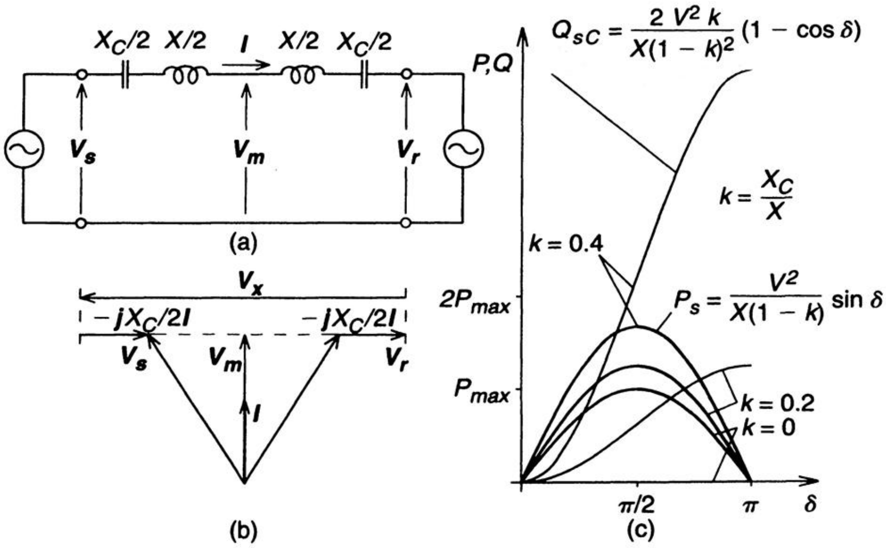

Figure 3.3: Power transmission systems with series compensation: (a) simplified model, (b) phasor diagram, (c) power angle characteristic [7]

From Figure 3.3 (a) the overall series inductance in transmission line can be expressed by:

$$X_{overall} = X - X_C = (1-k)X \quad (3.10)$$

where *k* is the degree of series compensation, i.e.:

$$k = X_c / X \quad (0 \le k < 1) \quad (3.11)$$

The active power and current transmitted in the line is given by:

$$P = \frac{V^2}{(1-k)X}\sin\delta \quad (3.12)$$

$$I = \frac{2V}{(1-k)X}\sin\frac{\delta}{2} \quad (3.13)$$

The reactive power supplied by the capacitor can be calculated as follows:

$$Q_C = I^2 X_C = \frac{2V^2}{X}\frac{k}{(1-k)^2}(1-\cos\delta) \quad (3.14)$$

The correlation between power (P), series capacitor reactive power (Q_c) and angle (δ) is presented in Figure 3.2(c). It can be seen that the value of transmitted active power in the transmission line increases sharply with the increase of *k*. In addition, an increase in *k* also results in the sharp rise of reactive power, which is supplied by a series capacitor.

3.2.2 Shunt Compensation Model

Figure 3.4(a) shows a simplified transmission model with shunt compensation, in which shunt compensator is coupled at the mid-point of the transmission line. The bus voltage magnitudes of $\boldsymbol{V_s}$, $\boldsymbol{V_m}$ and $\boldsymbol{V_r}$ are assumed to be equal to $\boldsymbol{V}$. The transmission line is also assumed lossless and represented by the reactance $\boldsymbol{X}$. At the mid-point of the transmission line VAR compensator is shunt-connected.

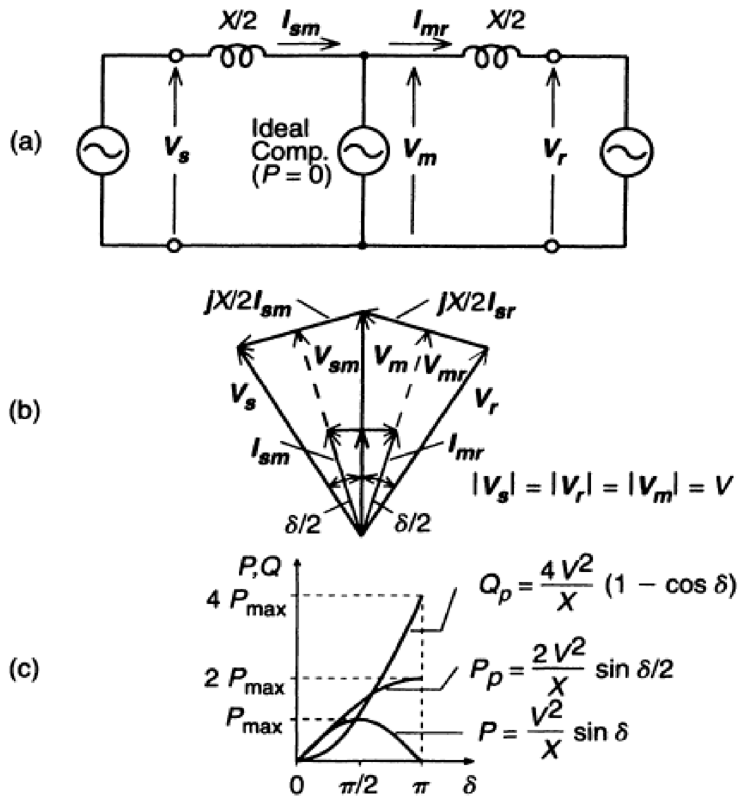

Figure 3.4: Power transmission systems with shunt compensation: (a) simplified model, (b) phase diagram, (c) power-angle curve characteristic [7]

From the foregoing discussion and assumption, the active powers at each terminal are equal as shown in the phase diagram of Figure 3.4 (b). The equation is given by:

$$P_1 = P_2 = \frac{2V^2}{X} sin\frac{\delta}{2} \qquad (3.15)$$

The value of reactive power injected by shunt-compensator is given by:

$$Q_{SC} = VI\, sin\frac{\delta}{2} = \frac{4V^2}{X}(1 - cos\frac{\delta}{2}) \qquad (3.16)$$

From the power angle curve characteristic in Figure 3.4(c) it can be seen that the value of transmitted power is significantly increased. It also shows that the wave curve changes from $\delta = 90^{\circ}$ to $\delta = 180^{\circ}$. It is obvious that the use of shunt compensation can enhance system operation limits and stability accordingly.

In general, power compensation is used in series, shunt or in combination, depending on the objective of the system. However, to improve the voltage quality, enhance power system stability and control the voltage magnitude, shunt reactive compensation is preferred and has been widely used [7].

3.3 Flexible AC Transmission System (FACTS)

FACTS controller history initially began around the seventies, when Hingorani proposed the scheme of power compensation in electrical power systems using power electronic applications [7]. Afterward, much research was conducted on the application of FACTS using self-commutated semiconductors and thyristor in transmission systems. Originally, FACTS devices were developed for transmission systems, which consisted of electrical conductors that have resistance, inductance and capacitance (R-L-C). The capacitive and inductive reactance in the transmission line generates and absorbs reactive power. The reactive power that flows along the line often causes further loss in the resistance of the conductor. For that reason, a FACTS device is required to enhance the power transfer capability and stability in the transmission systems. However, for the last decade this concept has been extended for improving power quality on distribution systems operation as well [49]. The application shown by Padiyar is to control and maintain the system stability, where in distribution level most of the loads are non-linear or dynamic [49].

The acronyms of FACTS and FACTS controller are defined differently by different authors on the basis of functionalities or capabilities. Therefore, the IEEE defined these terms [49] as:

- *Flexible AC transmission system (FACTS)* is an alternating current transmission system incorporating power electronic based and other static controllers to enhance controllability and increase power transfer capability.
- *FACTS Controller* is a power electronic based system and other static equipment that provides control of one or more AC transmission system parameters.

FACTS is one of the advanced technologies used for power system compensation. The devices include SVC, static synchronous series compensator (SSSC), static synchronous compensator (STATCOM), thyristor-unified power flow controller (UPFC), thyristor controlled series compensator (TCSC), thyristor-switched series capacitor (TSSC) and thyristor controlled reactor (TCR). These devices have many configurations, but can commonly be classified into series-connected controllers, shunt-connected controllers and a combination of the same. A detailed description of series and shunt-connected controllers is given by Hingorani and Gyugyi [7].

3.3.1 Series-connected Controller

A series-connected FACTS controller could be classified as a power electronic controller based variable impedance or converter model. Previously it includes TSSC, TCSC, thyristor-controlled series reactor (TCSR) and thyristor-switched series reactor (TSSR). Since, these controllers have been developed in the form of SSSC and generally based on a voltage source inverter (VSI) as shown in Fig 3.5 (a).

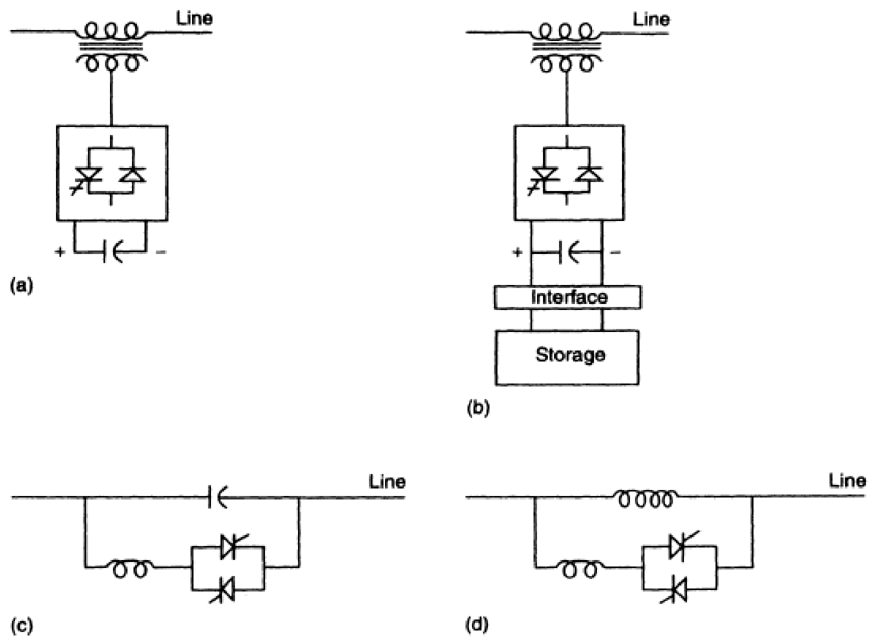

Figure 3.5: Various typical model of series-connected controller (a) SSSC, (b) SSSC with storage, (c) TCSC, (d) TCSR and TSSR [7].

SSSC can be used as variable reactive impedance and voltage source controller. The series-connected controller is operationally coupled in series with the transmission line as a controlled voltage source to control its current. Put simply, the SSSC works by enhancing voltage across the impedance of the transmission line, which subsequently increases the transmitted power and, correspondingly, the line current.

3.3.2 Shunt-connected Controller

FACTS controllers may be in the form of impedance or variable source type, which is based on thyristor without turn-off gate capability. The most common variable type of impedance controller includes SVC for shunt connected application, static synchronous compensator (STATCOM), TCR, thyristor-switched capacitor (TSC) and thyristor-switched reactor (TSR). The typical shunt-connected controller is shown in Figure 3.6.

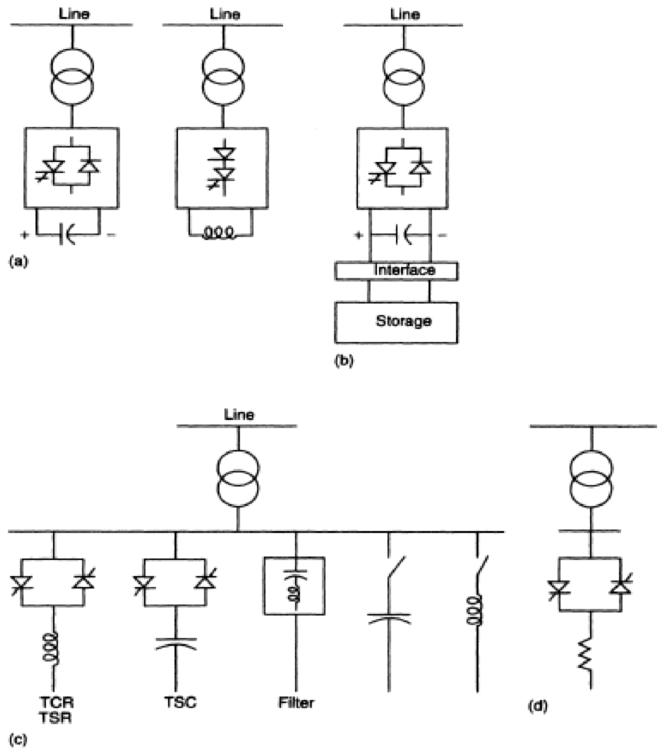

Figure 3.6: Typical of Shunt-connected Controller: (a) STATCOM based on voltage and current source converter, (b) STATCOM with storage, (c) SVC, (d) Thyristor-controlled Breaking Resistor [7]

These shunt-connected controllers have their own special characteristics and functionalities, depending on the purpose of the devices used in the control. However, in general its objective is to enhance maximum transmittable power in transmission line. This can be achieved by improving the transmission steady state characteristics and the system stability through the use of VAR compensation [7]. The SVC as the first generation of FACTS controller is able to provide reactive power support, load balancing, voltage regulation and system stability improvement [49]. Therefore, it has been chosen and considered as an ideal Smart Grid device.

3.4 Static VAR Compensator (SVC)

It has been discussed in the previous chapter that large- or small-scale integration of distributed generation may have significant impact on power system stability with respect to the rotor angle, voltage and frequency stability. Reactive power compensation and voltage control is fundamental to making the grid become smarter. Without this control, the presence of distributed generation may potentially cause system collapse. Therefore, a dynamic shunt reactive power compensator such as SVC is required to mitigate these issues.

SVC is 'a shunt-connected static VAR generator or absorber whose output is adjusted to exchange capacitive or inductive current so as to maintain or control specific parameters of the electrical power system (typically bus voltage)' [7]. SVC is based on thyristor-controlled and switched shunt components without gate turn-off capability. It is a variable impedance device using back-to-back connected thyristor valves to control the current flow through the reactor. SVC as a control device offers fast response time, much faster than traditional mechanically switched reactors or capacitors. The configuration of SVC as shown in Figure 3.6 (c) consists of two main components and their combination:

- thyristor-controlled and thyristor-switched reactor (TCR and TSR); and
- thyristor-switched capacitor (TSC).

TCR and TSR constitutes of a shunt-connected reactor controlled using paired parallel back-to-back connected thyristor. Using phase angle control, TCR generates an equivalent and constant variable inductive reactive power from zero to maximum. Conversely, TSR is controlled without phase angle control, which results in a step change in reactance and provides fixed inductive admittance.

TSC has similar operational characteristic and composition as TSR. It consists of a back-to-back thyristor pair in series with capacitors. The TSC is not continuously controlled because of transient phenomena at switch-on, it is instead is switched on and off independently. Therefore, the TSC cannot inject a reactive current with variable amplitude into the system. The transient phenomenon in TSC does not generate harmonics but if they appear, it is not a serious problem [50].

3.4.1 Control of SVC

The control system of general SVC with TSC-TSR configuration incorporating voltage regulator and reactive power measurement is illustrated in Figure 3.7.

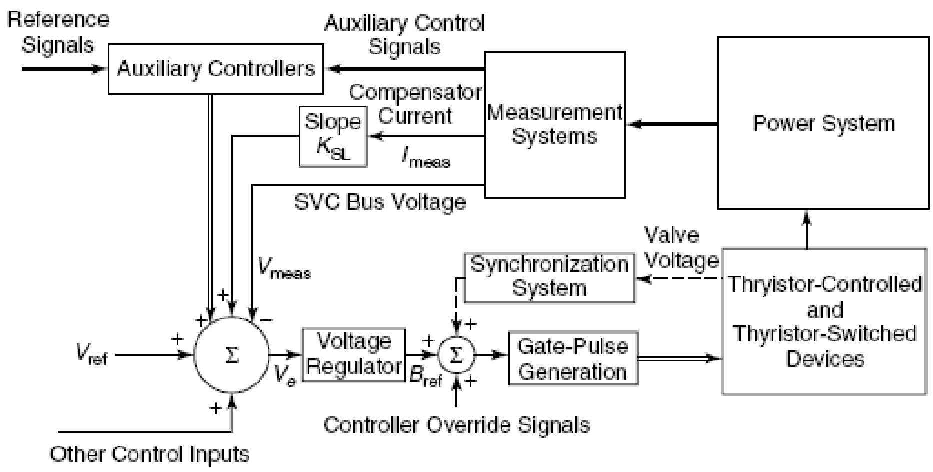

Figure 3.7: Fundamental diagram of an SVC control system [51]

The diagram shows that the measurement system obtains current, voltage and other signals from the power system. The measurement system's objective is to ensure that all the inputs are proportional for stable operation, as required by the system. It has three distinct mode controls: voltage, reactive power and auxiliary [51].

The voltage control system aims to keep the voltage within acceptable limits, especially at the point of common coupling (PCC), since it is vital for voltage regulation of the systems. To perform this, the voltage regulator processes all measured input variables and creates an output signal that is proportional to reactive-power compensation. The measured variables are compared with the voltage reference signal, denoted as V_{ref}, and the error becomes an input variable for the controller. The output of the controller creates a per-unit susceptance signal, which is denoted as B_{ref}, to reduce undesired signal error to zero in the steady-state operation; the signal is then transferred to the gate-pulse generation. The output signal (B_{ref}), derived from the voltage regulator, is transferred to the gate-pulse generation, which creates proper firing pulses for TCR-TSC of the SVC. Subsequently the undesired susceptance signal is rectified and the desired susceptance output is available at the SVC bus.

3.4.2 Equal Area Criterion for Transient Stability Analysis

As discussed earlier, with suitable and fast control it can be expected that SVC can be used to enhance the transient stability margin in power systems. The potential effectiveness of SVC on transient stability enhancement can be examined through the following discussion.

As depicted in Figure 3.8, assume that a single power generation machine with interconnecting lossless lines has a reactance (*X)*. Denoting the terminal voltages of generator machine and the infinite bus by $V_1\angle\delta$ and $V_2\angle 0$, power angle (δ) and the transmitted power as P, than without the SVC installed in the line, the value of the power transfer can be expressed by:

$$P = \frac{V^2}{X} sin\frac{\delta}{2} \qquad (3.17)$$

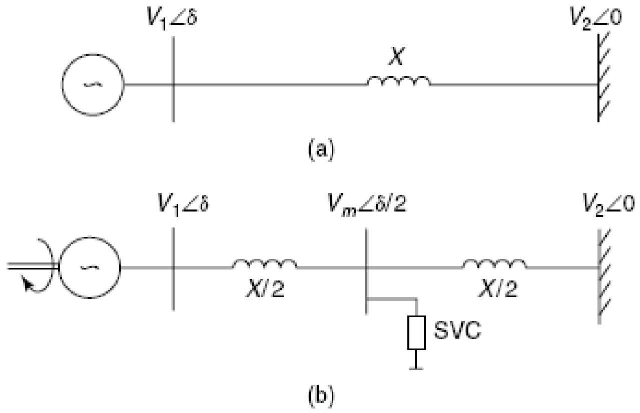

Figure 3.8: Simplified power systems (a) without SVC and (b) with SVC [51]

To understand the advantages of SVC, we shall assume that an SVC is installed at the mid-point of the interconnecting line. In that case, the reactance of the SVC between the machines and infinite bus is *X/2* ohms. Subsequently, the value of transmitted power can be calculated as:

$$\left[\frac{V^2}{(X/2)}\right]\sin\frac{\delta}{2} = 2\frac{V^2}{X}\sin\frac{\delta}{2} \tag{3.18}$$

From (3.17) it can be seen that the value of transmitted power is doubled, i.e. from V^2/X it goes to $2(V^2/X)$. Accordingly, the transient stability level is also increased. This fact can also be validated by the transient stability equal area criterion with SVC and without SVC, as shown in Figure 3.9.

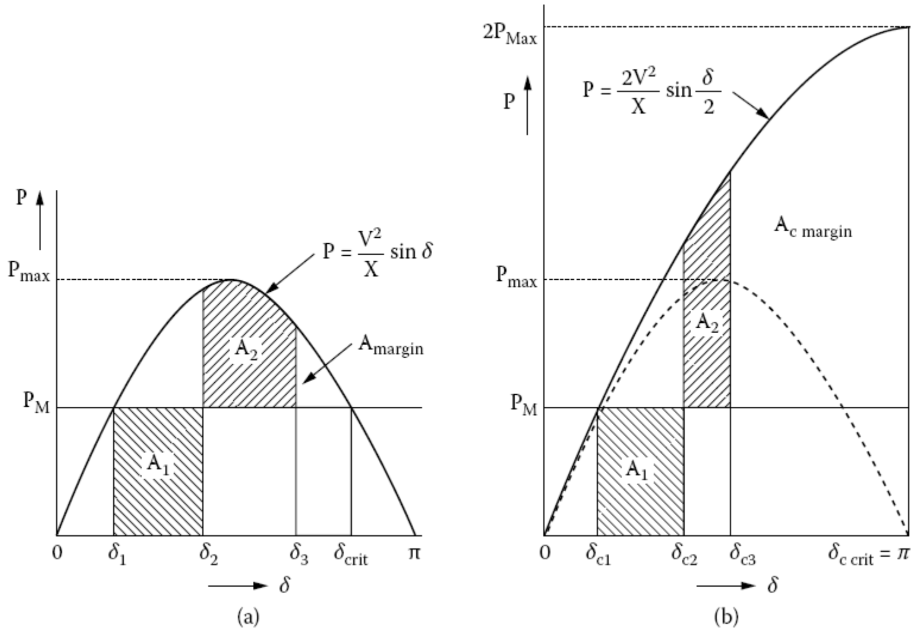

Figure 3.9: Equal areas illustrating transient stability limit without SVC (a) and with SVC (b) [52]

From Figure 3.9, it is evident that SVC is able to enhance the transient stability limit. In addition, it is obvious that transient stability is determined by power *(P)* against power angle(δ). With proper control and installation of SVC in the system, it can provide voltage support, while the increase in transmission capability will increase the transient stability margin.

3.4.3 Voltage Enhancement Analysis

Due to integration of distributed generation in power systems, reactive power could vary accordingly. This phenomenon may lead to voltage discrepancies and could affect system stability. SVC as one of the advance compensating devices for reactive power support can also be used for voltage improvement [52].

Figure 3.10 shows characteristics of receiving voltage end at various power factors, ranging from 0, 9 lag to 0, 9 lead. The max point at each dashed line curve represents the voltage instability corresponding to the system condition. The plot clearly indicates that when the limit of the voltage exceeds the nominal rate, the voltage could collapse. In this condition, the presence of SVC can effectively enhance the voltage stability margin by supplying the reactive power and controlling the terminal voltage as illustrated by the continuous line.

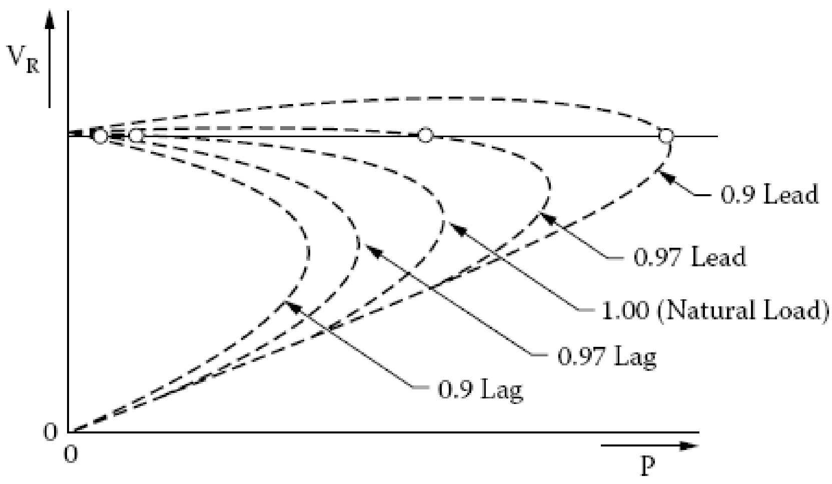

Figure 3.10: Variation of voltage stability limit of V_R (dashed line) and potential voltage control with variable VAR sources (constant line) [52].

3.5 Conclusion

This chapter has presented a broader understanding of FACTS devices. An elaborate discussion was given on the fundamentals of power compensation, as well as each model of power compensation for system stability. A detailed discussion of SVC was also presented. In view of the fact that the capabilities of the device to provide power reactive support, voltage enhancement, reduce voltage variations and enhance system stability, the SVC makes an ideal choice as a Smart Grid device.

Chapter 4: Experimental Analysis, Results and Discussion

4.1 Introduction

An overview of distributed generation and Smart Grid has been presented in the previous chapters. This chapter focuses on experimental analysis, results and discussion. Section 4.2 provides an overview of an experimental set-up while Section 4.3 describes experimental procedure. The detailed case studies on which the research was conducted are presented in Section 4.4. The research results and its discussion have been presented in Section 4.5. Finally concluding remarks are provided in Section 4.6

4.2 Experimental Setup

As discussed in the earlier chapters, the ideal framework and standards for Smart Grid configuration involve interdisciplinary research area in communication, automation, sensors and control. Nevertheless, due to the complexities of the Smart Grid system, it is unclear and even confusing to define the networks being ‘smart’ if a few of its key characteristics are neglected. Instead, it is preferable to consider the term 'Smart Grid' as the chance to enhance the power system performance and improve operational capabilities [40, 53].

In order to evaluate the impact of distributed generation on Smart Grid’s steady state voltage profile and system stability or dynamic behaviour, which is essential to establish an appropriate applied model, an experimental setup is required. The research considers a small and simple system configuration with easier control and design as shown in Figure 4.1. The test system network model is derived from the work of Chowdhury *et al.*, which presents successful islanding operation of distributed generation under Smart Grid environment [54]. However, this research only focuses on islanding examination and does not consider analysing the system transient stability. Therefore, it is essential to develop this research further using Smart Grid concepts by simplifying the system in respect of control, where FACTS devices, particularly SVC are used.

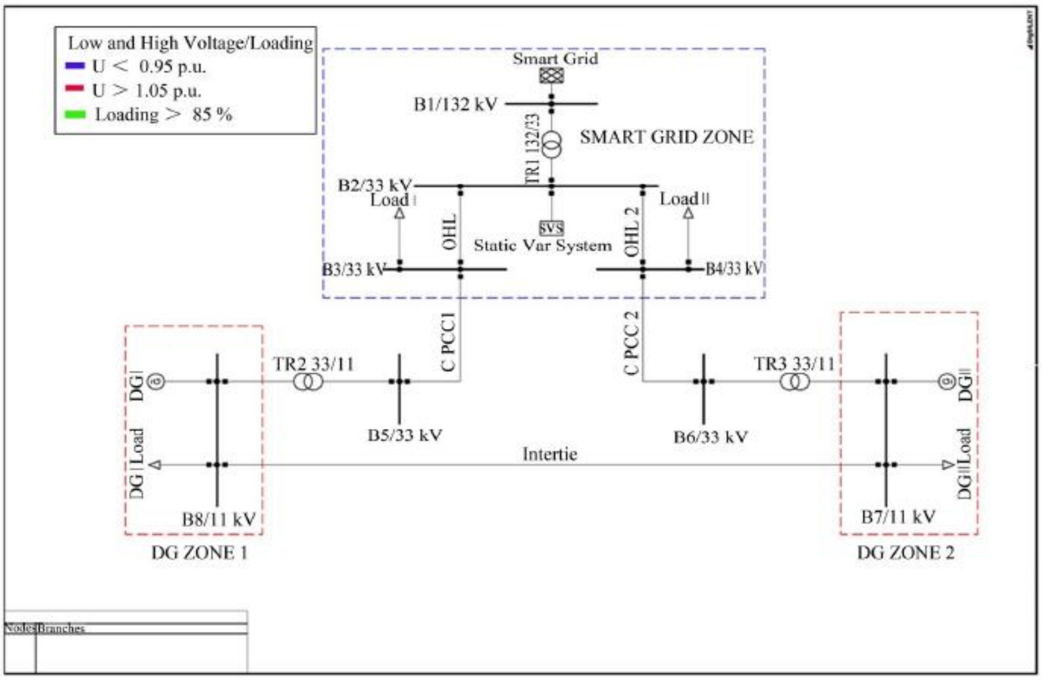

Figure 4.1: Smart Grid topology network

The considered Smart Grid network consists of a 132 kV, 50 Hz sub-transmission system with maximum short circuit levels of 5000 MVA and 4000 MVA respectively. The grid feeds a 33 kV distribution system through a 132 kV/33 kV, Δ/Y_g transformers with rated power equal to S_T = 35 MVA, V_{CC} = 13.18%. In the system, two types of distributed generation (DG) technology are considered as dispersed sources, named DG I and DG II. Each has rated power of 28.1 MVA and is separately coupled into the

11 kV bus through 33/11 kV transformers. The grid load in the Smart Grid zone is 1 MW, while the maximum load of the DGs is 23 MW. In addition to the test system described above, it requires a control device that is fast and reliable. In this investigation two controllers are considered to make the grid ‘smarter’:

- SVC controller; and
- power-frequency controller.

4.2.1 SVC Controller

The SVC controller, which is termed in this network as ‘Static VAR System’ (SVS), is installed in the grid at the mid-point of bus 2. The main objective of SVS is for system stability, such as during interconnection of distributed generation or fault by supplying or absorbing reactive power into the network. Figure 4.2 shows the Dig-SILENT library model of SVS control frame used in this simulation [55]. It is based on the IEEE model, consisting of TCR and TSC. The SVS has two types of control mode operation:

- Q control mode, where SVS controls reactive power according to a Q set-point; and
- voltage control mode, where the SVS monitor or control the voltage.

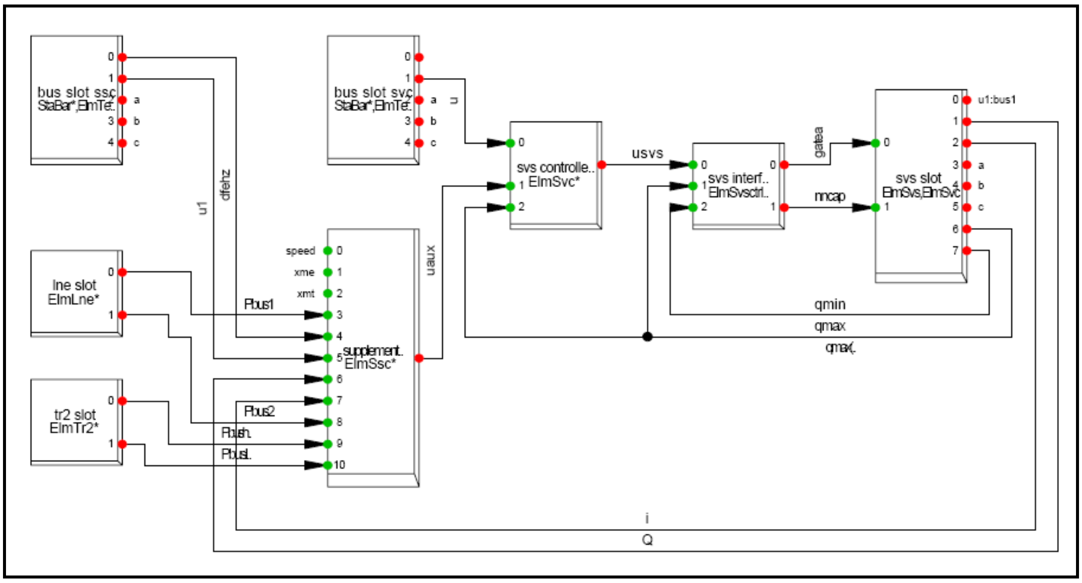

Figure 4.2: SVS control frame [55]

Figure 4.2 shows that the measurement element (ElmSsc*) obtains current, active and reactive power, voltage and other signals from the power system. The measurement system objective is to ensure that all inputs are proportional for stable operation as required by the system. These signals are then transferred to the SVS controller element (ElmSvc*), which has two distinct mode controls: voltage and reactive power control. The voltage control system aims to keep the voltage within acceptable limits, especially at PCC, since it is vital for voltage regulation of the systems. To perform this, the voltage controller processes all measured input variables and creates an output signal that is proportional to reactive-power compensation. The measured variables are compared with the voltage reference signal, and the error becomes an input variable for the controller. The output of the controller creates a per-unit susceptance signal to reduce undesired signal error to zero in the steady state operation; afterward the signal is transferred to the gate-pulse generation. The output signal derived from the voltage regulator is transferred to the gate-pulse generation, which creates proper firing pulses for TCR-TSC of the SVC slot, subsequently the undesired susceptance signal is rectified and the desired susceptance output is available at the SVC bus.

The SVS data and control parameters used in this simulation are summarised in Tables 4.1 and 4.2 respectively.

Table 4.1: Static VAR System parameters

TCR	Q Reactance (>0)	3 MVAR
	TCR Max Limit	3 MVAR
TSC	Max Number Capacitors	2
	Q per Capacitor Unit (<0)	-2 MVAR

Table 4.2 Static VAR System control parameters

Control Mode	Setting Point
Q Control	2 MVAR
V Control	1.0 p.u

4.2.2 Power-Frequency Controller

Following DG connection and disturbance, power system frequency can drop quickly if the system becomes imbalanced between the electrical load and the supplied power. Any short-term imbalance will result in an instantaneous change in system frequency. Major losses of synchronism in the system without any adequate response can lead to large frequency deviation outside of the allowed range. Therefore, two power-frequency controllers are used for independent control of DGs. The main objective of this secondary controller is to maintain power balance exchange between distributed generation and Smart Grid during integration. The default controller snapshot is shown in Figure 4.3

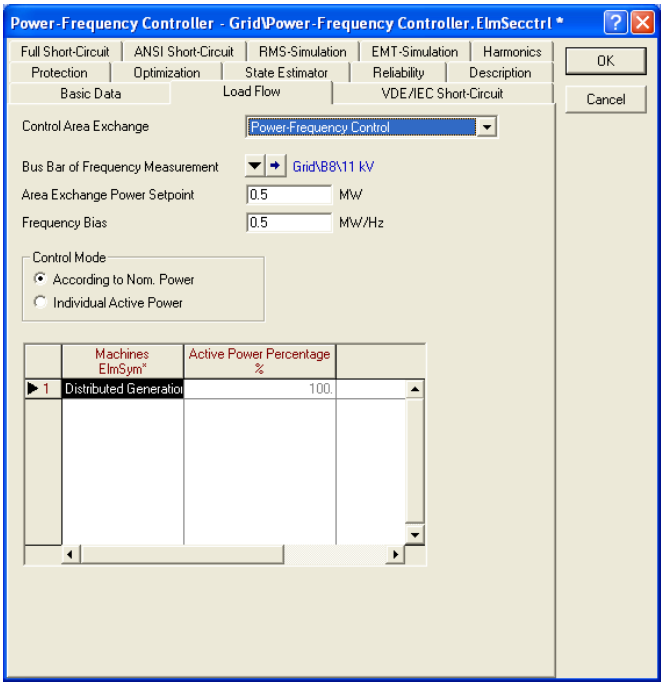

Figure 4.3: Snapshot of power frequency controller in DGs

4.3 Experimental Procedures

To observe the impact of DG on Smart Grid, one of the following primary operating parameters must be considered and satisfied:

1. The frequency, power angle and bus voltage magnitude should fall within acceptable ranges.
2. The active and reactive power losses should be minimised through reactive power flow control.
3. The voltage and transient stability is well maintained for secure power supply.
4. The phases, power factor is constant and has few interruptions.

Before observing the impact of DG on Smart Grid, the following procedure was adapted to address the three cases presented in Section 4.4. In all cases, steady state profiles have been evaluated using a load flow Newton-Raphson method. The distributed generation is modelled in PQ and PV node. The system is assumed to be in very high demand and under balanced conditions. The dynamic behaviour of loads is not considered.

Initially, during operation the voltage and frequency of the DG I is controlled by Smart Grid, thus the DG I at 11 kV bus is operated in PQ mode. Meanwhile, DG II operates independently in PV mode. For safety reasons, normally DG should not be operated in PV mode when it is connected to network. However, in this case study the operation mode of DG II is kept in PV mode when it is connected to the grid. This approach is intended to evaluate the reliability of connecting DG II to Smart Grid when DG II is modelled as PV node. In all case studies, DG II is connected to the grid at t = 4 seconds by closing the Point of Common Coupling (PCC) on bus 7 and the intertie line between GT I and GT II. In addition, to avoid system collapse due to power reactive injection or absorption from distributed generation the SVS is operated in reactive power control mode (Q mode).

4.4 Case Studies

This section provides a general overview of the case scenarios for the research and its assumption. In order to illustrate the impact of distributed generation on Smart Grid, steady state voltage analysis and transient stability analysis have been performed. The considered scenarios are as follows:

- Case 1: Steady state voltage profiles have been evaluated using a load flow Newton-Raphson method to check the voltage pattern and possibility of overloading.
- Case 2: Transient stability analysis was performed particularly when DG I and DG II are coupled into Smart Grid. The parameters being measured are frequency, voltage and power angle.

- Case 3: Transient stability analysis was performed particularly when faults occur in the system. The parameters being measured are frequency, voltage and power angle.

4.5 Experimental Results and Analysis

The subsequent section presents the results and analysis done for the simulations after following the experimental procedures. In all simulated case studies, the load flow calculation and initial system conditions have been performed successfully. At this stage, preliminary simulation shows that there was no error found in the system topology, such as over voltage or load. The default auto generated information in this regard is shown in Figure 4.4

```
DIgSI/info - Element 'Grid\Smart Grid.ElmXnet' is local reference in separated area 'Grid\B1\132 kV.StaBar'
DIgSI/info - Calculating loadflow...
DIgSI/info - -------------------------------------------------------------------------------------
DIgSI/info - Start Newton-Raphson Algorithm...
DIgSI/info - load flow iteration: 1
DIgSI/info - load flow iteration: 2
DIgSI/info - Newton-Raphson converged with 2 iterations.
DIgSI/info - Loadflow calculation successful.
DIgSI/info - Element 'Grid\Smart Grid.ElmXnet' is local reference in separated area 'Grid\B1\132 kV.StaBar'
DIgSI/info - Element 'Grid\Smart Grid.ElmXnet' is reference in 50.0 Hz-system
DIgSI/info (t=000:000 ms) - Initial conditions calculated.
```

Figure 4.4: Initial load flow and system conditions information

4.5.1 Smart Grid Steady State Voltage Profile Analysis (Case 1)

One of the main benefits of integration of distributed generation to electricity networks is an improvement of the steady state voltage profile of the system. However, voltage violation and fluctuation during the connection of distributed generation could happen and considerably influence the network transient stability. The power system operators (PSO) must verify that, in the worst situation, the networks steady state voltage variation is no greater than five per cent (p.u). This section addresses the impact of distributed generation on Smart Grid steady state voltage.

Regarding Smart Grid steady state voltage profile before employing DG I and DG II, it is assumed that in all case studies the entire system bus voltage remains constant at 1 p.u. The considered maximum and minimum voltage variation is ±5 per cent from nominal voltage. The result of steady state voltage profile obtained for all buses after employing DG I and DG II is presented in Table 4.3.

Table 4.3 Overall Smart Grid voltage profile after employing distributed generation

	Bus 1 (p.u)	Bus 2 (p.u)	Bus 3 (p.u)	Bus 4 (p.u)	Bus 5 (p.u)	Bus 6 (p.u)	Bus 7 (p.u)	Bus 8 (p.u)
Before	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
After	1.0	0.996	0.996	0.996	0.996	0.996	0.996	0.996

It can be seen from Table 4.3 that a voltage deviation in Smart Grid still occurs due to imbalances in active and reactive power generated by the DGs during integration. However, large violations of voltages are not evident on all buses. The overall voltage remains within the allowable range, which is 0.996 p.u. From the result presented in Table 4.3, it appears that the bus 1 (SG zone) is not sensitive when DG I and DG II units are utilised in Smart Grid.

4.5.2 Smart Grid Transient Stability Analysis

The Smart Grid response following integration of distributed generation to the network steady state profile has been examined. It demonstrates that the Smart Grid steady state voltage profile is within acceptable limits, between 0.95 p.u and 1.05 p.u. Nevertheless, this condition cannot guarantee that the system remains stable if a fault occurs on the system. Therefore, it is critical to examine the Smart Grid transient stability.

Transient stability analysis is the most vital requirement for the reliability and security of power supply. It could be defined as the ability of the system to maintain synchronism when subjected to perturbation, for example due to insertion of DG, loss of generation or load and short circuit. The subsequent section investigates the Smart Grid responses after distributed generation is integrated to Smart Grid and following fault occurrence. The considered indicator for stability study is determined by analysing Smart Grid voltage magnitude, voltage angle and frequency.

4.5.2.1 Grid Connected Mode Stability Analysis (Case 2)

This section discusses Smart Grid stability during integration of distributed generation or grid connected mode stability analysis. Figure 4.5 shows that for the period of connecting DG II, the voltage level of Smart Grid at bus 132 kV changes slightly, thereby causing temporary voltage instability. However, the voltage deviation remains in acceptable range and clearly shows that within five seconds the network regains its stability. The presence of voltage instability in this case results from a progressive rise in operating slip or speed of distributed generation to restore the power and synchronising the system, especially DG II as illustrated in Figure 4.6. As a consequence, the reactive power demand by DG II is greatly increased and might cause further voltage instability if reactive power controller is not used. Therefore, during grid connected mode, the SVS is operated in Q mode to regulate and provide the reactive power support. The SVS behaviour in this regards is shown in Figure 4.7

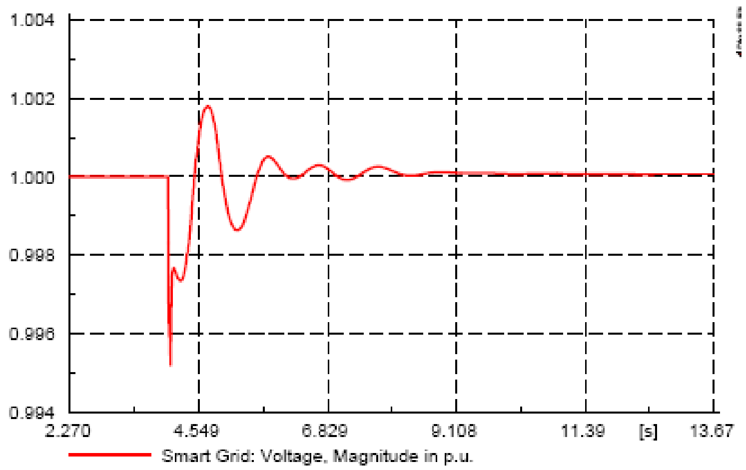

Figure 4.5: Smart Grid voltage magnitudes in p.u during integration of DGs

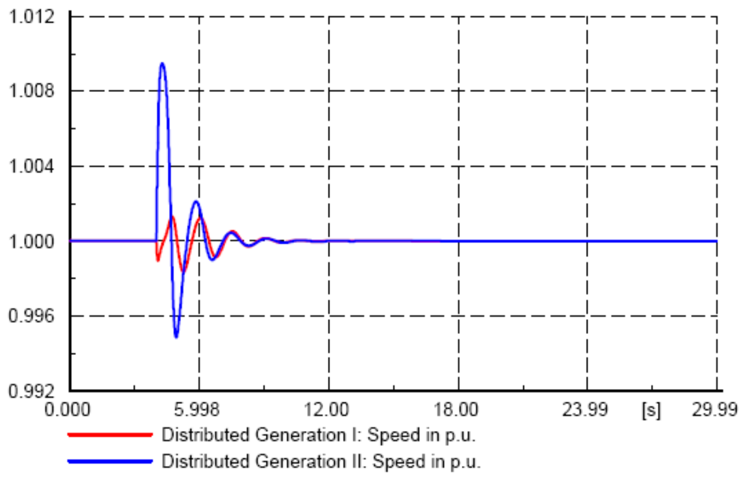

Figure 4.6: Distributed Generation speed during integration to Smart Grid in p.u

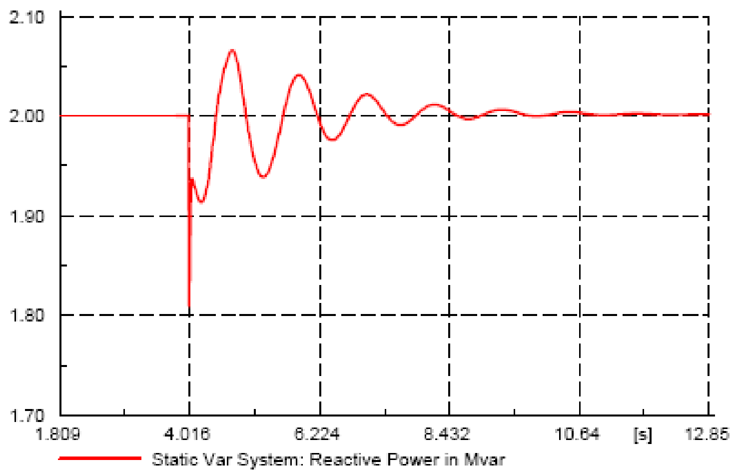

Figure 4.7: Static VAR System behaviours during integration of DGs

Following voltage imbalance, further studies were carried out to analyse the frequency stability of the Smart Grid. As illustrated in Figure 4.8, it can be seen that the frequency level increases slightly and occurs at the switching point where DG units are integrated to the Smart Grid. However, the network succeeded in maintaining a new steady frequency after integrating with DGs. In this case, the frequency rises from 50 Hz to 50.03 Hz when the PCC was closed at t = 4 seconds. Figure 4.9 shows the range of frequency deviation, which is only 0.04 Hz and is no more than ± 2 Hz from nominal 50 Hz. This frequency variation is acceptable and most of the end-users can bear this change. The Grid Code requires that the system frequency must be controlled within the limits of 47.5–52 Hz, in case the system frequency rises above the limit [56]. However, larger violations can result in network collapse, which leads to blackouts.

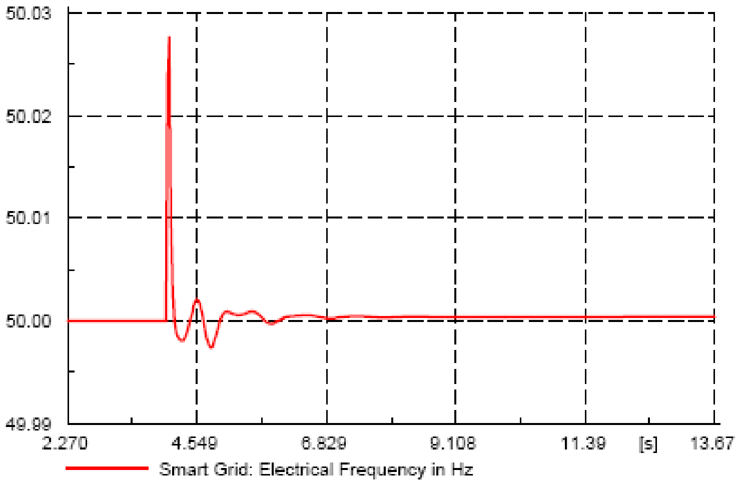

Figure 4.8: Smart Grid Frequency during integration of DGs in Hz

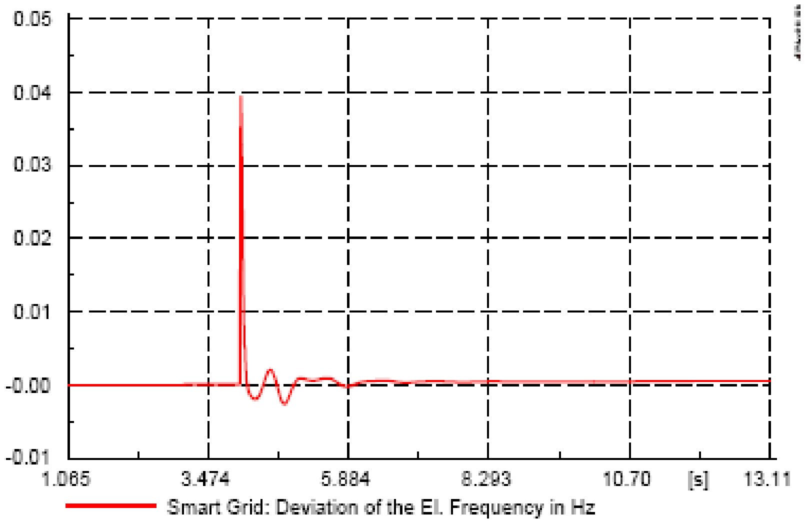

Figure 4.9: Smart Grid Frequency deviations during integration of DGs in Hz

In contrast, another indicator to asses Smart Grid transient stability during grid connected mode is the voltage angle stability. As can be seen from Figure 4.10, the integration of DGs units causes a change of voltage angle, which forces the network to operate at a new operating point and regain its stability. In this case, the maximum deviation was at t=4 seconds between 89.60° and 90.22°. The amount of reactive power absorption or injection by DGs during interconnection determines a significant response of power angle stability. If the system lacks sufficient reactive power support, it could cause an under voltage. However, it can be seen that the network returns the voltage angle back to original levels after five seconds.

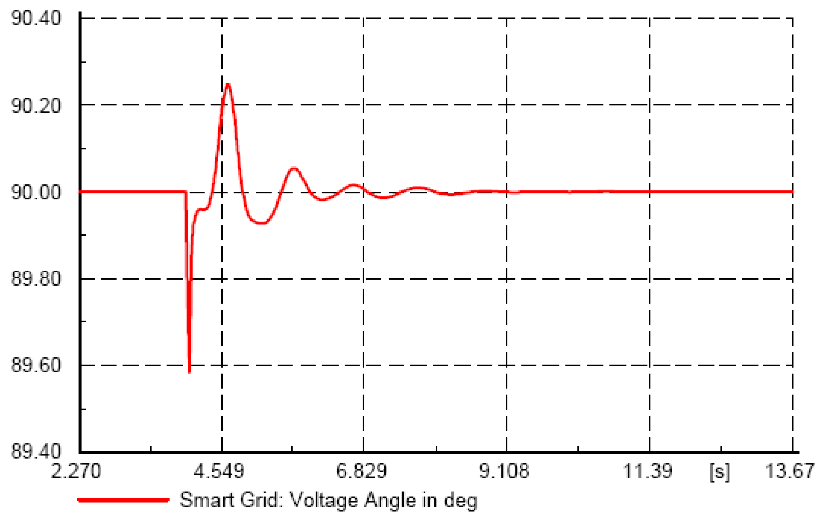

Figure 4.10: Smart Grid voltage angle during integration of DGs in degree

4.5.2.2 Three Phase Fault Stability Analysis (Case 3)

With the same network configuration and SVS connected, further Smart Grid stability is examined after the integration of DGs. The 200 ms self-clearing 3 phase fault was applied at fifteen seconds in the middle of transmission line connecting between Buses 2 and 3. The Smart Grid performance during this fault is depicted in Figure 4.11. As can be seen that during the fault, the AC voltage plunges from 1.0 to 0.986 p.u and causes the electric torque to drop. Accordingly, the DGs rotor speeds up and the reactive power absorption is greatly increased because of high rotor slip. However, due to fast dynamic power reactive support from the SVS, the Smart Grid voltage recovers within two seconds after the clearance of the fault and the system now goes to stable. The SVS response in this regard is shown in Figure 4.12

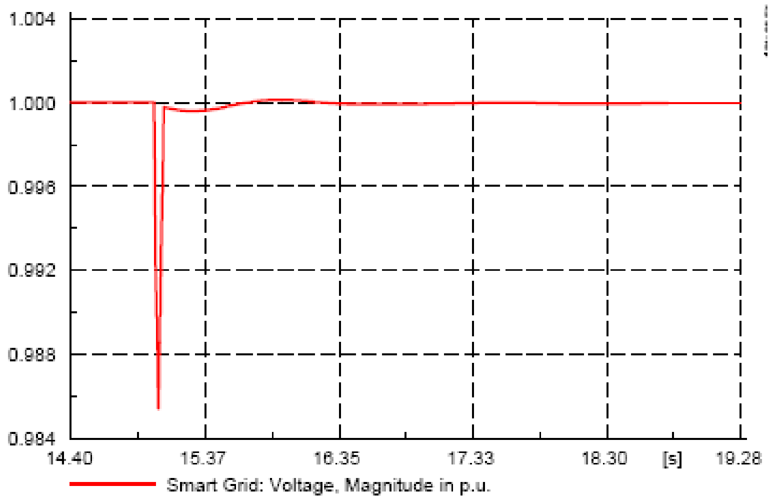

Figure 4.11: Smart Grid voltage behaviour during 3 phase fault in p.u

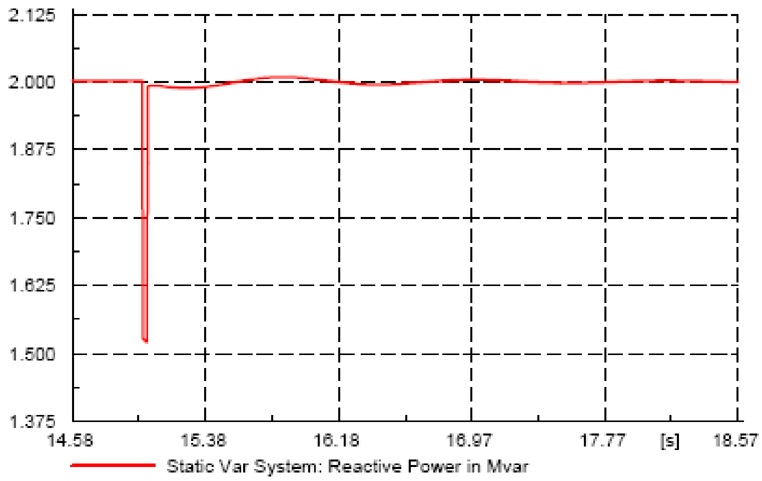

Figure 4.12: SVS behaviour during 3 phase fault in p.u

For the Smart Grid frequency stability response following the fault, Figure 4.13 indicates that during the fault, the system frequency plunges from 50 Hz to 49.996 Hz. Unfortunately, the post-fault frequency is slightly less than its nominal value between 49.998 Hz and 49.999 Hz. This phenomenon occurs as a consequence of imbalance between the electromagnetic and the mechanical torque of DGs after the fault. However, it tends not to be of significant concern. Moreover, as shown in Figure 4.14 the rotor speed is gradually reduced and equilibrium also restored gradually after the

SVS has sufficient reactive power support. Thus, the frequency level is regained to 50 Hz after about fifteen seconds

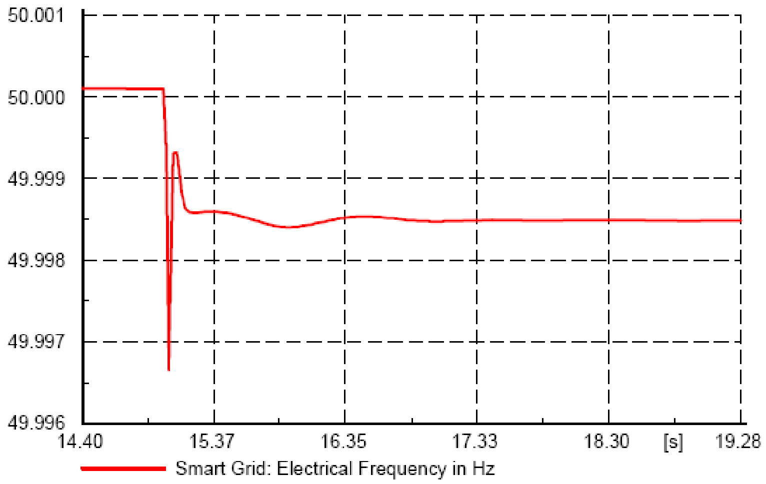

Figure 4.13: Smart Grid frequency behaviour during 3 phase fault in p.u

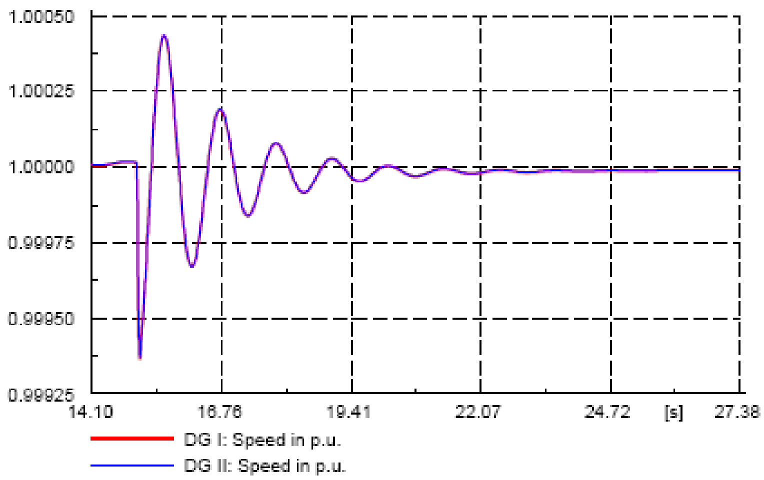

Figure 4.14: Distributed Generation speed during 3 phase fault in p.u

In contrast, as a consequence of three phase short circuit fault, the Smart Grid voltage angle dips approaching to 89.30° as depicted in Figure 4.15. This incidence leads to voltage drop as illustrated in Figure 4.11. In view of this, the change of the voltage angle will always correspond with the change of voltage and frequency limits. However, the use of SVS helps the system to maintain synchronism with the DGs during and post fault conditions. As shown in Figure 4.15, the voltage angle regains to 90° within two seconds. Thus, a new steady state value between DGs and Smart Grid is reached.

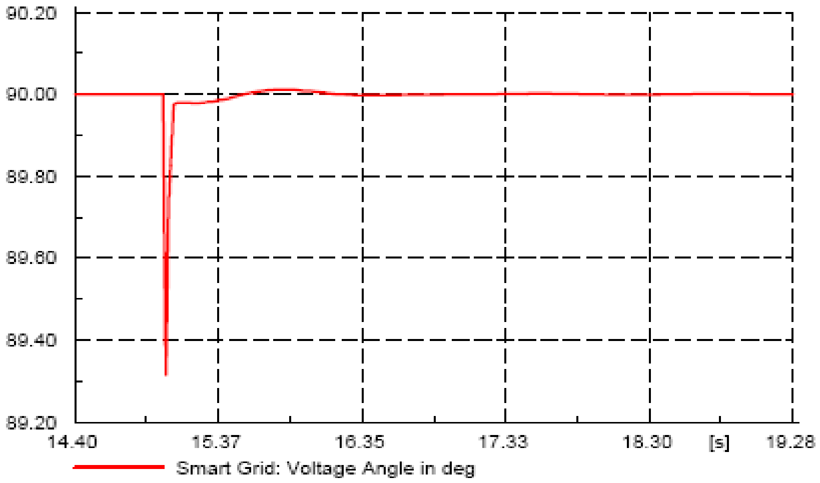

Figure 4.15: Smart Grid voltage angle behaviour during 3 phase fault in degree

4.6 Conclusion

Detailed experimental setup along with experimental procedure and experimental results have been presented in this chapter. Based on the results obtained from simulation, it is obvious that integrating distributed generation in a network requires an advanced control device such as SVS, which is critical to ensuring high reliability and stability of the power system. The next chapter presents the conclusion drawn from the results shown in this chapter and outlines the scope of future work in this area.

Chapter 5: Conclusion and Future Work

5.1 Introduction

This chapter details the major findings and achievements of this research and how the work has addressed the objectives proposed in Chapter 1. It also presents the conclusions that are drawn from the findings. Future recommendations and scope for future works are also outlined in this chapter.

Current existing electricity networks, in particular distribution and transmission systems, have been designed in radial topology with centralised generation as the main power source to supply the load. As a result, power flows from bulk generation to the end of feeder. However, with the presence of distributed generation the power flow is no longer radial but it can be reserved or meshed with the distributed generation sending power in any directions from where it is coupled. This occurrence definitely has created a series of new problems, some of them closely related to system reliability, power quality and stability. To address these impacts, various research projects have been conducted and the results have been described in Chapter 2. However, overall the research scenarios in the past were investigated on the technical impact of distributed generation of the distribution system. Moreover, none of the research scenarios dealt with the issues from a Smart Grid perspective.

Considering the rapid growth and installation of distributed generation in power system networks, it is critical to make the grid become smarter and evaluate its performance precisely under Smart Grid concept and framework. Thus, it can be applied appropriately and degradation of power quality and reliability can be avoided. The work done by Chowdhury *et al.* [54] analyses the control and operation of distributed generation based on power islanding under Smart Grid environment. Similarly, Vokony and Dan [57] examine Smart Grids in island operation. However, these works do not fully address the system transient stability. Therefore, this requires further development to see another impact from a different approach. This thesis examines the impact of distributed generation on Smart Grids, particularly from the system transient stability point of view. Ideas and findings have been reported in several publications in the 'List of Publications' section of this thesis. Section 5.2 of this chapter presents summary and the accomplished research results.

5.2 Summary and Results of the Research

The fundamental background of distributed generation and Smart Grid technologies has been presented in Chapter 2. Detailed studies on distributed generation models were investigated, which helped to understand their advantages and disadvantages. Further, the literature review provides insight into distributed generation operation issues and its technical impact on the host grid. Following such assessment and research on distributed generation systems, Smart Grid technologies, which are one of the most significant concepts and frameworks for future power system, were emphasised, concentrating on previous R&D efforts across the US and Europe. In addition, this chapter provides a comprehensive analysis into seven Smart Grid frameworks that need to be addressed to make the future electricity grid smarter. These include bulk generation, transmission, distribution, customer, operation, markets and service providers. A brief impression on Smart Grid barriers including technical, regulatory and economical was also discussed. Finally, the elaboration of basic Smart Grid transient stability analysis was described in last section of Chapter 2.

An overview of the fundamentals of power compensation for system stability and use of FACTS as Smart Grid devices has been presented in Chapter 3. It provides essential understanding of its model and benefit. Mathematical analysis to prove the advantages of SVC on enhancing system stability has been discussed through equal area criterion analysis.

The most important work in this thesis has been presented in Chapter 4. The experimental setup is described and developed. After successful development of the Smart Grid topology network, further work is carried out to make the grid become ‘smarter’ through the use of SVC and power-frequency controllers. In order to obtain the impact of distributed generation on the Smart Grid, three case studies on steady state profile, transient stability and self-clearing three phase short circuit have been performed. Finally, the research carried out in this work has the following results:

1. The integration of distributed generation on Smart Grid does not modify its steady state voltage behaviour. It shows that the steady state voltage deviation is still within limits although voltage oscillation is present.
2. The simulation result clearly indicates that the utilisation of SVC is able to maintain the voltage, frequency and voltage angle of the system in stability margins, following the connection of distributed generation and fault. Thus, this does not influence the Smart Grid transient stability by much. This fact is also confirmed through transient stability equal area criterion analysis in Chapter 3 that the existence of SVC helps significantly the transient stability of the system.
3. The result also shows the feasibility of integrating distributed generation on Smart Grid while its operation is in PV mode. Hence the bus voltage and frequency of distributed generation is regulated by its own controller.
4. The implementation of SVC with proper control allows the grid to be smarter, especially in terms of stability. This is because of the capability of SVC to

provide voltage enhancement by absorbing and/or supplying reactive power during integration of distributed generation and post fault conditions.

5. The results of this research shows that, in particular terms of stability and time recovery, a favourable comparison to Chowdhury *et al.* [54] and Vokony and Dan [57], which took more than eight seconds to settle after islanding. Therefore, due to its capability for successful integration of distributed generation and a rapid recovery after fault, it is suitable to be examined as Smart Grid.

5.3 Scope for Future Work

The experimental work carried out in this research analyses the impact of distributed generation on Smart Grid, particularly in the case of system stability. In this research, SVC has been chosen as an ideal Smart Grid device due to its advantages as discussed in Chapter 3. However, this work is not feasible on large power system networks, as it is difficult for the network to handle many different cases. The following research works can be undertaken as extensions to this study:

1. This work incorporated only two distributed generations. Future experimental platforms must consist of different models of distributed generation technologies to provide diverse input. It also looks at the size of distributed generation using real time data.
2. Future work could also be to look at the presence of two or more SVC controllers on the system as well as its location. Thus, the dynamic performance of the system can be analysed further. In addition, future work should also investigate the system stability if another Smart Grid device is used, for example STATCOM. With different SVC or STATCOM ratings and controls, the

system can become more complex and this obviously has an impact on network strength and stability.

3. Due to insertion of distributed generation with various power electronic converters in Smart Grids, future work could look at the system power quality concern, such as harmonic, flickers and voltage sags or dips.
4. Transient stability is of major concern towards Smart Grid development. The adoption of a Smart Grid scheme allows making the current power system smarter. However, significant research direction is required to look at the application of standards based on the Smart Grid concept that will make the grid truly a Smart Grid.

References

[1]. Lopes, J. A., Hatziargyriou, N., Mutale, J. and Jenkins, N., 'Integrating distributed generation into electric power system: A review of drivers, challenges and opportunities', *Electric Power Systems Research,* vol. 77, 2000.

[2]. Momoh, J. A., 'Smart grid design for efficient and flexible power networks operation and control', *Power Systems Conference and Exposition, PES '09, IEEE/PES*, 2009, pp. 1–8.

[3]. Katz, J. S, 'Educating the Smart Grid', *IEEE Energy 2030 Conference,* November 2008.

[4]. DeBlasio, R. and Tom, C., 'Standard for the smart grid', *IEEE Energy 2030*, Atlanta USA, November 2008.

[5]. Hammons, T. J., 'Dispersed generation and its impact in europe on power system structure and secure power system operation', *UPEC,* 2007.

[6]. Zhang, X. P., 'A framework for operation and control of smart grids with distributed generation', in *Power and Energy Society General Meeting - Conversion and Delivery of Electrical Energy in the 21st Century,* IEEE 2008, pp. 1-–5.

[7]. Hingorani, N. and Gyugyi, L., 'Concepts and technology of flexible AC transmission systems', *Understanding FACTS*, IEEE Press 2000, p. 452.

[8]. Grunbaum, R., 'Facts for voltage control and power quality improvement in distribution grids’, *Smart Grids for Distribution, IET-CIRED, CIRED Seminar*, Frankfurt, no. 4, 23–24 June 2008, pp. 1–4.

[9]. Driesen, J. and Belmans, R., 'Distributed generation: challenges and possible solutions', *Power Engineering Society General Meeting,* IEEE 2006, p. 8.

[10]. Ackermann, T. and Andersson, G., 'Distributed generation: a definition', *Electric Power Systems Research*, vol. 57, no. 3, 2001, pp. 195–204.

[11]. Lopes, J. A., Hatziargyriou, N., Mutale, J. and Jenkins, N., 'Integrating distributed generation into electric power system: A review of drivers, challenges and opportunities', *Electric Power Systems Research,* vol. 77, 2000.

[12]. El-khattam, W. and Salama, M. M. A., 'Distributed Generation Technologies, definitions and benefits', *Electric Power Systems Research*, vol. 71, 2004, pp. 119–12.

[13]. Mahadanaarachchi, V. P. and Ramakuma, R., 'Impact of distributed generation on distance protection performance: A review', *Power and Energy Society General Meeting—Conversion and Delivery of Electrical Energy in the 21st Century, 2008 IEEE*, vol., no., pp. 1–7, 20–24 July 2008.

[14]. Hatziargyriou, N. et.al., CIGRE Technical brochure on 'Modelling new forms of generation and storage', TF 38.01.10, November, 2000.

[15]. Lopes, J. A., 'Integration of dispersed generation on distributed networks-impact studies', *IEEE,* 2002.

[16]. Khoan, T. and Vaziri, M., 'Effects of dispersed generation (DG) on distribution systems', *Power Engineering Society General Meeting,* IEEE, 2005, vol. 3, pp. 2173–2178.

[17]. Calderaro, V., Milanovic, J. V., Kayikci, M. and Piccolo, A., 'The impact of distributed synchronous generators on quality of electricity supply and transient stability of real distribution network', *Electric Power Systems Research*, vol. 79, no. 1, 2009, pp. 134–143.

[18]. Jenkins, N., ‘Embedded generation’, *IEE Power Engineering Series,* no. 31, 2000.

[19]. Prata, R. A., 'Impact of distributed generation connection with distribution grids—Two case-studies', *IEEE Power Engineering Society General Meeting*, pp. 8, 2006.

[20]. Mahmood, A., Aamir, M. and Anis, M.I., 'Design and Implementation of AMR Smart Grid System'*, IEEE Electric Power and Energy Conference,* Canada, pp. 1–6, 2008.

[21]. Chai, C-I., Wei-Jen, L., Fuangfoo, P., Williams, M. and Liao, J. R., 'System impact study for the interconnection of wind generation and utility system', *IEEE Transactions on Industry Applications*, 2005, vol. 41, no. 1, pp. 163–168.

[22]. Kumar, A. A., Massannagari, A. R., Srivastava, A. K. and Schulz, N. N., 'Impact of biomass based distributed generation on electrical grid', *Clean Technology 2008*, pp. 222–225.

[23]. Lui, T. J., Stirling, W. and Marcy, H. O., 'Get smart', *Power and Energy Magazine, IEEE*, vol. 8, no. 3, pp. 66–78, May-June 2010.

[24]. Gellings, C. W., Samotyj, M. and Howe, B., 'The future's smart delivery system [electric power supply]', *Power and Energy Magazine, IEEE*, vol. 2, no. 5, pp. 40–48, September-October 2004.

[25]. European Technology Platform Smart Grid, 'Strategic research agenda for Europe's electricity networks for the future', European Commission, Directorate General for Research, Directorate Energy, 2007.

[26]. Roncero, J. R., 'Integration is key to smart grid management', *Smart Grids for Distribution, 2008. IET-CIRED. CIRED Seminar*, vol., no., pp. 1–4, 23–24 June 2008.

[27]. 'Grid 2030 – A National Vision fro Electricity's Second 100 Years', US Department of Energy, Office of Electric Transmission and Distribution, July 2003, available from http://www.oe.energy.gov/DocumentsandMedia/Electric_Vision_Document.pdf.

[28]. National Institute of Standard and Technology website, available from http://www.nist.gov/smartgrid/.

[29]. GridWise® Alliance website, available from http://www.gridwise.org/.

[30]. GridWise® Architecture Council website, available from http://www.gridwiseac.org/.

[31]. Title XIII—Smart Grid, Energy Independence and Security Act of 2007, available from http://www.nist.gov/smartgrid/upload/EISA-Energy-bill-110-140-TITLE-XIII.pdf.

[32]. Electric Power Research Institute website, available from http://intelligrid.epri.com/.

[33]. European Technology Platform Smart Grid website, available from http://www.smartgrids.eu/.

[34]. European Technology Platform Smart Grids, 'Strategic research agenda for Europe's electricity networks of future', European Commission, Directorate General for Research, Directorate Energy.

[35]. iGrid CSIRO, 'Industry Forum', *Introducing the Intelligent Grid: the Vision and the Research,* Adelaide 5 December 2008.

[36]. NIST Special Publication 1108 on the January 2010, 'NIST framework and roadmap for smart grid interoperability standard, release 1.0', Office of the National Coordinator for Smart Grid Interoperability, National Institute of Standard and Technology, U.S Department of Commerce.

[37]. SEL website, available from http://www.selinc.com/mirroredbits/.

[38]. De La Ree, J., Centeno, V., Thorp, J. S. and Phadke, A. G., 'Syncrhonized phasor measurement applications in power systems', *IEEE Trans. On Smart Grid,*. vol. 1, no. 1, pp. 20–27, June 2010.

[39]. Schewizer Engineering Laboratories, 'The syncrophasor report', available from https://tesla.selinc.com/emailmarketer/display.php?M=12626&C=7114023c0fe9099bf0e911a246630d60&S=250&L=7&N=216.

[40]. Hidayatullah, N. A., Paracha, Z. J. and Kalam, A., 'Impacts of distributed generation on smart grid', *International Conference of Electrical Energy and Industrial Electronic System (EEIES)*, Malaysia 7–8 Dec. 2009.

[41]. Griinbaum, R., Halonen, M. and Stromberg, G., 'SVC for 69 kV direct grid connection', *Transmission and Distribution Conference and Exposition, 2008. T&D. IEEE/PES*, vol., no., pp. 1–7, 21–24 April 2008.

[42]. Fan, J. and Borlase, S., 'The evolution of distribution', *IEEE Power & Energy Magazine*, March-April 2009.

[43]. Aggarwal, A., Kunta, S. and Verma, P. K., 'A proposed communications infrastructure for the smart grid', *Innovative Smart Grid Technologies (ISGT), 2010*, vol., no., pp. 1–5, 19–21 Jan. 2010.

[44]. Nagesh, D. Y. R., Krishna, J. V. V. and Tulasiram, S. S., 'A real-time architecture for smart energy management', *Innovative Smart Grid Technologies (ISGT), 2010*, vol., no., pp. 1–4, 19–21 Jan. 2010.

[45]. Jin-Shyan Lee and Yang-Chih Huang, 'ITRI ZBnode: A ZigBee/IEEE 802.15.4 platform for wireless sensor networks', *Systems, Man and Cybernetics, 2006. SMC '06. IEEE International Conference on*, vol. 2, no., pp. 1462–1467, 8–11 Oct. 2006.

[46]. GridWise Architecture Council, 'GridWise Architecture Council', available from http://www.gridwiseac.org.

[47]. Kundur, P., Paserba, J., Ajjarapu, V., Andersson, G., Bose, A., Canizares, C., Hatziargyriou, N., Hill, D., Stankovic, A., Taylor, C., Van Cutsem, T. and Vittal, V., 'Definition and classification of power system stability IEEE/CIGRE joint task force on stability terms and definitions', *Power Systems, IEEE Transactions on*, vol. 19, no. 3, pp. 1387–1401, Aug. 2004.

[48]. Zhang, X. P., 'A framework for operation and control of smart grids with distributed generation', in *Power and Energy Society General Meeting—Conversion and Delivery of Electrical Energy in the 21st Century,* IEEE 2008, pp. 1–5.

[49]. Padiyar, K. R., 'Facts controllers in power transmission and distribution', New Age International (P) Ltd Publisher 2009, p. 532.

[50]. Watanabe E. H. et al., 'Flexible AC transmission system', *Power Engineering Handbook*, Elsevier Inc., 2007.

[51]. Marthur, R. M. and Varma, R. K., *Thyristor-based FACTS controllers for electrical transmission systems*, IEEE press 2002, p. 493.

[52]. Sastri Vedam, R and, Sarma, M. S., *Power quality VAR compensation in power sytems*, CRC Press 2009 pp. 268.

[53]. Potter, C. W., Archambault, A. and Westrick, K., 'Building a smarter smart grid through better renewable energy information', in *Power Systems Conference and Exposition, PES '09, IEEE/PES*, 2009, pp. 1–5.

[54]. Chowdhury, S. P., Chowdhury, S., Ten, C. F. and Crossley, P. A., 'Operation and control of DG based power island in Smart Grid environment', *Electricity Distribution—Part 1, 2009. CIRED 2009. 20th International Conference and Exhibition on*, vol., no., pp. 1–5, 8–11 June 2009.

[55]. Dig-SILENT Power Factory Software 13.2.

[56]. *The Grid Code*; Issue 4 Revision 3, National Grid Electricity Transmission plc, London, 2010.

[57]. Vokony, I. and Dan., A., 'Examination of smart grids in island operation', *IEEE Bucharest Power Tech Conference,* July 2009.