

POWER QUALITY IMPROVEMENT USING ENERGY
STORAGE FOR DISTRIBUTION NETWORKS WITH
RENEWABLES

WONG JIANHUI

MASTER OF ENGINEERING SCIENCE

FACULTY OF ENGINEERING SCIENCE
UNIVERSITI TUNKU ABDUL RAHMAN

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ABSTRACT

POWER QUALITY IMPROVEMENT USING ENERGY STORAGE FOR DISTRIBUTION NETWORKS WITH RENEWABLES

Today's climate change and the increased fossil fuel consumption have led to the emergence of Green Technology. Green Technology application is one of the sensible solutions which are being adopted by many countries around the world to address the issues of energy and environment simultaneously. Building Integrated Photovoltaic System (BIPV) has been categorized as one of the Green Technologies and it is likely to become the dominant type of renewable energy source in the Malaysian low voltage (LV) distribution network due to its abundant solar energy as well as the initiative and efforts taken by the Malaysian government to promote and embrace the renewable energy technology. However, the design of the networks does not take into account the installation of anticipated growth of BIPV system which allows bi-directional flow but only designed to accommodate unidirectional flow of current.

The growth of the Building Integrated Photovoltaic System (BIPV) systems in low voltage distribution network has the potential to impose several technical issues including the power quality and distribution system efficiency due to the possibility of reverse power flow when aggregate amount of PV systems are connected. The possible technical issues are listed as follows:-

- i) Voltage regulation and voltage rise,
- ii) Voltage unbalance,
- iii) Network power losses, and

iv) Cable and transformer thermal limits.

The thesis proposes an integrated energy storage unit with a four-quadrant converter and a control algorithm for mitigating voltage unbalance factor as well as improving the efficiency of the network. In the study, power system simulation tool, namely PSCAD, is used to model two generic low-voltage distribution networks, BIPV systems and an energy storage system in order to simulate the performance of the networks with various levels of BIPV penetrations. A control algorithm is developed and implemented into the energy storage model in order to study the improvement of the network after the energy storage system is used. The simulation carried out shows the effectiveness of the energy storage unit in reducing voltage unbalance and improving the efficiency of the networks.

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FACULTY OF ENGINEERING AND SCIENCE

UNIVERSITI TUNKU ABDUL RAHMAN

Date: 5th September 2011

SUBMISSION OF THESIS

It is hereby certified that WONG JIANHUI (ID No: 09UEM09118) has completed this thesis entitled **POWER QUALITY IMPROVEMENT USING ENERGY STORAGE FOR DISTRIBUTION NETWORKS WITH RENEWABLES** under the supervision of **DR. LIM YUN SENG** (Supervisor) from the Department of Physical Science, Electrical and Electronic Engineering, Faculty of Engineering and Science, and **DR. STELLA MORRIS** (Co-Supervisor) from the Department of Physical Science, Electrical and Electronic Engineering, Faculty of Engineering and Science.

I understand that University will upload softcopy of my thesis in pdf format into UTAR Institutional Repository, which may be made accessible to UTAR community and public.

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WONG JIANHUI

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This dissertation entitled “**POWER QUALITY IMPROVEMENT USING ENERGY STORAGE FOR DISTRIBUTION NETWORKS WITH RENEWABLES**” was prepared by **WONG JIANHUI** and submitted as partial fulfillment of the requirements for the degree of Master of Engineering Science at Universiti Tunku Abdul Rahman.

Approved by:

(DR. LIM YUN SENG)

Date: _____

Supervisor

Department of Physical Science, Electrical and Electronic Engineering

Faculty of Engineering and Science

Universiti Tunku Abdul Rahman

(DR. STELLA MORRIS)

Date: _____

Co-Supervisor

Department of Physical Science, Electrical and Electronic Engineering

Faculty of Engineering and Science

Universiti Tunku Abdul Rahman

DECLARATION

I hereby declare that the dissertation/thesis is based on my original work except quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at UTAR or other institutions.

Name: WONG JIANHUI

Date: 5th September 2011

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LIST OF ABBREVIATIONS

ASDs	Adjustable speed drives
BIPV	Building integrated photovoltaic system
C	Battery capacity
CHP	Combined heat and power
CO ₂	Carbon dioxide
DG	Distributed generators
DNOs	Distribution network operators
DOD	Depth of discharge
EHV	Extra high voltage
FACTS	Flexible AC transmission system
FFT	Fast Fourier transform
GEO	Green energy office
HV	High voltage
IEC	International electrotechnical commission
IGBT	Insulated-gate bipolar transistor
LV	Low voltage
LVDB	Low voltage distribution board
MBIPV	Malaysian building integrated photovoltaic
MV	Medium voltage
NEMA	National electrical manufacturer association
PF	Power factor
PTM	Pusat Tenaga Malaysia
PV	Photovoltaic
Q	Charge delivered by the battery
RMS	Root mean square
SOC	State of charge

LIST OF ABBREVIATIONS

SREP	Small renewable energy program
SSEZ	Small scale energy zones
STATCOM	Static synchronous compensator
SVC	Static VAr compensator
TCSC	Thyristor controlled series capacitor
Tx	Transformer
UPS	Uninterruptible power supply
VCU	Voltage control unit
VPS	Virtual power station
VR	Voltage regulation
VSC	Voltage source converter
VUF	Voltage unbalance factor

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CHAPTER 1

INTRODUCTION

1.1 Research Background

Today's climate change and the increased fossil fuel consumption have led to the emergence of Green Technology. Green Technology application is one of the sensible solutions which are being adopted by many countries around the world to address the issues of energy and environment simultaneously.

Building Integrated Photovoltaic System (BIPV) has been categorized as one of the Green Technologies and it is likely to become the dominant type of renewable energy source in the Malaysian low voltage (LV) distribution network due to its abundant solar energy as well as the initiative and efforts taken by the Malaysian government to promote and embrace the renewable energy technology. However, the design of the networks does not take into account the installation of anticipated growth of BIPV system but only designed to accommodate unidirectional flow of current instead of bi-directional flow. This network configuration has the potential to impose

several technical issues related to power quality and distribution system efficiency such as (Cipcigan, L., et. al., 2009; P. F. Lyons, et. al., 2009): i) voltage regulation, ii) voltage rise, iii) voltage unbalance, iv) network power losses, and v) cable and transformer thermal limits.

There are several ways to compensate and mitigate the reactive power in the power network, such as the shunt and series compensation (R. Mohan Mathur et. al., 2002). Series devices such as TCSC (Thyristor controlled series capacitor) inject a voltage with a controllable angle in series with the line controls the real and reactive power flow. Whereas, shunt devices such as SVC (Static VAr Compensator) and STATCOM (Static Synchronous Compensator) inject a current with a controllable angle which controls real and reactive power flows. STATCOM uses shunt capacitors to increase the power-transfer capacity, to compensate the reactive voltage drop in the line, reduce flickers and harmonics and hence mitigate the power stability issues of the power system. STATCOM is categorized as one of the FACTS (Flexible AC Transmission System) devices, a concept of power flow control through AC transmission lines. Therefore, STATCOM is commonly used on the transmission networks. STATCOM utilizes VSC (Voltage Source Converter) as main component connected to the network through a transformer as shown in figure 1.1. The dc link voltage is provided by capacitor which is charged with power taken from the network. The control system ensures the regulation of the

bus voltage and the dc link voltage. Application of STATCOM has been widely discussed in Chen Shen et. al. (2000) and Z. Yang et. al. (2001)

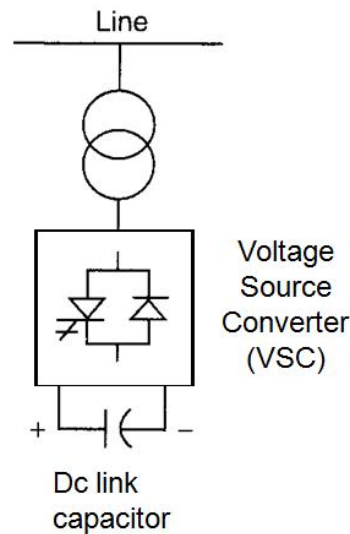


Figure 1.1 Diagram of a STATCOM (Static Synchronous Compensator)

PV systems installed in Malaysian network are in single phase. When a high penetration of single phase PV systems occurs, voltage unbalance factor in the LV distribution network are likely to hit the limit. Furthermore, most countries apply plug and inform system, whereby customers are allowed to install the PV systems in advance and inform the utility companies later. This might lead to the possibility that majority of the PV systems are installed in one phase, hence creating a number of technical issues such as voltage rise, voltage unbalance, increase in power losses and reverse power flow.

Specially designed FACTS devices are presently used in the MV and LV networks to provide voltage control. These systems are very expensive at present (Padraig Lyons, 2009). Alternatively, this research project introduces a

new approach of using a four quadrant converter integrated with energy storage in order to deliver/absorb the real and reactive power flow in the distribution network for voltage correction as well as to enhance the power efficiency within the LV distribution level. Initially, the impacts of high penetration level of PV on LV distribution networks are investigated based on two case study networks in Malaysia.

1.2 Research Objectives

The main objectives of this work are listed as follows:-

- i To use PSCAD/EMTDC to model commercial and residential LV distribution networks.
- ii To investigate the impact of anticipated amount of PV connected onto the two networks.
- iii To quantify the allowable PV capacity on the case study networks without violating any of the limit.
- iv To design and develop an energy storage unit integrated with four quadrant converter in order to mitigate the power quality issues cause by the anticipated amount of PV.
- v To evaluate the designed energy storage unit and increase the penetration of renewable energy sources on the network

1.3 Research Methodology

The research was carried out using simulation approach to study and determine the characteristics and technical issues of Malaysian LV distribution network in an urban area under an anticipated penetration of PV systems on the networks.

Step 1: Literature review was carried out to explore the design and characteristics of Malaysian LV distribution network, modeling approach of the PV system, existing methods to mitigate the power quality issues within LV distribution system.

Step 2: Simulation software namely, PSCAD/EMTDC (Power System Computer Aided Design/ Electromagnetic Transients including DC) was used to perform the work. The work was carried out in two stages. The first stage of the work was to model two urban LV distribution networks for commercial and residential area in Aman Jaya based, on the layout diagram and network characteristics obtained from the Peninsular utility company, namely Tenaga Nasional Berhad, TNB.

Step 3: The study was to investigate the technical issues arising due to an anticipated amount of distributed generation, i.e. PVs are connected on the LV distribution networks.

Step 4: A range of studies was performed to determine the effects of anticipated amount of PVs on the voltage rise, power flow, voltage unbalance factor and

the equipment thermal limit. PV systems are most likely to be single phase and connected to the LV distribution networks through “install and inform” principle by customers. Therefore, during the first stage of the simulation, PV systems distributed uniformly and non-uniformly will be studied.

Step 5: Modeling the four-quadrant converter integrated with energy storage in PSCAD/EMTDC. Developing a control algorithm for controlling the operation of the four-quadrant converter based on the operating conditions of the distribution networks.

Step 6: Generating and analyzing the results from the computer models in order to identify the effectiveness of using the energy storage system in mitigating the technical issues.

1.4 Scope of Thesis

The structure of the thesis is outlined in the following manner:

Second chapter summarises the findings from the literature review on the characteristics and design of the Malaysian LV distribution networks, common power quality issues, the existing technologies and methods used to mitigate power issues within LV distribution level and the storage technologies and applications.

Chapter three presents the details of the modeling approach for commercial and residential LV distribution networks and the PSCAD model of photovoltaic system. Chapter four presents the impact of an anticipated amount of PV connected onto the LV distribution network uniformly and non-uniformly.

Chapter five describes the modeling of the energy storage unit integrated with four quadrant converter. The modeling objectives for the system are initially presented. This chapter elucidate about the approach to reduce voltage unbalance factor and enhance power efficiency within the LV distribution network. Chapter six presents the operation results of energy storage unit with respect to the technical issues associated with large penetration of PV on LV distribution networks. Voltage variations, voltage unbalance of the system and network power losses are detailed. Chapter seven discusses an experimental validation done in Durham University by using the control algorithm that was proposed in this research project. Finally, a discussion illustrating the key findings of the research is presented in chapter eight. In this chapter, the conclusions drawn as a result of the research are detailed.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

The Malaysian Prime Minister has made a commitment to achieve the goal of reducing the emission of CO₂ by 40% in the year 2020 with respect to the margin in year 2005. Moreover, the Malaysian government has encouraged the use of Green Technology by promoting a series of activities such as the Small Renewable Energy Power (SREP) Program in 2001, National Suria 1000 Program also known as the Malaysian Building Integrated Photovoltaic (MBIPV) in 2005, and recently, construction of Green Energy Office (GEO) building based on environmental friendly and green concepts. The Malaysian Government places in substantial efforts to explore and increase the utilization of renewable energies in order to reduce the Greenhouse Gases (Mahlia, 2002; Abdul Rahman Mohamed, et. al., 2005). GEO, a pilot project in Malaysia for the future sustainable office buildings has demonstrated the concept of using latest technologies while taking care of the environment. In this GEO, the PV system generates electricity for the lighting system within the office building.

In order to achieve the low-carbon margin, the government has encouraged the development of clean and green technologies including decentralized cogeneration and tri-generation plants. Furthermore, today's climate change and the increase in fossil fuel consumption have led to the emergence of Green Technology. Green Technology application is one of the sensible solutions being adopted by many countries around the world to solve the issues of energy and environment simultaneously. Building Integrated Photovoltaic System (BIPV) has been categorized as one of the Green Technologies and is likely to become the dominant type of renewable energy sources in the Malaysian low voltage (LV) distribution network due to its abundant solar energy availability as well as the initiatives and efforts taken by the Malaysian government to promote and embrace the renewable energy technology. As mentioned earlier, the design of distribution network does not take into account of the installation of anticipated growth of BIPV but only designed to accommodate unidirectional flow of current instead of bi-directional flow. The growth of BIPV system on distribution network has the potential to impose several technical issues related to power quality and network efficiency such as voltage regulation, voltage rise, voltage unbalance, reverse power flow, network power losses and cable and transformer thermal limits.

The objective of this chapter is to investigate the future challenge of connecting the anticipated amount of PV system onto the current design of LV distribution networks in Malaysia. Initially, a review of the literature related to the conventional power systems, the current design of LV distribution networks as well as the trend of PV in Malaysia was conducted. In order to study the power

quality issues that may arise, a literature review on the possible technical issues and the introduction of PV system in Malaysia was conducted. Existing methods to enhance the power quality issues are also described in this chapter. Furthermore, as the voltage source converter integrated with energy storage device seems to be one of the solutions to mitigate the power quality issues, a review on these technologies is also presented.

2.1.1 Conventional Power System in Malaysia

Utility companies in Malaysia namely Tenaga Nasional Berhad (TNB), Sabah Electricity Sdn Bhd (SESB) and Sarawak Electricity Supply Corporation (SESCO) take charge of the national grid. According to the Malaysia Power Report Quarter Q2 2008, more than 420 substations in Peninsular Malaysia are linked together extensively to the transmission network with voltage rating of 132kV, 275kV and 500kV.

This research is focused only on the Peninsular Malaysia. Therefore, a brief introduction to the TNB is given. According to the TNB Handbook, TNB is a public listed utility company, and has the dominant role in supplying electricity to the Peninsular Malaysia. TNB is charged with the following responsibilities:

- To generate, transmit, distribute, and sell energy to consumers throughout Peninsular Malaysia

- To plan, install, operate and maintain the electrical infrastructure for the generation, transmission and distribution of electricity.

Malaysia has approximately 13 gigawatts (GW) of electricity generation capacity of which 84% came from thermal and 16% is hydroelectric. These plants convert the mechanical energy of the turbine shaft into electrical energy. The national grid of Malaysia is electrically interconnected to the transmission network of the Electricity Generating Authority of Thailand via overhead lines and Singapore Power via submarine power cable through the sea.

Conventional power system has the disadvantage of high emission factor. Generally, there are several ways to reduce the CO₂ emission by replacing the conventional coal or gas based generations with renewable energy sources. Apart from generating electricity by renewable energies, nuclear power plant may be one of the approaches to generate electrical power that is free from CO₂ emission.

The transmission network voltages are 500kV, 275kV, and 132kV whilst the distribution voltages are 33kV, 11kV and 415V for 3 phase systems and 240V for single phase systems. However, in some of the region of Johor and Perak, the distribution voltages may also include 22kV and 6.6kV. The HV and EHV systems use the 3 phase configuration where the system is solidly grounded or grounded through an impedance. The HV and EHV systems utilise overhead

lines and underground cables. The LV systems are of 3 phase 4 wire type. The neutral point is solidly earthed with a combination of overhead lines, underground cables and aerial insulated cables.

The installed generation capacity in Peninsular Malaysia is increased from 19,723MW in 2008 to 21,817MW in 2009. During the 1st and 2nd quarters of year 2010, the installed generation capacity remained at 21,817MW as shown in figure 2.1. The maximum demand in Peninsular Malaysia increased from 14,007MW in year 2008 to 14,245MW in year 2009, which is a 1.7% increase. Later in the 2nd quarter of year 2010, the maximum demand has increased to 15,072MW.

The number of unscheduled interruptions reported in Peninsular Malaysia in year 2009 is reduced to 108,708 compared to 112,064 in year 2008.

Figure 2.2 shows the breakdown of the total interruptions, approximately 55% of the total unscheduled supply interruptions reported were due to fault in the network such as loose contacts, quality of work, overloading and inadequate maintenance, followed by interruptions due to unknown causes at 13.6% and interruptions due to vandalism at 12.6%. Ageing of insulation, design defect, relay malfunction and transient overload are categorized in others.



Figure 2.1 Maximum demand and installed generation capacity in Peninsular Malaysia for the first half year of 2010 (Courtesy to TNB Interim Report for the first half year of 2010)

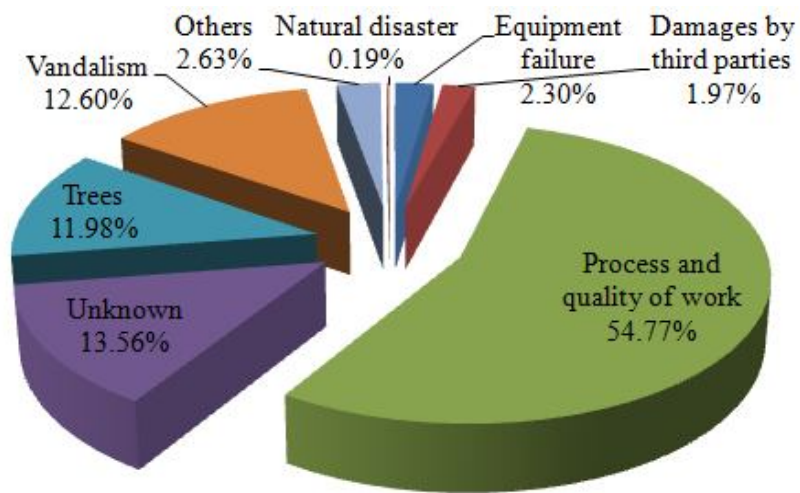


Figure 2.2 Causes of unscheduled electricity supply interruptions in Malaysia (Courtesy to TNB Interim Report for the first half year of 2010)

2.1.2 PV in Malaysia

The Malaysian government has set up a Malaysian Energy Centre (PTM), and introduced several programmes such as the SREP in the year 2001, Suria 1000 in year 2006 and has offered incentives in 8th, 9th and 10th Malaysia Plan to develop & establish the renewable energy industry and market. These include the research, development as well as the commercialisation, and renewable energy funding. PTM is a non profit organization established in year 1998 to fulfill the need for national energy research centre. It promotes the national renewable energy and energy efficiency programme under the 5th Fuel.

Furthermore, PTM coordinates and facilitates most energy research and development projects. SREP, also known as the Small Renewable Energy Power Programme for the promotion of renewable energy power generation, has been launched by the Malaysian Minister of Energy, Communications and Multimedia in the year 2001 with the aim of promoting a wider use of the huge amount of renewable energy resources available in Malaysia.

According to the Suria 1000, PTM has launched its BIPV project with a target to install a total of 1000 roof top and grid connected PV systems with a capacity of 790 kWp in the year 2006. Grid connected PV systems are often integrated into building or ground based structures whereas an off grid PV system also known as stand-alone PV system, is designed to operate at home or business without drawing any additional power from the utility company.

In the year 2005, Malaysian government has introduced MBIPV (Malaysia Building Integrated Photovoltaic) project which is partially funded by the United Nations Development Program. The objective of the MBIPV project is to reduce green house gas emission by reducing the long term cost of BIPV technology. Figure 2.3 shows the trends of cost reduction of grid connected PV system from year 2005 to year 2010. It is shown that the unit cost of grid connected PV system reduces over the years. In fact, the cost has been reduced more than what it is expected.

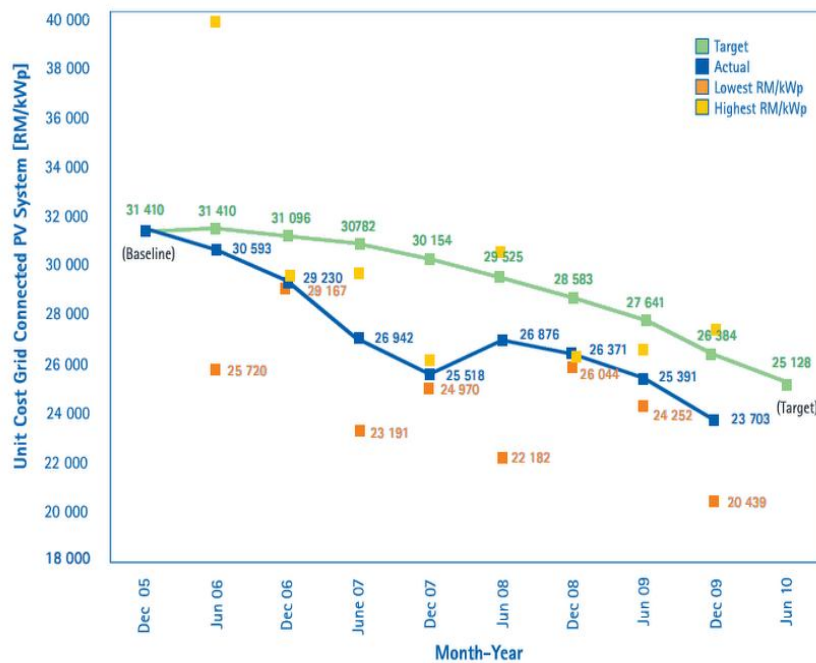


Figure 2.3 The unit cost of grid connected PV system in Malaysia (Courtesy to IEA – PVPS Annual Report 2009)

BIPV provides opportunity to utilise renewable energy sources in the urban area such as 7.36kWp by Monash University in Malaysia while 91.96kWp by Pusat Tenaga Malaysia Green Energy Office. Malaysia’s tropical climate offers a good potential for PV systems as the average daily isolation for most area in

the country is between 4.5 to 5.5 kWh/m² as shown in figure 2.4 (Ali Askar Sher Mohamad, Jagadeesh Pasupuleti, Abd. Halim Shamsuddin, 2009). Malaysia has a steady solar radiation throughout the year. The only problem in Malaysia is the rainy and humid climate which caused most of the sunlight to be diffused instead of direct.

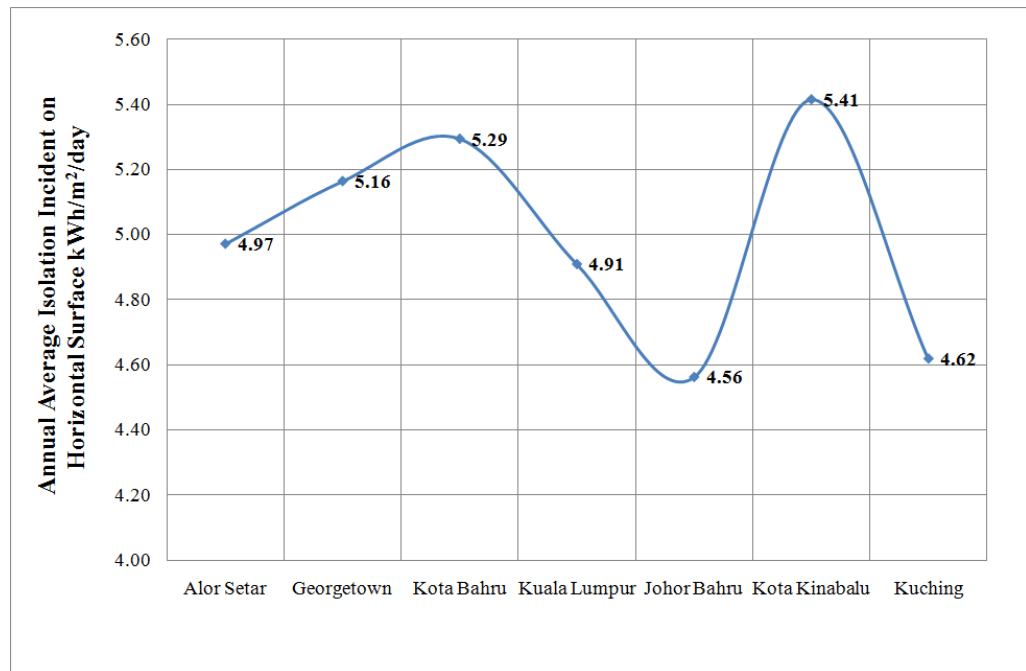


Figure 2.4 The annual average isolation incident on horizontal surface in various city of Malaysia.

The 8th Malaysia Plan on Energy Policy has included several incentives to promote clean energy. This has indirectly promoted PV system as it generates clean and renewable energy from the sunlight. Furthermore, feed-in tariff and renewable energy fund have been included in the latest 10th Malaysia Plan in year 2010. As the government believes feed-in tariff is seen as a step in the right direction to promote renewable energy.

According to the IEA (International Energy Agency) Photovoltaic Power System Annual Report 2009, Malaysia has a cumulative installed grid connected PV capacity of approximately 1063kW and off grid PV capacity of about 10MW. In future, the Malaysian PV market will have a modest growth once the feed-in tariff is introduced and PV will be one of the most promising renewable energy sources.

With all these issues mentioned above and with the current design of our LV distribution network, it is worth to investigate the technical issues that will arise if anticipated amount of the PV systems are to be connected onto the weak network in near future. Later, a proposed method by using energy storage unit to mitigate the power quality issues will be discussed in Chapter 4.

2.2 Power Quality Issues

Thomas S. Basso (2008) has identified several technical issues that might arise when a high penetration of large PV and wind turbine systems is considered at the distribution level such as, the issues related to voltage regulation, power quality such as harmonics, flicker, load and generation imbalance. This paper has pointed out that PV connected at distribution level mainly relate to feeder level issues such as the power flows, protection and voltage impacts.

Farid Katiraei, Konrad Mauch, and Lisa Dignard-Bailey (2006) have discussed about the high penetration of photovoltaic power systems in distribution networks and mini-grids. The results data for the analysis were from participating International Energy Agency (IEA) member countries. The paper has identified major power quality issues such as voltage variation, and current harmonics. The presence of multiple PV inverters in a distribution network can potentially increase the total amount of current harmonics injected into the grid. Loo Chin Koon and Abdul Aziz Abdul Majid, (2007) have discussed the guidelines and recommendations of various technical issues such as network losses, voltage regulation and control, fault level and etc. to ensure the system reliability and efficiency when DG are connected.

John Olav Gioever Tande (2000) has identified that injection of wind power into a distribution system affects the voltage quality. The most common voltage quality constraints are related to maintaining steady state voltage level and the emission of flickers within the limits. There are several solution to overcome these constraints, such as reinforcement of new distribution lines, regulation of reactive power and introduction of load management. However, local conditions of the distribution network should be considered before any solution is applied.

2.2.1 Voltage Rise and Voltage Regulation

The installation of DG onto the weak network can impact the overall voltage profile of the system. In addition, voltage rise can become a problem when the demand is minimum and power generation of a DG is maximum. Furthermore, voltage rise has been identified as a problem in future networks with high concentrations of DG (S. Conti, S. Raiti, and G. Tina, 2003; Philip P. Barker, Robert W. de Mello, 2000). These papers have analyzed the impacts of DG on voltage regulation, losses, as well as voltage flickers and harmonics. The papers explained that distribution system designs and operating practices are normally based on radial power flows. The papers have also described that the size and location of the DG, the voltage regulator settings and impedance characteristic of the line must be considered. So that the installation of DG onto the distribution network will not degrade distribution system quality, safety and reliability. This is due to the reason that DG can confuse the voltage regulator settings and can cause the voltage to deviate above or below the permissible range.

Padraig Lyons (2009) has identified voltage rise issue has become major concern in the UK LV network. P. F. Lyons, P. Trichakis, P. C. Taylor, G. Coates, (2009) have presented an implementation of a control approach to overcome steady state voltage rise and voltage drop. R. C Dugan, Thomas E. M (2002) have discussed the operating conflicts and voltage regulation issues that often arise from the application of distributed generation on distribution

systems. The authors believe that the systems were designed for unidirectional flow and as the penetration of DG increases, several voltage conflicts would arise. The impact of high penetration of distributed generation on LV distribution network has been widely discussed by the researchers in the UK and European countries (Murray Thompson and David. G. Infield, 2007; Rafael Amaral Shayani and Marco A. G. de Oliveira, 2010). Table 2.1 shows the mean voltage for various PV and CHP (combined heat and power) penetration. The data has quantified voltage rises caused by the installation of DG in different levels of penetration. The 1st row of the data shows the base case where there is no installation of DG and the other rows show the impact at different levels of DG penetration. Consequently, as the penetration of DG increases, the voltage level increases as well.

Penetration (%)		Mean Voltage (V)	
PV	CHP	Winter	Summer
0	0	239.7	246.2
50	0	240.7	247.6
0	100	243.6	247.2
50	100	244.5	248.6
30	0	240.3	247.0
0	23	240.7	246.5
28	23	241.2	247.2

Table 2.1 Mean voltages for various PV and CHP penetration (Murray Thompson and David G. Infield, 2007)

Farid Katiraei, Konrad Mauch, and Lisa Dignard-Bailey (2006) conclude that a high penetration of PV installed at the end of a long feeder may cause an

adverse effect on voltage profile of the network and hence a tangible voltage rise beyond the acceptable limit at the point of PV neighbourhood connection.

2.2.2 Voltage Unbalance

In a three phase network, voltage unbalance takes place when the magnitude of each phase voltage is different or the phase angle between any two phase voltages differs from the balanced conditions. In general, voltage unbalance can be defined in two different ways. According to the NEMA (National Electrical Manufacturer Association), voltage unbalance can be defined as the ratio of maximum deviation of the three-phase line voltages to the mean of three-phase line voltages. The IEC (International Electrotechnical Commission) defines voltage unbalance as the ratio of negative sequence voltage component to the positive sequence voltage component. The greatest effect of voltage unbalance could cause damage to induction motors due to excessive heat. When a three-phase induction motor is supplied by an unbalanced system, the resulting line currents show a degree of unbalance that is several times the voltage unbalance.

P. Trichakis, P. C. Taylor, L.M. Cipcigan, P. F. Lyons, R. Hair, T. Ma (2006) have investigated the voltage unbalance in UK LV networks with high penetration of small scale embedded generators. The paper has revealed that voltage unbalance has a potential to become serious concern for distribution network operators since the distribution of small scale embedded generators are

not centrally planned. According to the IEC standard, a voltage unbalance can create 6 to 10 times the current unbalance. Consequently, the current unbalance can create unnecessary heat in the motor windings that degrade the performance and shorten the lifespan of the induction motor. Table 2.2 illustrates how voltage unbalance affects the current and temperature rise of a typical three-phase electric motor rated 5hp, 230V, and 1725rpm.

Characteristic	Performance		
Average voltage	230 V	230 V	230 V
Percentage of unbalanced voltage	0.3	2.3	5.4
Percentage of unbalanced current	0.4	17.7	40.0
Increased temperature rise °C	0	30	40

Table 2.2 Voltage unbalance effects on a typical electric motor (Thomas H. Bishop, 2008)

Figure 2.5 shows the percentage of the expected temperature rise versus the amount of voltage unbalance. From the graph, it is seen that the temperature rise increases exponentially as the voltage unbalance is increased. Apart from producing unnecessary heat in the motor winding, a voltage unbalance can introduce harmful harmonic currents into the system.

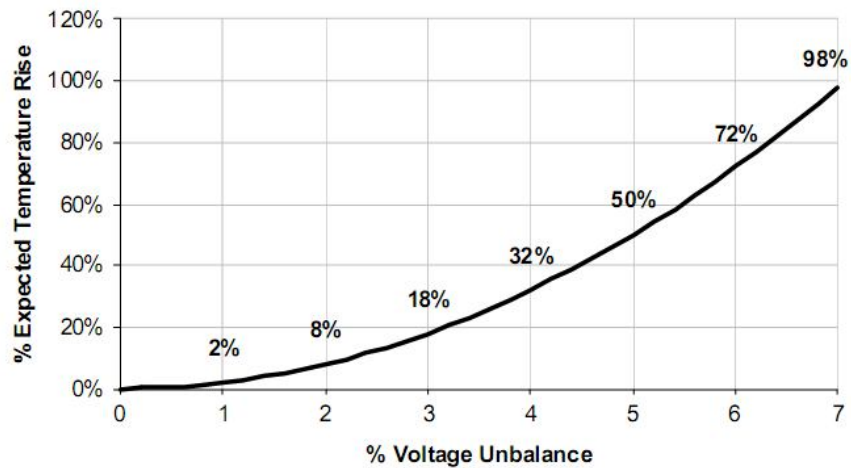


Figure 2.5 Percent temperature rise due to voltage unbalance (courtesy to Pacific Gas and Electric Company report)

Furthermore, voltage unbalance will cause extra loads to utilities and additional charges to consumers. Therefore, reducing system unbalance will benefit both utilities and consumers.

2.2.3 Thermal Limit

Underground and overhead lines are the components used to deliver power from the utility to the customers. Such components usually come with a thermal rating to determine the maximum current carrying capacity. If the underground or overhead lines are loaded with a high current, which violate its thermal limit, it will overheat and cause permanent damage. With a high penetration of DG into the distribution network, the current flow through the network tends to increase, resulting in system equipments operating closer to their thermal limits.

2.2.4 Reversed Power Flow

L. M. Cipcigan and P. C. Taylor (2007) have investigated the ability of power transformer to facilitate the required power flow associated with the anticipated high penetration of DG. The paper has identified the impact of different DG penetration levels that could cause reverse power flow back up onto 11kV and 33kV UK generic networks. The paper clearly shows that the change in real power flows caused by DG has important technical implications for the power system. Therefore, it may become necessary to limit the net export to higher voltage system through the transformers and this could be achieved by using an active local controller operating within the zone. The proposed method to control the generation output as well as control the load and energy storage within the zone would be able to minimize reverse power flow.

2.3 Existing Method for Power Quality Enhancement

Recently, research on power quality has become trendy due to technical reasons that may affect the existing building's system performance, saving in energy cost, reduction in production line interruptions and extended equipment lifespan. An European power quality survey conducted in 2007 shows significant impact on company turnover with poor power quality. The data analysis shows that several companies suffered a financial loss of about 10% of

their turnover to poor power quality and a total wastage in service sectors is almost certainly under reported (Leornado Energy; 2007).

Furthermore, the existing power system no longer behaves traditionally as there are more and more distributed generators (DG) connected on the distribution network. DG technologies include photovoltaics, wind turbines, fuel cells, stirling-engine based generators and combined heat and power. Currently, there are several existing approaches for mitigating the power quality problems. It can be categorised as follows:-

- Demand side management
 - Increase or manage the load demand in order to utilise the excess power generated by the DG
- Reinforcement of network cables
 - Reinforce the underground and overhead lines in order to accommodate the excess power flow by the DG
- Curtailment of renewable energy sources
 - Decrease the active power exported by DG
- Static synchronous compensator (STATCOM)
 - Power electronic based system that provides the control of system voltage.

The methods listed above can be utilised in order to mitigate the power quality issues caused by an aggregate amount of DG penetration into the weak distribution network.

2.3.1 Demand Side Management

Distribution network operators (DNOs) have a responsibility for maintaining their power system voltage within statutory limits. High penetration of DG may impose several technical issues to electricity utilities and customers such as voltage rise at the distribution network. One of the approaches to mitigate the voltage rise is by demand side management. It is the implementation of policies. The demand side management is for the utility company to control, influence and reduce the electricity demand of the customers. The demand side management aims at improving the quality of electricity by maintaining a balance between generation and electricity in the system. By maintaining the balance, the management will be able to maintain the stability of the power systems and reduce the number of interruptions to customers as well as eliminate overloading in the power systems. The advantages of demand side management is to mitigate the voltage rise issues with minimum network reinforcement and minimum constraints of DG power output.

The paper (M. Ibrahim, M. Zamzam Jaafar, M. Ruddin Abd. Ghani, 1993) has outlined some demand side management related projects that have been developed and implemented in Peninsular Malaysia. This paper has discussed about the benefits of demand side management to the utility company and customers from the innovative tariffs. This paper did not describe whether the proposed method is suitable when aggregate amount of renewable generators

are connected onto the LV distribution networks. This is mainly because renewable energy sources has not been widely discussed during the 90's.

John Olav Gioever Tande (2000) has introduced load management as an efficient way of overcoming voltage quality issues in relation to wind power. Nearby loads are controlled to match the wind power production in order to minimize the technical issues. However, suitable loads are not always available to be controlled as required, this may be because these loads are simply not present in the nearby area or the owner of these loads will only cooperate at a very high cost.

Later, another paper (Y.S Lim, S. White, G. Nicholson, P. Taylor, 2005) has described that demand side management has a potential role in solving voltage rise problems at power systems integrated with a large numbers of renewable generators. This can be done by constraining the real power output of DG when it is likely to hit the statutory limits. Controlling the power factor of DG such that DG imports the necessary amount of reactive power from electrical networks can be used to maintain the system voltage within its limit.

2.3.2 Reinforcement of Network Cables

John Olav Gioever Tande (2000) has proposed to install new lines to overcome the possible technical issues enabling more wind power to be connected onto

the distribution networks. Installation of new network cables on the LV distribution networks to distribute the renewable energy is the easiest way to ensure that it does not disturb the voltage quality. However, the drawback is that the new network cables are costly which may not be economical, for examples, approximately 30,000 USD per km for a new 10kV, 100mm² AL PEX cable. Therefore, it is important to find another approach to mitigate the power quality issues and find a cheaper approach for connecting more renewable energy sources to the networks.

2.3.3 Curtailment of Renewable Energy Sources

Concern about global warming and the increase of fuel prices have prompt many governments to provide incentives for the development of renewable energy technologies. Therefore, the penetration of DG, i.e photovoltaic systems and wind turbines is expected to increase significantly over the coming years. As the penetration of distributed generator increases, the voltage at the load end might also increase. Curtailment of renewable energy sources has been widely investigated as a method to control the voltage on the distribution systems (Q. Zhou, J. W. Bialek; 2007). As the penetration of renewable energy sources on the distribution network increases, the existing weak network is expected to evolve into a new stage where active network management will have to be applied. It has the capability to manage electricity flow using a flexible network topology.

The active power curtailment of renewable energy sources restrict the amount of active power flow into the distribution networks, such as shutting down some or all the renewable energy sources. As a result, the voltage at the remote end remains at the desired level. John Olav Gioever Tande (2000) has described a concept of dissipating wind turbine energy for maintaining steady state voltage level within its limits. This concept has been implemented at the Cronalaght wind farm in Ireland as a part of a Thermie funded project. There is a voltage control unit namely VCU, it is used to facilitates voltage reductions of the wind farm output power. Whenever the wind farm gives an unacceptable high voltage, the VCU gives the wind farm control signal to reduce the output power.

According to Padraig Lyons (2009), curtailment of renewable energy sources towards remote end of the network has a greater effect on voltage rise as generators nearer to remote end of a radial distribution network feeder have a greater impact on voltage rise than those closer to the network connection. This type of control may be effective for renewable energy sources that are connected to a weak network to mitigate flickers and avoid network reinforcement. However, the approach may be effective under a limited number of wind turbines on the distribution networks. As a result, the number of wind turbines that can be installed on the network would be limited.

2.3.4 STATCOM with Energy Storage Unit

Flexible AC Transmission System (FACTS) device integrated with energy storage unit has been proposed by several authors. (A. Arulampalam, J.Ekanayake, and N. Jenkins, 2003; M. L. Kothari, J. C. Patra, 2005; R. Kuiava, R. A. Ramos, N. G. Bretas, 2009; Kazuhiro Kobayashi et. al., 2003). With the recent advances in energy storage technology, the application of a STATCOM, a member of FACTS device, with energy storage unit has become feasible for voltage control and mitigate power quality issues in distribution systems and it has been widely discussed (A. Arulampalam, J. B. Ekanayake and N. Jenkins, 2003; Aysen Arsoy, Yiliu Liu, Shen Chen, Zhiping Yang, M. L. Crow, P. F. Ribeiro, 2001; Z. Yang, C. Shen, L. Zhang, M. L. Crow, S. Atcitty, 2001, Z. Yang, M. L. Crow, C. Shen, and L. Zhang, 2000). As the traditional STATCOM without energy storage unit has no significant active power capability, it is not possible to impact both active and reactive power simultaneously. For STATCOM integrated with battery storage unit, the steady state operation modes are extended for active and reactive power control. Z. Yang, C. Shen, L. Zhang, M. L. Crow, S. Atcitty (2001) has proposed a method of control that provides active and reactive power command using PI controller to achieve the desired system response. The paper has presented both simulation and experimental results and found to be effective in transmission capacity control, voltage control and oscillation damping.

S. M. Muyeen, M. H. Ali, R. Takahashi, T. Murata, J. Tamura, et. al. (2007) have analyzed the usage of STATCOM integrated with battery energy storage system (STATCOM/BESS). The simulation results in this paper show that the proposed STATCOM/BESS can significantly decrease the blade-shaft torsional oscillations of wind turbine generator system. The simulation shows short circuit fault that causes voltage drop at the terminal of the wind generators. The purpose of STATCOM/BESS is to provide necessary real and reactive power to restore the voltage back to normal.

Bostjan Blazic and Igor Papic (2006) have developed a new algorithm which enables separate control of positive and negative sequence currents to coordinate D-STATCOM under unbalance current conditions. The problem of dc-side voltage ripple and ac-side harmonics generation due to unbalance currents are solved by using switching function modulation of a capacitor on the dc-side. The authors have simulated two cases. In the first case, the D-STATCOM responses to a sudden network voltage unbalance while the second case utilizes the D-STATCOM to compensate an unbalance load. Zhengping Xi, Babak Parkhideh, and Subhashish Bhattacharya (2008) have proposed to integrate STATCOM with a supercapacitor energy storage system for distribution system voltage regulation and voltage sag mitigation.

2.4 Storage Technologies and Application for LV Distribution Networks

Practically, energy storage units are used to store electrical energy including batteries, flywheels, ultra capacitor and fuel cells. The storage capacity of a battery is often defined in ampere-hours, Ah. The most common way to store electricity is the electrochemical storage by the lead battery with Sulphuric acid as an electrolyte. Electrochemical elements are mainly used for storage over short or medium term periods, and are known as batteries. Batteries can be categorized as the primary and secondary types (D. F. Warne, 2005). Primary batteries stores electrical energy in a chemical form, when it is discharged, the chemically stored energy will be depleted, and the battery is no longer serviceable. Secondary batteries known as the rechargeable batteries also store electrical energy in a chemical form and release when it is required, however, the batteries can be recharged with further intake of electrical energy. There are several types of batteries such as lead acid battery, nickel cadmium and lithium ion battery. Due to economic reasons, lead acid battery has dominated the market (D. F. Warne, 2005).

2.4.1 Operation of Energy Storage

The main operation of an energy storage unit can be categorized as charging and discharging modes. The total charge that can be stored in a battery model is defined by the nominal capacity. This parameter is given by the

manufacturers, usually by measuring the charge delivered by the battery in a given time period with specific discharge rate and temperature. Apparently, the standard time lengths provided by the manufacturers are 5h, 10h and 100h. According to these time lengths, the nominal capacities are defined by C_5 , C_{10} , and C_{100} with unit Ah where the subscript indicates the discharge time length. The equivalent model of a battery is shown in figure 2.6.

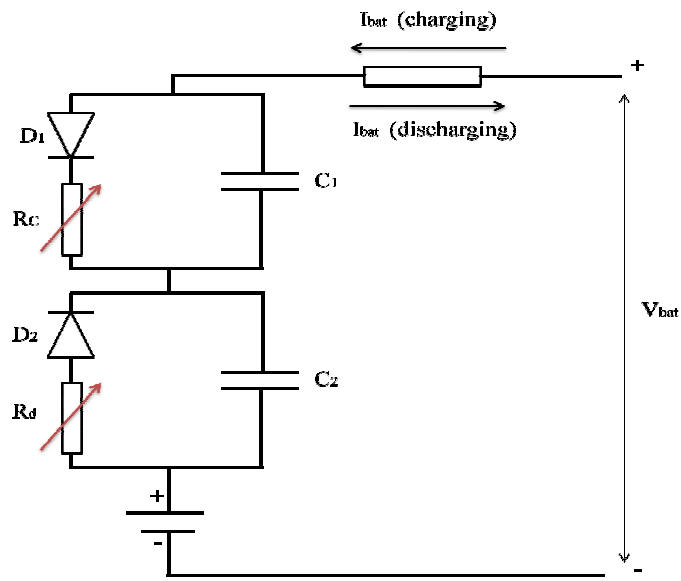


Figure 2.6 Equivalent battery model

During charging mode the current, here known as I_{bat} , flows into the battery at the positive terminal, while the battery voltage, V_{bat} , increase slowly as the stored charge increases. The state of charge (SOC) is an important parameter as it measures the fraction of charge remaining in the battery. SOC may be expressed in percentage. 100% indicates full battery, and 0% represents an empty battery. SOC can be represented by the following equation:

$$SOC = \left(1 - \frac{Q}{C}\right) \quad (2.1)$$

$$0 \leq SOC \leq 1$$

Where

C (Ah) : battery capacity

Q (Ah) : charge delivered by the battery

During discharging mode, the current I_{bat} , will tend to flow out from the positive terminal, while the battery voltage V_{bat} , decreases the supplying charge to the load. Another parameter to represent the fraction of battery discharge, is known as the depth of discharge, DOD. It is then represented as the following:

$$DOD = 1 - SOC \quad (2.2)$$

2.4.2 Energy Storage Application

Energy storage unit often plays an important role in the power system. The use of high capacity storage device in the distribution network can supply electric demand when the renewable energy source is not producing sufficient generation. For instance, the excess electricity generated by the renewable energy sources can be stored in the energy storage unit, and it can be utilized during night time when photovoltaic systems are unable to generate electricity. Furthermore, energy storage unit provides contingency service where it is capable to provide electricity to serve customer demand during short term electricity interruption occurs.

Energy storage could act as a great responsive device to smooth power delivery during switching events, short outages, and plant run up. An UPS (Uninterruptible power supply) is the most suitable examples, it provides emergency power to a load when the utility company failed to supply electricity. Practically, energy storage unit is expected to perform support functions such as backup service during the occurrence of power interruption. Beside providing energy and power, the duration of discharge and the DOD should be considered in order to determine the right technology (Jason Makansi, Jeff Abboud, 2002).

M. A. Kashem, G. Ledwich, (2007) have discussed that integration of distributed energy resources (DER) into distribution systems is capable of improving system capacity and stability, feeder voltage and supply quality and reliability. While, Joseph A. Carr, Juan Carlos Balda, and H. Alan Mantooth (2008) have presented a survey to integrate DER and energy storage on the utility grid. The paper states that DER will play a large role in the future energy infrastructure due to its lower carbon imprint, lower fuel costs and reduced power flows on transmission lines. However, the unreliability of renewable energies due to the intermittent nature of their supply, can be mitigated with energy storage that bring benefits including frequency control and power quality compensation.

John P. Barton and David G. Infield (2004) has discussed that the usage of energy storage can increase the penetration of intermittent embedded

renewable generation on a weak UK network and enhance the value of electricity generated by time-shifting delivery to the network. This can be done by the local utility company to charge the electricity when the value is low and discharge the electricity when the value is high. Furthermore, N. Wade, P. Taylor, P. Lang, J. Svensson (2009) have agreed that the use of energy storage unit is able to increase the penetration of DG and provide wider network improvement such as reduction in the steady state voltage fluctuation and the reverse power flow when DG exports more power than the local demand.

2.5 Future Active Distribution Network

P. Trichakis, P. C. Taylor, P. F. Lyons, R. Hair (2009) have introduced a small scale energy zones (SSEZ) concept which aims to facilitate the proliferation of DG by maximizing their potential commercial and environmental benefits while ensuring that the technical challenges are overcome. A SSEZ contains a mixture of customer owned DG, distributed energy storage unit and controllable loads. It is a concept that is similar to microgrids, while research on the microgrids focuses on alternative future network design and the SSEZ concept considers the integration of DG to the existing LV distribution networks. The paper has demonstrated the functionality of the agent and developed a laboratory based experimental SSEZ at Durham University, UK. The control system described in the paper was shown to overcome steady state voltage rise issues in a radial LV feeder. P. Trichakis, P. C. Taylor, G. Coates

and L. M. Cipcigan (2007) and P. F. Lyons, P. Trichakis, P. C. Taylor, G. Coates, (2009) have further described the distributed control approach for SSEZ.

Further discussion by putting several aggregated SSEZ together to form a virtual power station (VPS) has been discussed by L. M. Cipcigan, P. C. Taylor, and P. F. Lyons (2009). The VPS has the potential to offer significant improvements in the commercial value and environmental impacts of the installed DG by enabling provision of ancillary services. This paper is to evaluate the effectiveness of this concept, by increasing the value of DG and controlling their outputs. Throughout the study, several challenges have been identified by the authors as the DG increases on the LV distribution network. A dynamic model of benchmark VPS is developed in the paper based on a generic UK network. This model has been applied to evaluate the effects of aggregation and to identify critical nodes within the distribution network as well as to assess DG penetration levels.

P. Trichakis, P. C. Taylor, P. F. Lyons, R. Hair (2008) have proposed a method to predict the technical impacts of DG on LV networks without the need for developing a detailed computer based model of the power system and simulating a range of operating scenarios. The discussed methodology is drawn from an analysis of the key electrical characteristic that determine the response of LV networks to the addition of DG, focusing on the following technical aspects: i) voltage regulation, ii) voltage rise, iii) voltage unbalance iv) cable and transformer thermal limits and v) network power losses. The proposed

methodology is then applied to an existing public UK LV network operated by E. ON UK Central Networks. The simulation results and the predicted results show a good agreement between them.

2.6 Conclusions

With the efforts of Malaysian Government in promoting the utilisation of renewable energy sources, PV tends to become the most dominant type of renewable energy sources under the MBIPV and SREP projects. Future distribution networks are likely to have a high penetration of DG. However, numbers of technical issues have been identified. As a result, the penetration of DG could be limited by such issues. Therefore, it is important to determine the allowable margin faced by the existing Malaysian LV distribution network when anticipated PV are connected. The existing method on mitigating power quality issues, especially reinforcing network cables might not fulfill the economic margin of the utility companies. Nevertheless, the VSC integrated with energy storage unit seems to give positive result for mitigating power quality in LV distribution network, including dynamic voltage control, mitigating voltage unbalance and reduction in network power losses.

CHAPTER 3

MODELING APPROACH OF COMMERCIAL, RESIDENTIAL LOW VOLTAGE (LV) DISTRIBUTION NETWORKS & PHOTOVOLTAIC (PV) SYSTEM

3.1 Introduction

In order to investigate the future challenge of LV distribution networks with the anticipated amount of PV, it is necessary to develop a typical LV distribution network. Evaluation is based on the case study profile obtained from the utility company including the load profile, LV distribution network characteristics and properties. The growth of PV systems on LV distribution networks has the potential to impose several serious technical issues relating to power quality, distribution efficiency and possible equipment overloading. The assesment is based on the commercial and residential network in Aman Jaya, SS15, located at the urban area of Selangor state.

Due to a different load profile in commercial and residential area, LV distribution networks are analyzed in 2 different ways:

- Maximum load demand and maximum PV generation, in commercial area.
- Minimum load demand and maximum PV generation, in residential area.

The modeling approach uses a power system modeling software package known as PSCAD/ EMTDC (Power System Computer Aided Design/ Electromagnetic Transients including DC) that solves differential equations for both electromagnetic and electromechanical systems in time domain. It is a fast, accurate and user friendly power system simulation software for the design and verification of all types of power systems. Furthermore, PSCAD is suitable for simulating time domain instantaneous responses in electrical and control systems. It has graphical user interface that allows user to efficiently construct a circuit schematic, run a simulation, analyze the results and manage the data.

3.2 Case Study 1: Commercial Area

PSCAD/EMTDC was used to model two public distribution networks with a range of different PV penetration levels. One is the commercial LV distribution network at Petaling Jaya in Selangor, Malaysia. The commercial network is a three-phase four wire system. The LV public distribution networks are radial with a large number of LV feeders from the LV busbars of the 11kV/415V transformers. Consumers are connected at the remote end of the feeders. The transformers are equipped with off-load taps at the HV side, providing a typical

regulation range of $\pm 5\%$. The secondary side of the 11kV/415V transformers are wye connected and are solidly grounded. There are three main configuration for earthing, TT systems where both the transformer neutral and the installation frame are earthed; TN systems, only the transformer neutral is earthed while the installation frame is connected to the neutral; IT systems, the transformer neutral is isolated and the installation frame is earthed. Normal practise in Malaysia LV distribution networks adopt the TT earthing. The length of the LV feeder, the cable emanating from the LV feeder pillar, varies from 35m to 80m. Customers are not connected along the LV feeders. They are connected at the end of the LV feeders with three phase supply. Figure 3.1 and figure 3.2 show the single-line diagram and PSCAD model of the commercial network respectively.

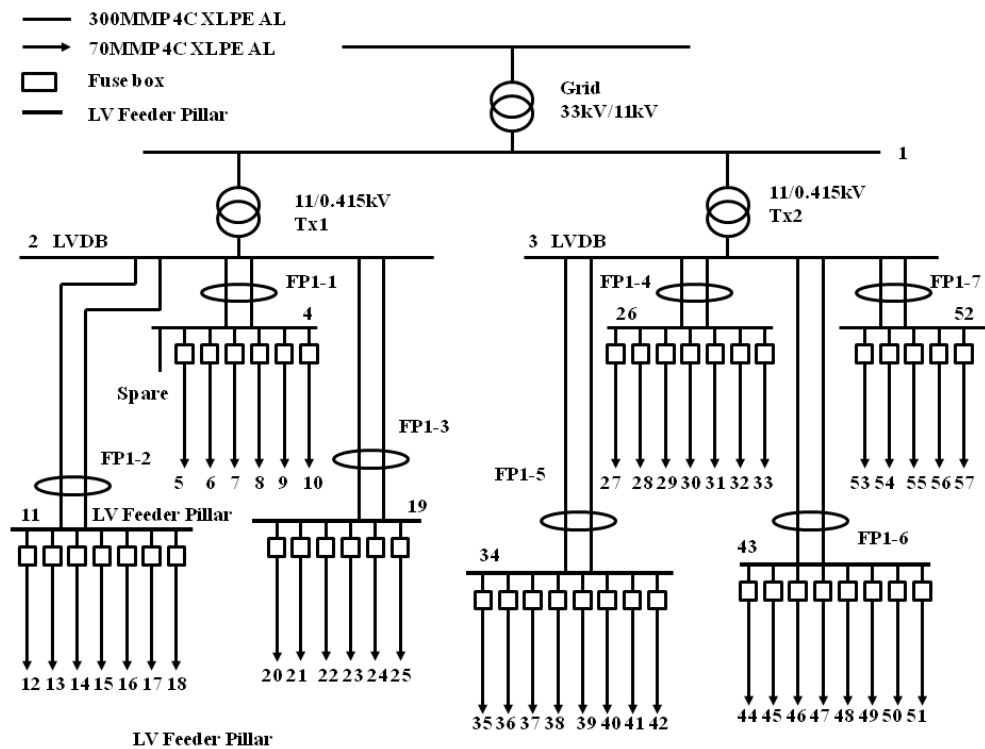


Figure 3.1 The layout of Aman Jaya commercial area LV distribution network

The commercial distribution network consists of 7 double circuits using 300MMP 4C XLPE Al cables from the low voltage distribution board (LVDB) to a low voltage feeder pillar. The length of the double circuits varies from 65 m to 200 m and it is represented with double lines in figure 3.1. The advantages of having such double circuits are that they allow more power to the customers and in case of a single circuit break down, the utility company would still be able to supply power to their customers. However, with such design, the utility company needs higher investment to build the network.

Fuses are used at the out-going and in-coming points of the feeders with the current rating of 1.6 kA. There are 47 low voltage feeders branching out from the end of the double circuits. The LV feeders use 70 MMP 4C XLPE Al type underground cables to supply electricity to 47 commercial shops. The parameters of these two types of cables are given in table 3.1. The maximum demand is approximately 13 kW per shop that is likely to occur during business hours starting from 12pm to 5pm. Figure 3.3 shows the load profile of feeder FP1-3 in Aman Jaya commercial area. During business hours, the power usage in the commercial shop-lots has reached the maximum. The maximum voltage level experienced on these LV feeders is about 240 V as shown in figure 3.4. The power factors vary within 0.7-0.92 lagging as shown in figure 3.5. According to the data obtained from the utility, minimum demand of the case study network is recorded as 86.6kW, while during peak hour the maximum demand tends to increase up to 530.0kW.

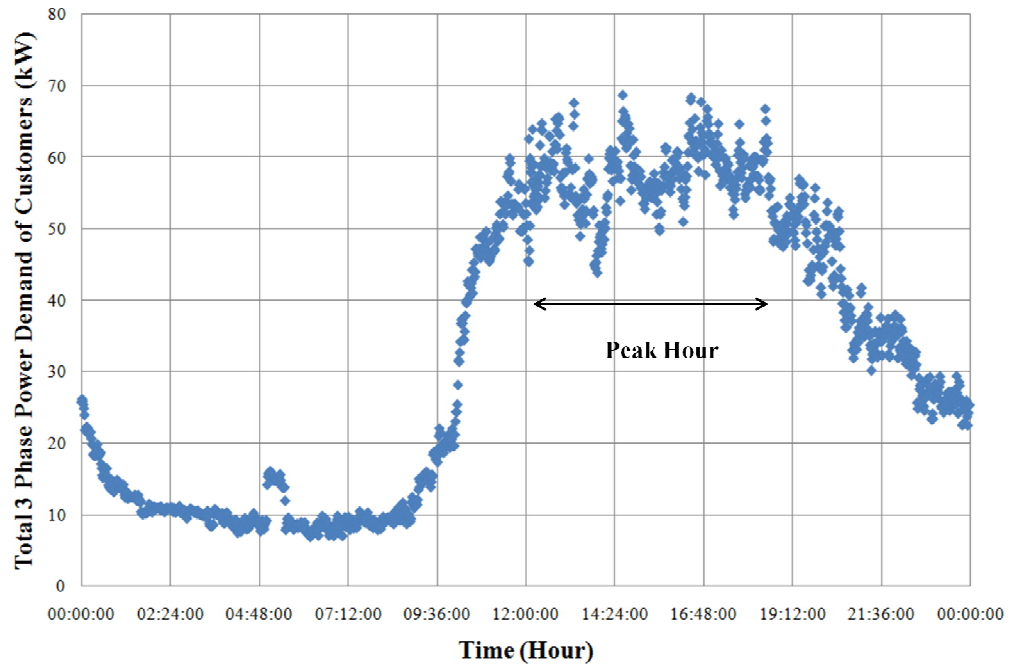


Figure 3.3 Load profile of Aman Jaya commercial area LV distribution network for feeder FP1-3

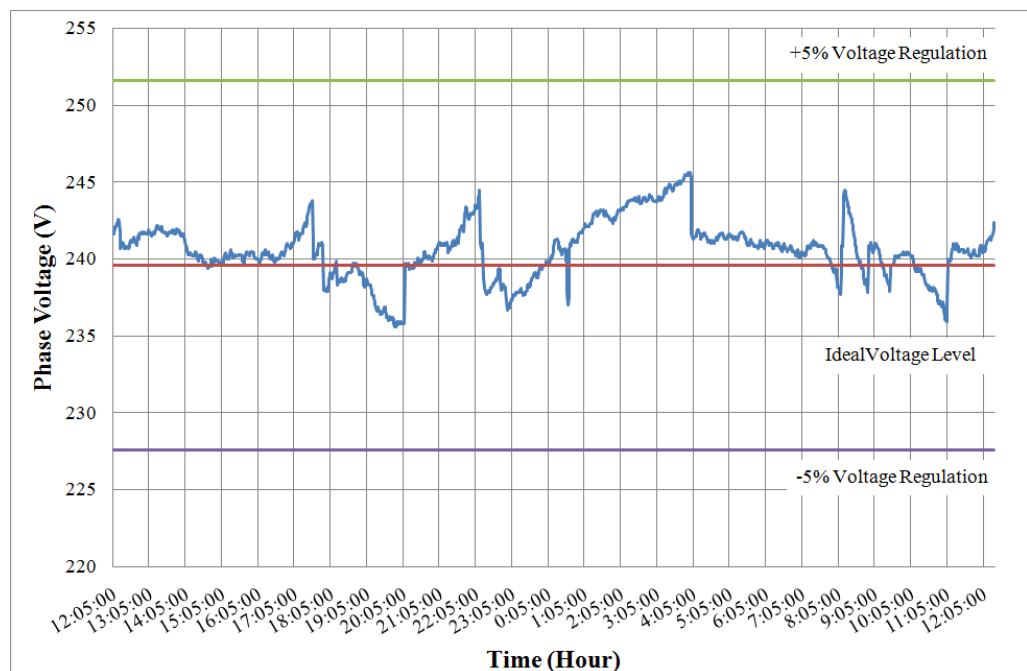


Figure 3.4 Voltage level of Phase A distributed to the load end from the utility company to Aman Jaya commercial area LV distribution network for feeder FP1-3

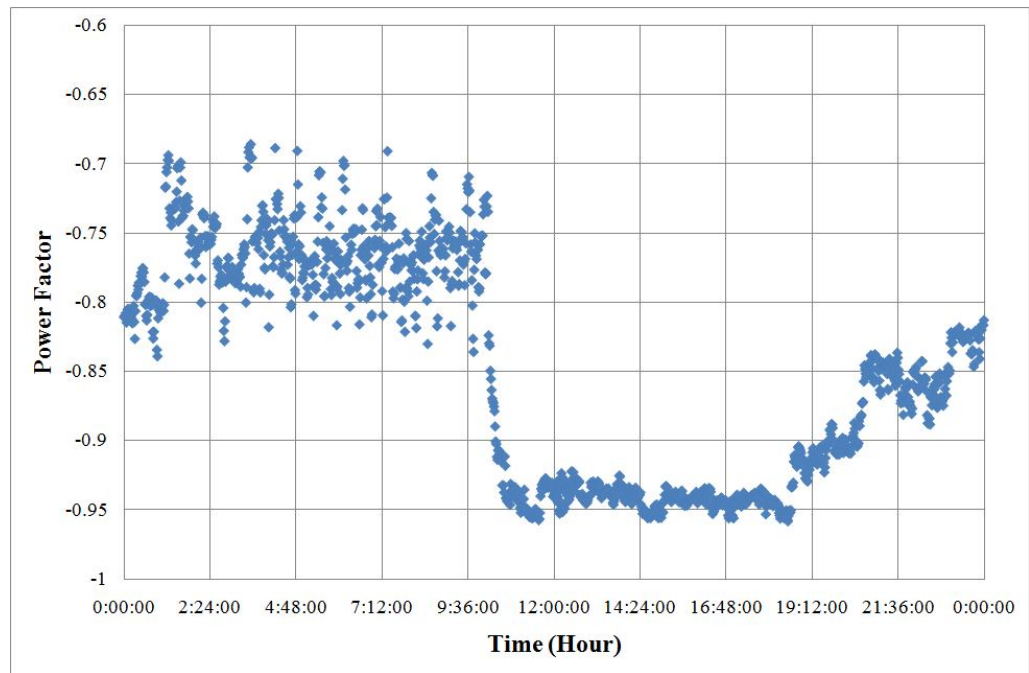


Figure 3.5 Power factor of Aman Jaya commercial area LV distribution network for feeder FP1-3

Type of Equipment or Cable	Resistance (at 50 Hz at 90 ⁰ C)	Reactance (at 50 Hz)
300MMP 4C XLPE Al	0.13 ohms/km	0.072 ohms/km
70MMP 4C XLPE Al	0.568 ohms/km	0.075 ohms/km

Table 3.1 Parameters of the cables for Commercial Area

3.3 Case Study 2: Residential Area

The residential distribution network has fewer feeders compared to that of the commercial network. The network is radial with an underground cable of 300MMP 4C XLPE Al being used between the low voltage distribution board (LVDB) and the end of the out-going feeders. This network has 18 feeders

which are configured at the low voltage feeder pillar such that three-phase cables are provided to bungalows and semi-detached houses. Single-phase cables are provided to terrace houses. Figure 3.6 and figure 3.7 show the single-line diagram and the computer model of the residential network respectively. The maximum demand along a feeder is about 13 kW that may occur during night between 9pm and 5am as shown in figure 3.8. The system voltage level is set at 240 V through an appropriate setting of the off load taps on the distribution transformer. Figure 3.9 shows the voltage level of phase A at the feeder end of FP3-1. The power factors vary within 0.9-0.99 lagging, as shown in figure 3.10. Minimum total demand of the case study is approximately 18.9kW while the maximum total demand is recorded as 441.9kW.

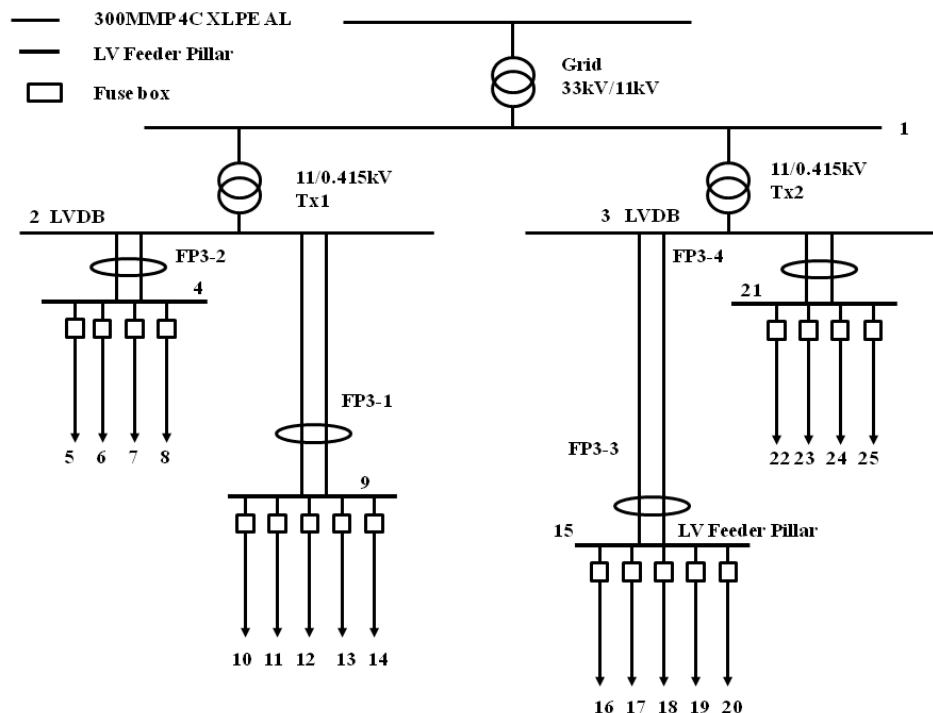


Figure 3.6 The layout of Aman Jaya residential area LV distribution network

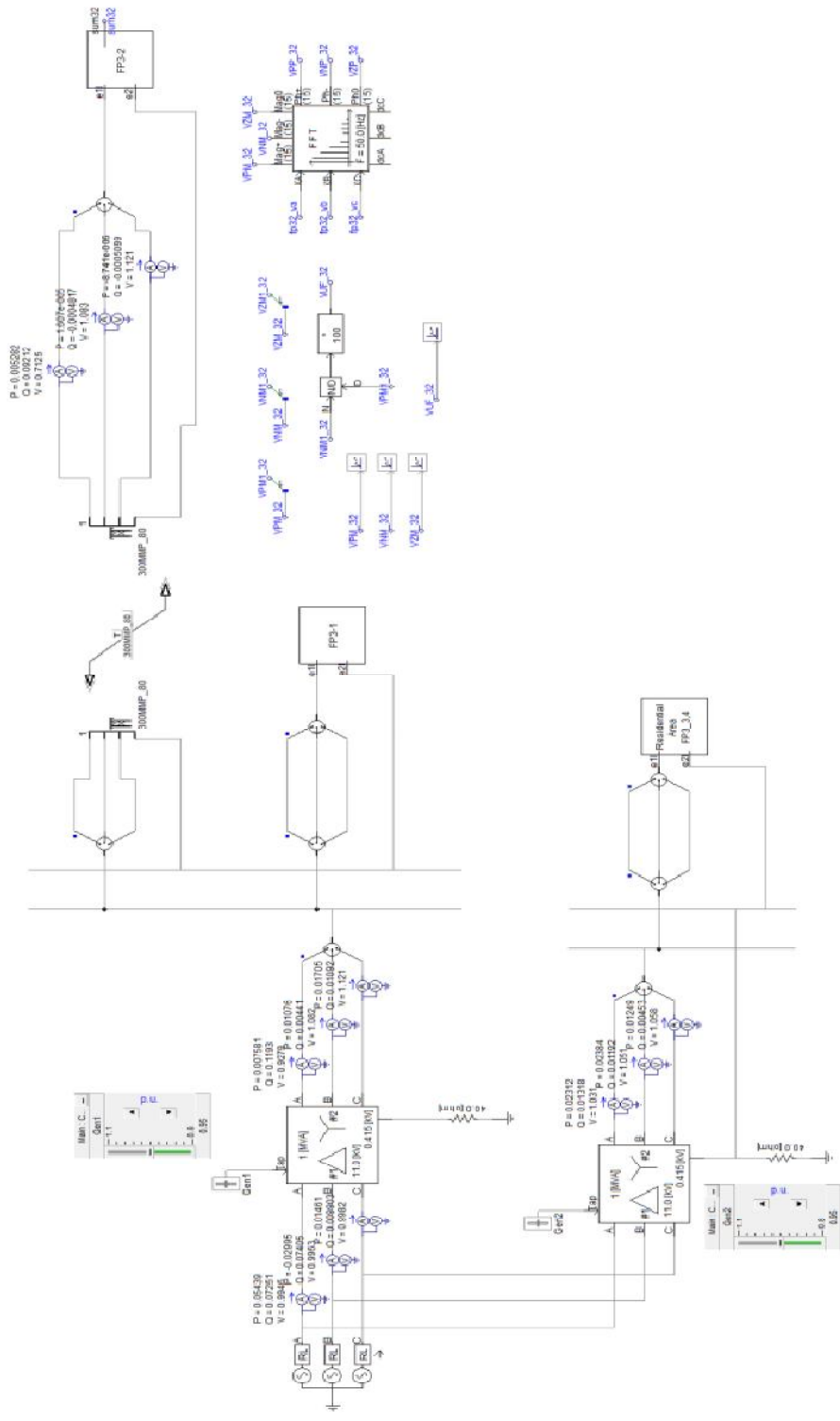


Figure 3.7 PSCAD block diagram of Aman Jaya residential area LV distribution network

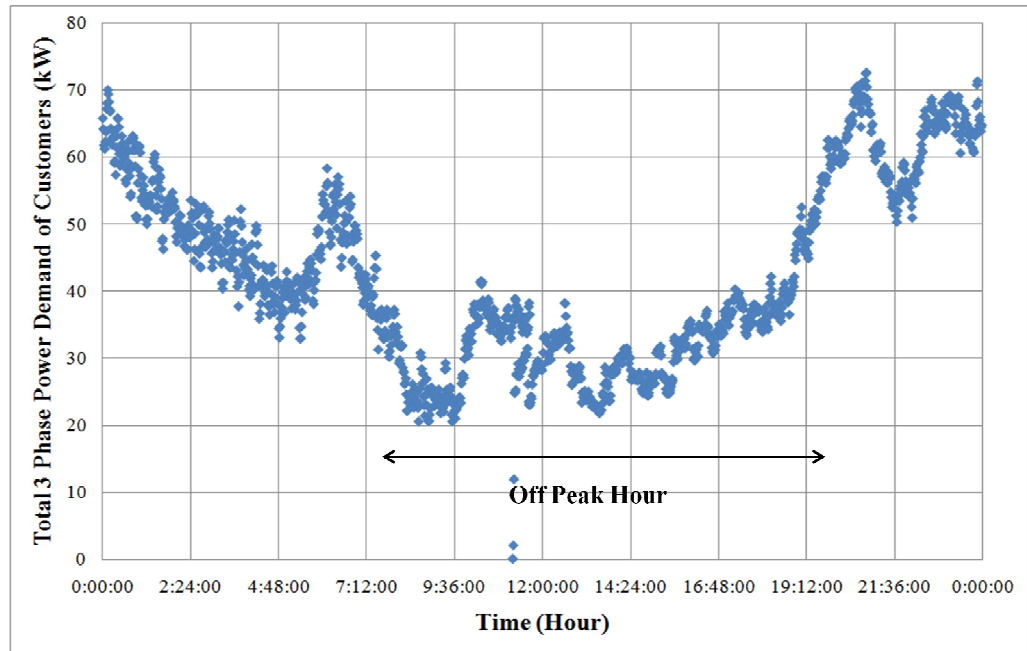


Figure 3.8 Load profile of Aman Jaya residential area LV distribution network for feeder FP3-1

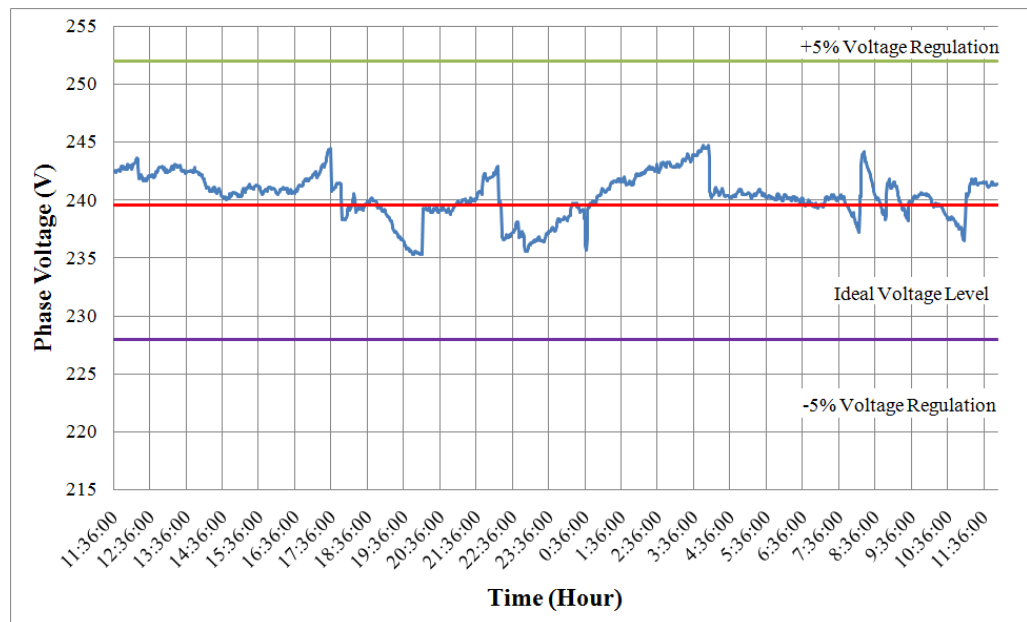


Figure 3.9 Voltage level of Phase A distributed to the load end from the utility company to Aman Jaya residential area LV distribution network for feeder FP3-1

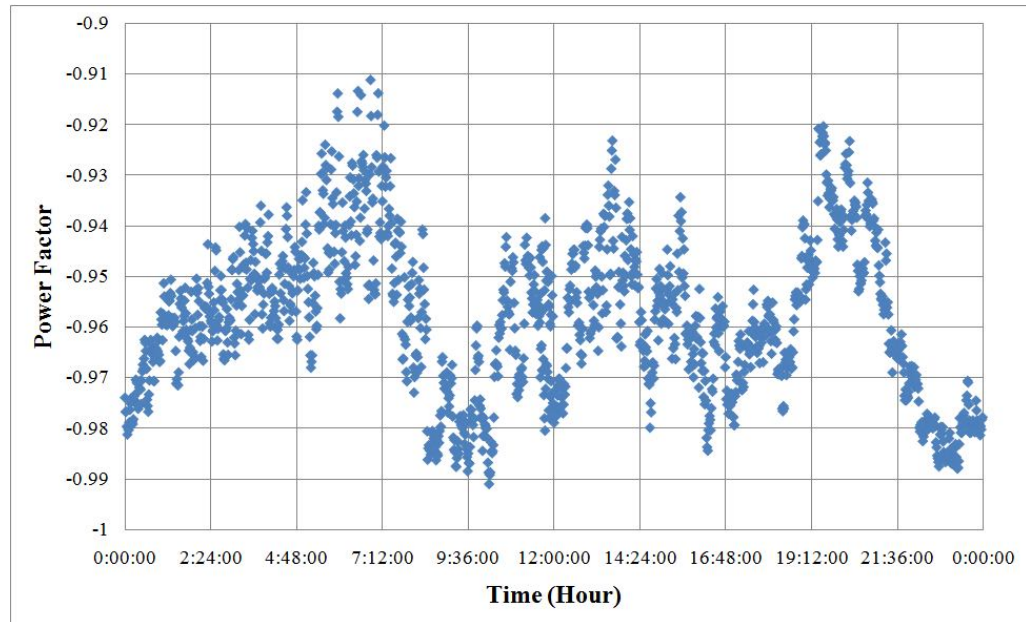


Figure 3.10 Power factor of Aman Jaya residential area LV distribution network for feeder FP3-1

3.4 Modeling LV Distribution Network using PSCAD/EMTDC

3.4.1 Distribution Lines

There are several ways to construct the distribution line in PSCAD. Remote ends method is the most suitable method, as the configuration involves two distribution line interface components representing sending and receiving ends of lines and a distribution line configuration component as shown in figure 3.11.

During modeling, ensure that the following steps are taken:

- Ensure that the segment names in both distribution line configuration and the distribution line interface components are identical.
- Ensure that the number of conductors in both distribution line configuration and the distribution line interface components are identical.

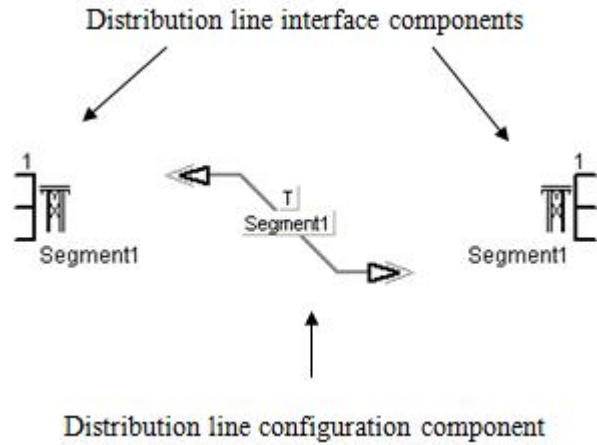


Figure 3.11 PSCAD library model of distribution line

Figure 3.12 shows the properties of the distribution line model that consists of 3 blocks, each representing a line model general data, an interface on Bergeron Model options and manual entry of admittance/ impedance, respectively.

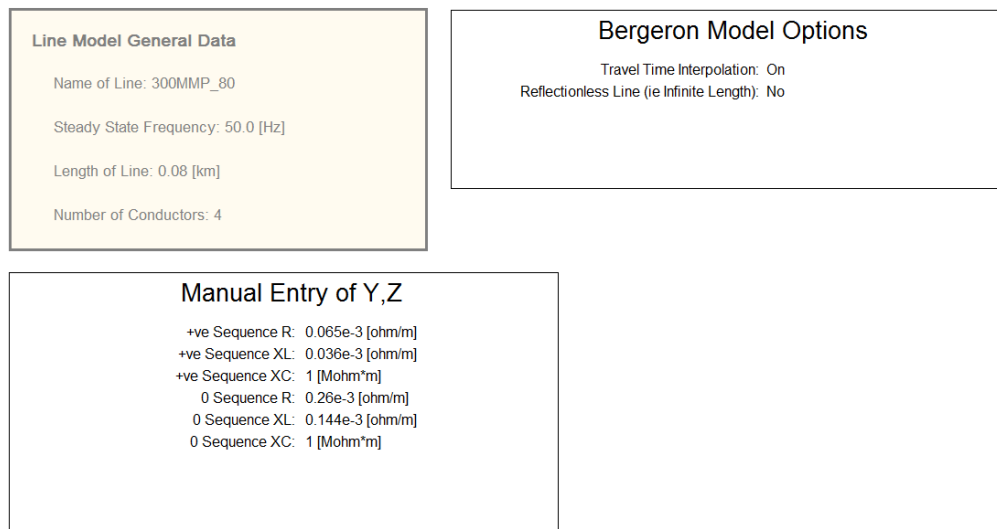


Figure 3.12 Configuration of transmission line in PSCAD model

Figure 3.13, figure 3.14 and figure 3.15 show the equivalent circuit of the positive, negative and zero sequence networks. The positive and negative sequence impedances of the distribution line are identical as shown in figure 3.13 and figure 3.14 the zero sequence impedances are different from the positive and negative sequence impedances since the magnetic field that creates the positive and negative sequence current in the network are different. The zero sequence network impedance can be represented as follows:

$$Z_0 = 3Z_n + Z_Y \quad (3.1)$$

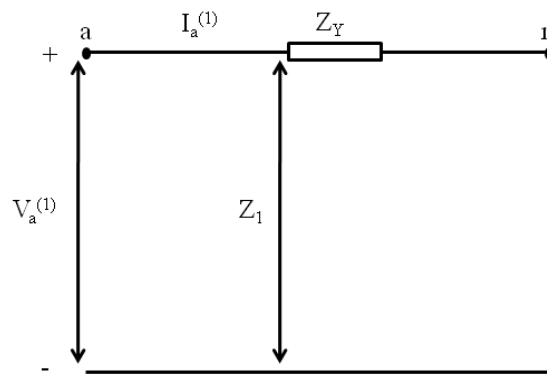


Figure 3.13 Equivalent positive sequence network and current flows for a synchronous generator. (Juan M. Gers and Edward J. Holmes, 2004)

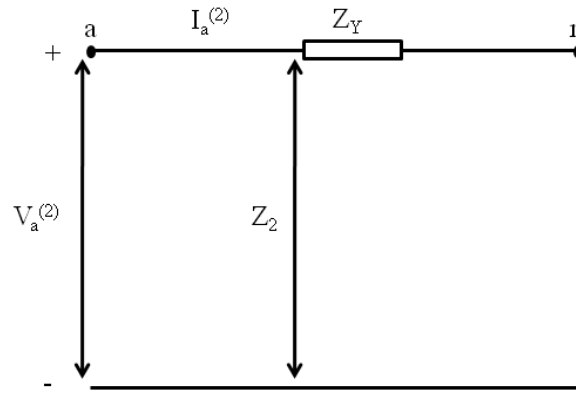


Figure 3.14 Equivalent negative sequence network and current flows for a synchronous generator. (Juan M. Gers and Edward J. Holmes, 2004)

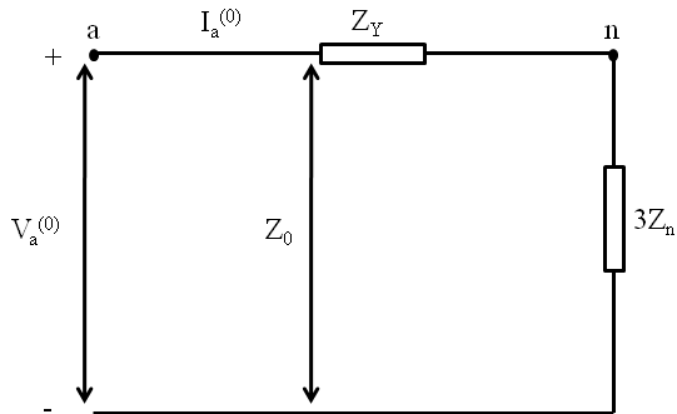


Figure 3.15 Equivalent zero sequence network and current flows for a synchronous generator. (Juan M. Gers and Edward J. Holmes, 2004)

3.4.2 Transformers

During the modeling of LV distribution networks, a transformer is necessary in order to step down 11kV of the electric distribution system to 0.415kV of the utilisation voltage serving the customer in a three-phase networks. The PSCAD

model shown in figure 3.16 is a 3 phase 2 winding transformer, with the 11kV delta connected primary winding and 0.415kV, wy connected secondary winding.

The neutral wire is connected at the neutral point of the transformer. Figure 3.17 represent the schematic diagram of the delta-wye connected transformer. During unbalanced condition, a neutral current I_n flows through the neutral wire at the secondary side of the transformer.

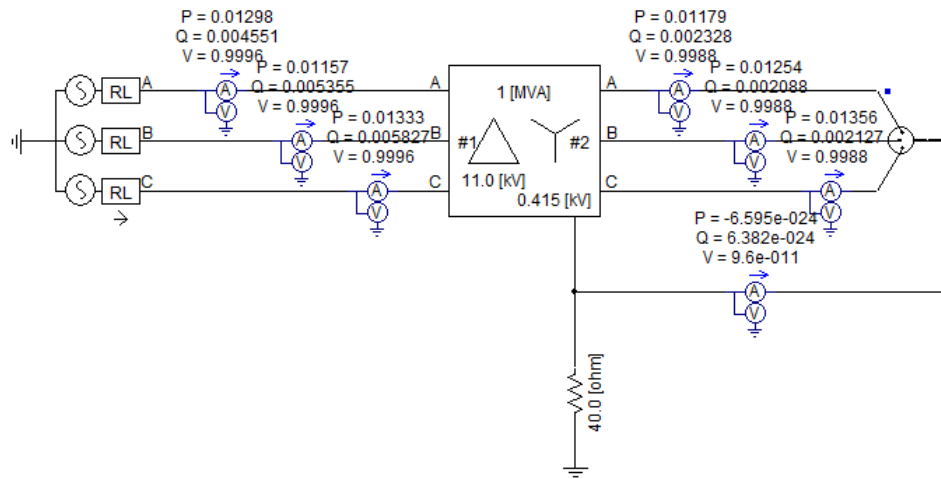


Figure 3.16 Transformer block model in PSCAD

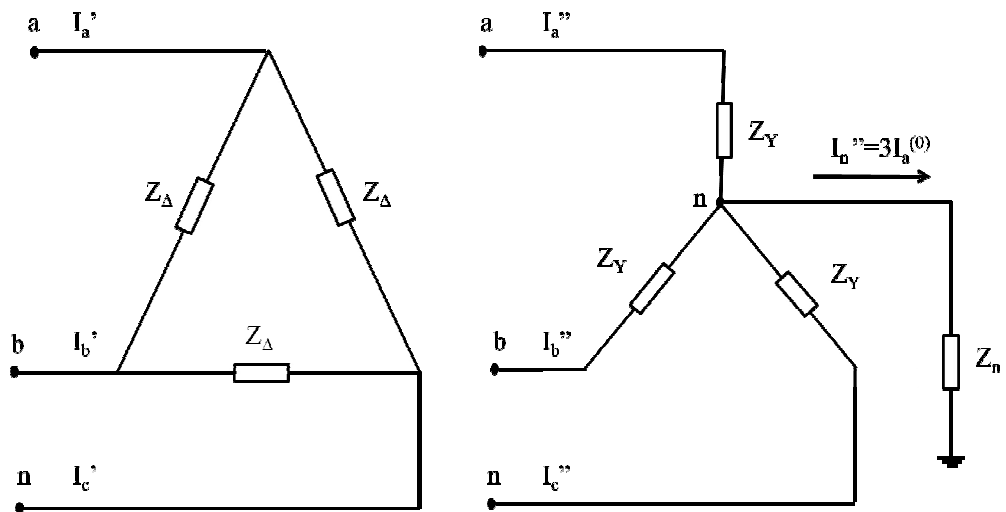


Figure 3.17 Delta-Y connection of the transformer

The capacity of a transformer is determined by the transformer rating, which gives the allowable current it can carry continuously at rated voltage without exceeding the temperature limit. This rating is represented by voltage-ampere (VA) regardless of the power factor. Table 3.2 shows the parameter of the transformer for both commercial and residential area.

No	Transformer Properties	Commercial Area	Residential Area
1	3 Phase Transformer Rating	1 MVA	0.75 MVA
2	Base Operation Frequency	50 Hz	50 Hz
3	Primary Winding #1 Type	Delta	Delta
4	Secondary Winding #2 Type	Y	Y
5	Winding Voltage (#1/#2)	11kV/ 0.415kV	11kV/ 0.415kV
6	Resistance(at 50 Hz at 90 ⁰ C)	0.00385 ohms	
7	Reatance (at 50 Hz)	0.00807 ohms	

Table 3.2 Parameters of the transformer for commercial and residential area

3.5 Photovoltaic System

3.5.1 Introduction

Keen interest in the development and utilization of renewable distributed generation has been observed worldwide due to several reasons. These include low carbon emission and limiting the growth in energy costs associated with the use of conventional energy sources such as fossil fuel. Solar energy greatly

depends on the meteorological condition such as solar irradiance and ambient temperature. Consequently, analysis on the solar characteristic is necessary.

The major elements and components to build up a PV system consist of a solar panel and DC-AC inverter. Materials of the solar panel will determine its efficiency to generate electricity from solar irradiance. The DC output power will be converted to AC using a DC-AC inverter. A PV system is well known to generate electricity from sunlight using solar panel when they are exposed to sunlight. The actual creation of electric current in a solar panel takes place at the atomic level. Mechanism of the PV system involves light energy from the Sun, known as the solar irradiance hits the solar panel to excite electrons in a semiconductors to conduct current. Solar cells are made from solar grade silicon that is treated with negatively (electron) and positively (photon) charged semiconductor, Phosphorous and Boron. Photon whose energy is greater than the band gap energy can excite the electron from valence to conduction band where they can flow through external circuit to generate electrical power. When the photon energy is lesser than the band gap energy, it fails to excite electrons. This is known as the photovoltaic effect. Back to the year of 1839, Photovoltaic effect was first introduced by a French physicist, Alexandre-Edmund Becquerel. He observed that “electrical currents arose from certain light induced chemical reactions” (D. Yogi Goswami, Frank Kreith and Jan F. Kreider; 1999). Edmund has published his observations about the nature of photovoltaic phenomenon of materials.

Most basic designs of a PV System with battery storage is represented by

figure 3.18. The system consists of PV module, charge controller, batteries and DC to AC inverter. During daytime, PV modules absorb sunlight and output DC voltage to the charge controller, so that the controller could charge the battery and in the mean time prevents overcharging the battery. Battery provides storage for the excess power generated by the PV module and utilizes the energy during night. A DC to AC inverter converts the DC power to AC power for most household appliances. These are typical for standalone residential PV systems. Inverter rating can be varied from few hundred watts at 115Vac or several hundred KW at 480Vac, three phase.

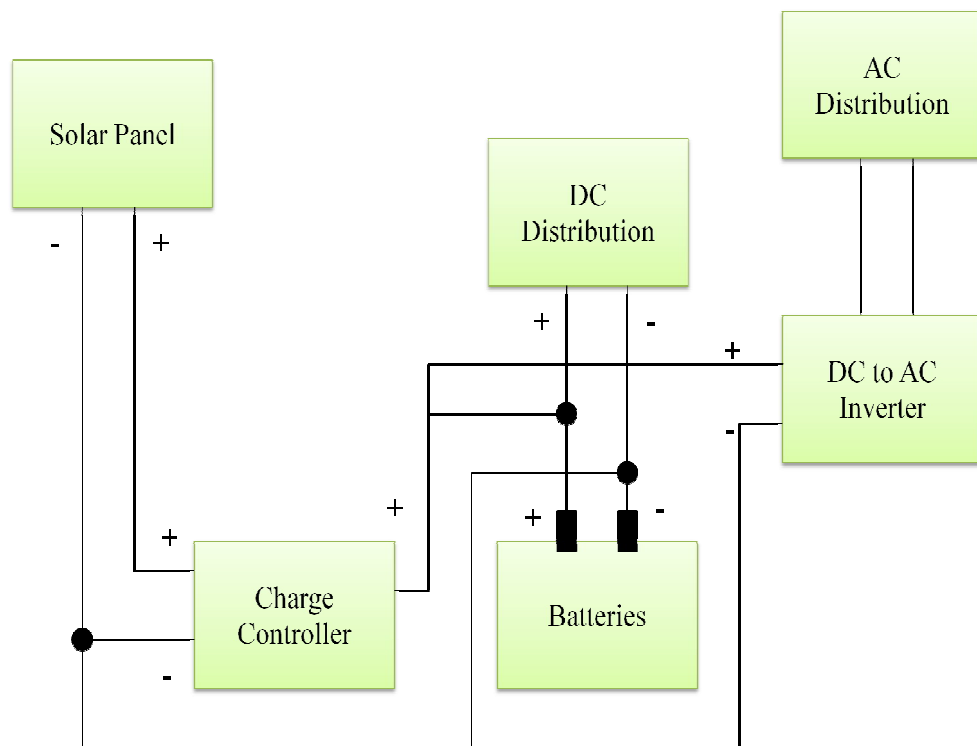


Figure 3.18 Layout design of a photovoltaic system with battey storage

In literature, single phase photovoltaic inverters have been developed for simulation based on several programming environment such as Pspice, Matlab Simulink, Labview and PSCAD (D. F. Hasti, 1994; E. Koutroulis, K.

kalaitzakis, 2003; ST. Kourtesi and et. al., 2007). In PSCAD, the photovoltaic inverter circuit is designed using Gate-Turn-Off thyristor (GTO) to model a full-bridge inverter, the inverter is then connected to a coupling circuit before it is connected onto the AC system (ST. Kourtesi and et. al., 2007). This inverter model was used in conjunction with an AC voltage source to show real and reactive power flow. The inverter circuit is capable to absorb and generate active power.

3.5.2 Modeling PV System with PSCAD

The majority of the customers use single-phase inverters for their photovoltaic systems. At present, the inverter is installed at any of the three phases in the customers' premises. Therefore, single-phase photovoltaic inverter is modeled in the distribution networks using PSCAD/EMTDC. The inverter circuit is made of insulated-gate bipolar transistor (IGBT) .These IGBT models are normally used as controlling switches in high voltage devices with large power ratings. A PV generator represents the PV cell, module or array. Figure 3.19 shows the computer model of the PV system in PSCAD.

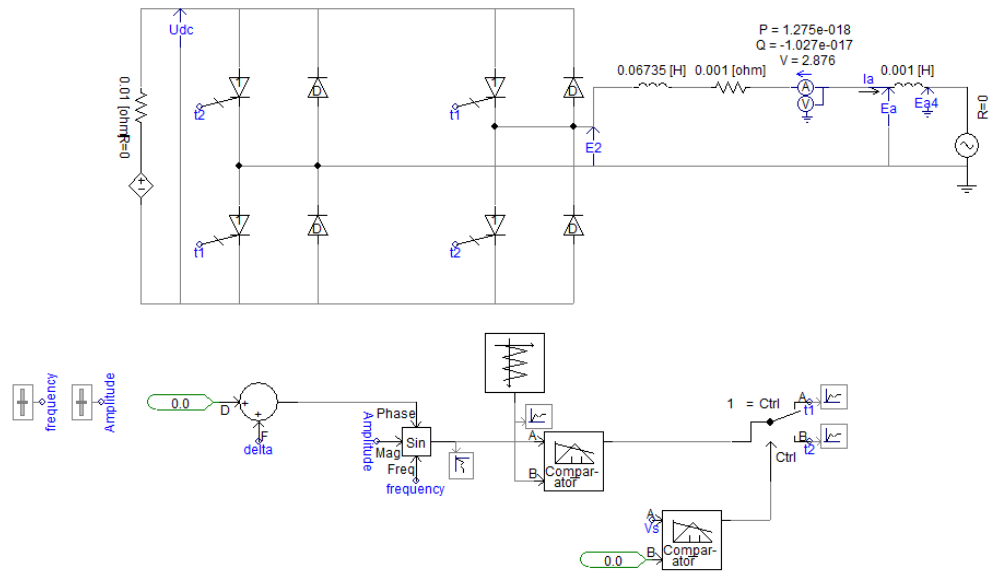


Figure 3.19 PSCAD model of PV equivalent circuit with full bridge inverter

Appropriate gate triggering pulses are generated and applied to the terminals of the thyristors which result in a square wave output. The triggering pulses are generated by programming the components in the required manner as represented in figure 3.19. The inverter is then connected to one of the three phases at the customers' side via a coupling circuit consisting of a resistor and an inductor. The value of the inductor is 67.35 mH and resistor is 0.001 ohms. The real power output of the inverter is a function of the power angle δ between the fundamental component of the inverter output voltage and the grid voltage. A positive phase shift (δ) of 2° is introduced resulting in the inverter output voltage leading the grid voltage by 2° . During this leading mode of operation, real power is exported to the grid. The reactive power output of the inverter is a function of the voltage magnitude between the inverter output and the grid voltage. If the magnitude of the fundamental component of the inverter output voltage is set to 250 V rms and the magnitude of the grid voltage to 230 V rms, then a current of 1.3 A rms flows from the inverter to the grid. If the

magnitude of the inverter output voltage is reduced to a value below 230 V rms, then the reactive power flows from the grid to the inverter. Figure 3.20 shows the output sinusoidal waveform after the coupling circuit. Figure 3.21 shows the daily power output of a 5.25 kW PV system on a bungalow in Semenyih.

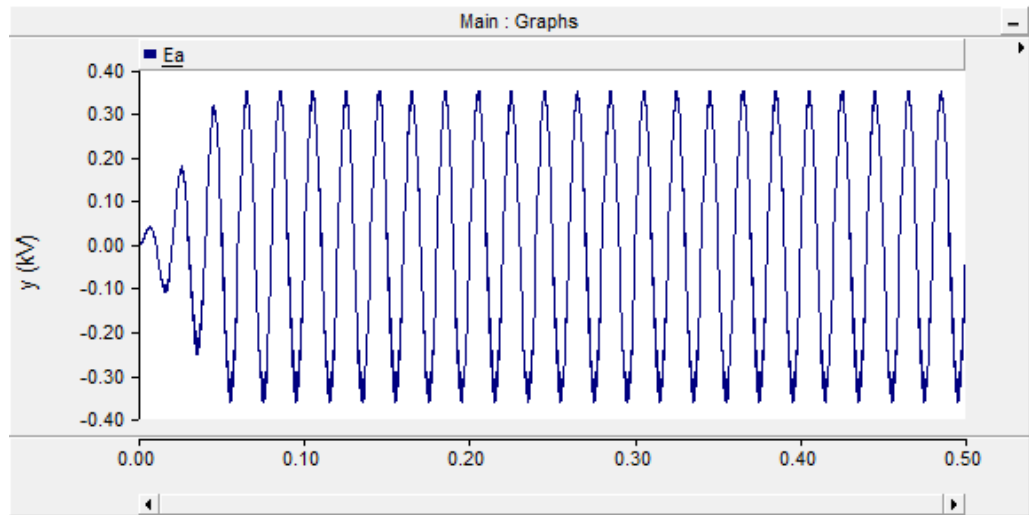


Figure 3.20 Output sinusoidal waveform for DC-AC Inverter

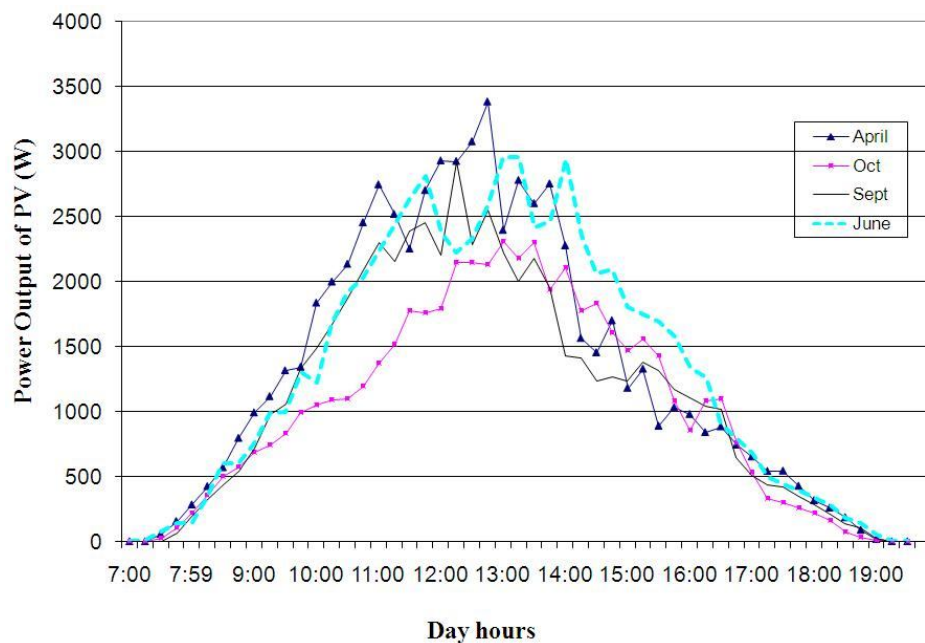


Figure 3.21 Daily power output of a 5.25 kW PV system on a bungalow in Semenyih

3.6 Description of The Methodology

The computer models of the commercial and residential networks were used to study how different aggregated volumes of PV can influence the network voltage level, voltage unbalanced factor, network losses, power flow and current flow. For each network, two extreme scenarios, namely uniform distribution and non-uniform distribution of PV, were created as described below.

1. Uniform distribution of PV. All the customers coordinate with each other such that they can install their PV systems in the appropriate phases in order to create the best possible balanced condition for the network.
2. Non-uniform distribution of PV. All the customers coordinate with each other to install their PV systems in the same phase only, say Phase A, in order to create the worst unbalanced condition for the network.

At present, customers install their PV systems under the plug and inform policy. The two extreme scenarios of PV distribution may not happen. However, it is necessary to simulate these two scenarios in order to establish the possible range of negative effects caused by the penetration of PV on the networks.

The computer models were to simulate the operating conditions of the networks during which PV systems export the highest amount of real power to the networks. The PV systems export the maximum power at 12pm-2pm as shown in figure 3.21. Therefore, maximum demand was used in the simulation model for the commercial network because the commercial customers consume

the highest power during noon. On the other hand, the residential customers consume the lowest power during noon. Therefore, minimum demand was used in the computer model of the residential network.

3.7 Conclusions

This chapter described the characteristic and properties for both LV distribution networks considered for the case study. In order to investigate the technical issues that will arise, both networks have been modelled using PSCAD. This software was found to be useful in analysing power system. PSCAD enables user to schematically design or model a power system, graphically simulate and analyze it. Furthermore, PSCAD comes with a master library of pre-tested models and elements that include passive elements such as resistors, capacitors and inductors, user pre-defined sources, transmission lines and cables and so on. This was followed by a discussion on the PV system modeling using full bridge inverter formed by IGBT. The inverter is controlled by triggering pulses and then connected to the LV distribution network via a coupling circuit in order to provide real power flow to the distribution network. Using metering and measuring model, voltage unbalance, voltage level, current, real power flow and reactive power flow at each branches are shown in graphs and digital meter.

CHAPTER 4

**INVESTIGATION OF THE IMPACTS ON LOW VOLTAGE
DISTRIBUTION NETWORKS WITH ANTICIPATED
PHOTOVOLTAIC PENETRATION**

4.1 Introduction

Distributed Generation (DG) is predicted to play an increasing role in the residential and commercial sectors of the power system. DG provides an alternative technology to the traditional electricity sources such as oil, gas, coal and water. The DG technologies such photovoltaic (PV) system, wind turbine, fuel cells and etc. become increasingly popular due to low carbon emission, low noise levels and high efficiency. However, the introduction of generation on the distribution system can significantly impact the power flow and voltage level conditions at customers and utility equipment. As per the discussion in Chapter 3, two case study LV distribution networks are modelled with PSCAD. The impacts of both radial LV distribution networks are related to the effects of high concentration of PV systems. This chapter focuses on analysing the impact of PV installation on distribution network operation including voltage analysis, voltage unbalance of the system, electric network power losses and the thermal limit of LV underground cables and transformers.

To begin with, the impact of uniform distribution of PV across the LV distribution commercial network with various PV penetration levels are explored. Secondly, the investigation is extended for non-uniform distribution of PV. Finally, the research involves case study that explore the impact of various penetration levels across the residential LV distribution network.

4.2 Technical Issues of the LV Distribution Network

With the growth of renewable energy on the weak network, it is critical to study the impact of it. Malaysia distribution network uses the radial network configuration, which allows only uni-directional power flow. As the capacity of DG is increased and the power generated is more than the demand, power tends to flow in reverse direction. This could cause several technical issues related to:

- Voltage unbalance
- Voltage rise/ voltage regulation
- Network power loss
- Thermal limit of LV underground cable and transformers

4.2.1 Voltage Unbalance Factor (%VUF)

According to the IEC Standards, voltage unbalance in a three-phase distribution system describes the condition whereby the three-phase voltage

differs in magnitude or displaced from their normal 120 degree phase relationship. Voltage unbalance can be defined as the maximum deviation from the average of the three-phase voltages or currents, divided by the average of the three-phase voltages or currents, expressed as a percentage (R. C. Dugan, M. F. McGranaghan, H. W. Beaty; 1996). However, according to the Engineering Recommendation P29, %VUF can be calculated as the ratio of negative to the positive sequence component as follows:-

$$\%VUF = \frac{V^-}{V^+} \times 100 \quad (4.1)$$

Where

%VUF Voltage unbalance factor expressed in percentage

V^- Negative-sequence voltage (pu)

V^+ Positive-sequence voltage (pu)

The negative and positive sequence components of the system voltage can be computed as follows:-

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \begin{bmatrix} V^0 \\ V^+ \\ V^- \end{bmatrix} \quad (4.2)$$

Where,

V_a, V_b, V_c = Three-phase voltages

V^0, V^+, V^- = Symmetrical components of the three-phase voltage

Unequal magnitude or phase angle will result in an unbalanced supply. The voltage at the distribution end can be unbalanced due to several factors:

- i) Unsymmetrical loads such as single phase PV systems, distribution of single and double phase load across the three-phase network
- ii) Continuous changing of the instantaneous demand
- iii) Unbalance or unstable utility supply
- iv) Unsymmetrical distribution systems in which equipment and phase conductors present different impedance values.
- v) Unequal transformer tap settings

Distribution system often serves a wide range of customer loads. Load demand varies from time to time. Furthermore, renewable energy sources such as PV systems with single-phase inverter have been widely used nowadays; the growth of the PV systems on the LV distribution network is mainly driven by the customers and is not centrally planned. This causes an increase in the voltage unbalance factor, likely to hit the limit set by the Standards & Industrial Research Institute of Malaysia (SIRIM). Therefore, voltage unbalance level is likely to increase as the amount of single-phase PV systems in the networks becomes significant. When the unbalance voltage becomes excessive, it can create problem for the induction motor. Ching Yin Lee (1999) has widely discussed the effect of unbalance voltage on the operation performance of a three-phase induction motor.

The voltages can be balanced at the generation and transmission level, however at the utilization level, voltage can become unbalanced due to unequal usage of single-phase loads and single-phase PV inverter installed in the same phase of the distribution network. Therefore, the %VUF is likely to hit the limit. Excess

voltages unbalance lead to unbalance current flow in the distribution network. Such unbalance current flow in the rotor and stator may cause power losses.

According to the Tenaga National Handbook, statutory limit of the %VUF is 1.0 % in Malaysia. While the %VUF has a statutory limit of 1.3% in the UK and 2.0% is the standard limit used in European network (P. Trichakis, P. C. Taylor, P. F. Lyons, R. Hair, 2008). The allowable PV volumes to be accommodated on the networks before the voltage unbalance factor at any points on the network exceed the limits are determined under uniform distribution of PV across the phases of the network and non-uniform distribution of PV. Voltage unbalance factor can be calculated by using the ratio of negative to positive sequence components. Figure 4.1 shows the fast fourier transform (FFT) which can determine the harmonic magnitude and phase of the input voltage signal. This block diagram takes a three-phase voltage input and calculates the FFT preliminary output through a sequencer, which output the positive, negative and zero sequence magnitude and phase values of the fundamental and other harmonic components. As a consequence, %VUF can be obtained by the ratio of negative sequence to the positive sequence voltage.

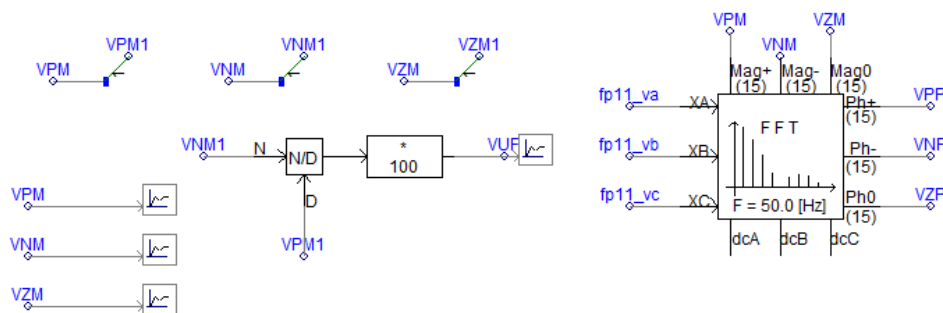


Figure 4.1 PSCAD block diagram to compute voltage unbalance factor by extracting positive and negative sequence voltage

4.2.2 Network Power Losses

The network losses in the distribution system are due to the impedance of the underground cable and overhead lines. Figure 4.2 shows the PSCAD block diagram to compute network power losses based on the following equation:

$$P_{\text{loss}} = I_a^2 R_a + I_b^2 R_b + I_c^2 R_c + I_n^2 R_n \quad (4.3)$$

Where,

I_a, I_b, I_c, I_n = Line current for phase A, B, C, and the neutral respectively

R_a, R_b, R_c, R_n = Line resistance in phase A, B, C and the neutral respectively

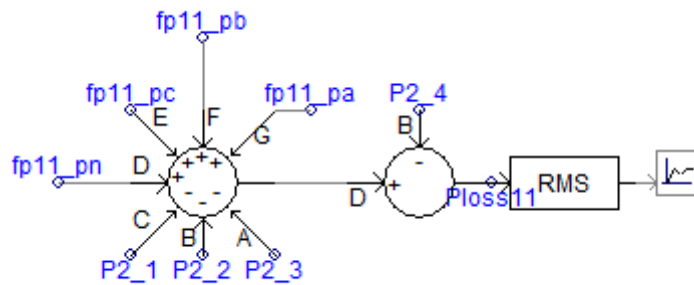


Figure 4.2 PSCAD block diagram to compute network power losses

The power losses vary depending on the PV size. Minimum losses occur when the PV size is equal to the load demand. However, when the generation PV is greater than the load demand, excess reverse power flow causes power loss and voltage unbalanced to increase. Under unbalanced conditions, the LV distribution system will incur additional losses and heating effects. The voltage unbalance is also detrimental to equipment such as induction motor, power electronic converters and adjustable speed drives (ASDs) (N. Stannard, J. R.

Bumby, P. C. Taylor, L. M. Cipcigan, 2007). Excessive level of voltage unbalance leads to unbalance currents, and consequently, excessive temperature rise in the motor winding that results in the motor insulation (S. Conti, S. Raiti, G. Tina, 2003) and hence degradation of the performance and life span of the three-phase induction motor. The majority of PV systems are single-phase and their growth on the LV distribution network is driven by customers and is not centrally planned.

4.2.3 Voltage Rise and Voltage Regulation

Voltage rise studies are carried out to determine the effects of PV penetration on the system voltage levels. According to the standards listed by SIRIM, the statutory tolerance for voltage excursion on the low voltage distribution network is +5% and -10% of the nominal value which is in the range of 252V to 216V. To determine the total capacity of PV systems that can be accommodated at the connection points, the voltage rise magnitudes (%) at the substations and loads are determined with respect to the total capacity of PV systems on the networks. Voltage regulation (VR) is also determined with respect to the capacity of PV systems on the networks. VR is defined as the voltage magnitude deviation between the low voltage busbars of the MV/LV substation and the end of service. It is known that $\pm 5\%$ is the VR limit in Malaysia. The standard is shown in table 4.1.

	UK Generic LV Distribution Network	European Generic LV Distribution Network	Malaysian LV Distribution Networks
Allowable Voltage Rise	+10, -6%	± 10%	+5% and -10%
Allowable Voltage Regulation	± 5 %	± 5 %	± 5 %

Table 4.1 Allowable voltage rise and voltage regulation for UK, European and Malaysian LV distribution network

4.2.4 Thermal Limit of Underground Cables

LV network components such as underground cables and overhead lines have a thermal rating determined by the maximum current carrying capacity of the component. The presence of PV systems may increase the overall current flow in the network, causing the equipment to operate at or beyond their thermal limits. During low demand and high power output of PV systems, surplus power can be fed into the higher voltage system through distribution transformers and may exceed their nominal rating. Table 4.2 shows the allowable thermal limit for both LV underground cables.

Cable Type	300MMP 4C XLPE AL**	70MMP 4C XLPE AL**
Cable Thermal Limit (A)	434	166

**=Four-core armoured cables with aluminium conductor

Table 4.2 Allowable current rating for LV underground cable

The growth of PV systems will affect the magnitude and direction of the real power flow for varying levels of generation. Reverse flow of real and reactive powers may cause problems for the utility company's voltage control and protection systems as well as metering systems. The 33/11kV on load transformer tap changers may not be adequately rated to accept significant flow of reverse real powers. The voltage control schemes for tap changers may also be affected by the flows of reverse real and reactive power. Both these issues are largely dependent on the type of equipment installed and their effects become significant on networks where PV penetration levels could cause reverse power flow back up onto the 11kV system.

4.3 Simulation Results for Case Studies Network

4.3.1 Commercial Area LV Distribution Network

For each network, the allowable PV volumes are determined based on two scenarios of PV distribution; i) Uniform distribution of PV across the three phases of the network and ii) PV installed on Phase A of the networks only. The allowable PV volumes that can be accommodated on the networks before violating any limit of the voltage magnitude, voltage unbalance factor and

thermal limit of the underground and transformer rating are determined.

Figure 4.3 shows the increase in the voltage magnitude at several buses of the commercial network when the capacity of PV is increased. At the PV capacity of 100 %, the voltage magnitude is about 1.05 pu which is the upper limit of allowable voltage excursion. As a result, 100 % of PV capacity is the allowable PV volume that can be accommodated by the commercial network as long as the voltage magnitude is kept below the upper limit. Table 4.3 shows the allowable uniform and non-uniform distribution of PV volumes that can be accommodated by the commercial networks before the voltage magnitude at any point exceeds the limits. However, if the PV systems are not uniformly distributed, then the amount of PV that can be accommodated is reduced by 50% as compared to that of the uniform distribution of PV. The allowable PV volumes to be accommodated on the networks before causing any voltage regulation violation is about 60% of the total load demands in the commercial networks. However, if PV is not uniformly distributed, then the total allowable PV volumes, with respect to voltage regulation, are reduced by 50 % as compared to that of the uniform distribution of PV.

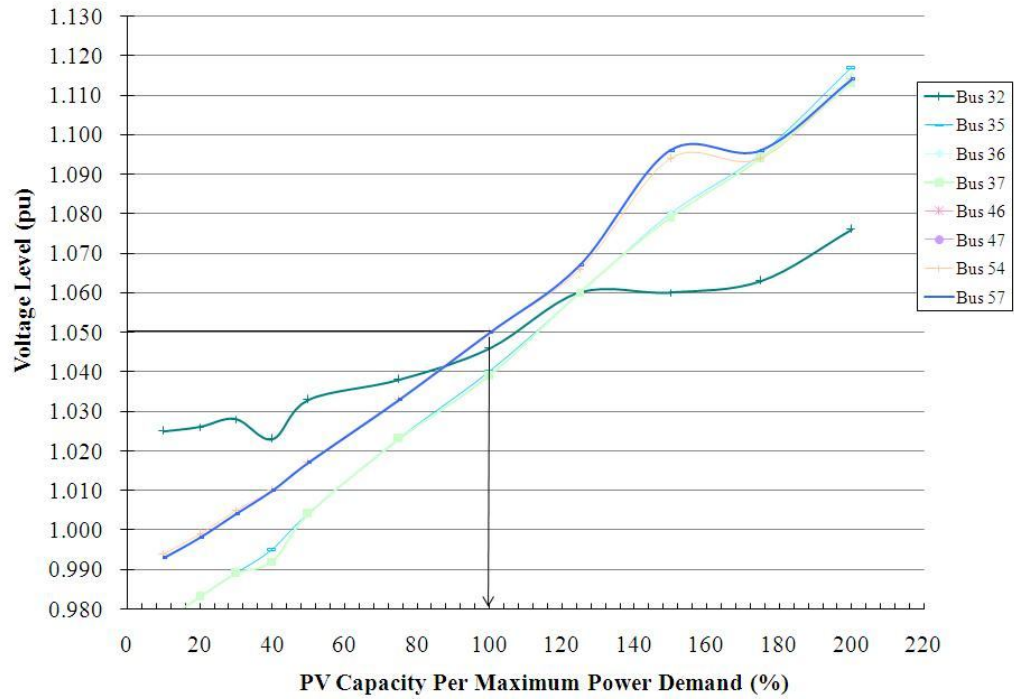


Figure 4.3 Voltage magnitude (pu) with the increase in PV capacity in the commercial network under uniform distribution of PV

Scenarios	Uniform distribution of PV	Non-uniform distribution of PV
Allowable PV Volume Before Violation of Voltage Rise	530 kW (100%)	265.5 kW (50%)
Allowable PV Volume Before Violation of Voltage Regulation	530.9 kW (100%)	265.5 kW (50%)

Table 4.3 Allowable PV volumes (kW) on the commercial networks before the violation of the voltage rise limit

Figure 4.4 shows the increase in voltage unbalance factors at several feeders as the capacity of PV grows on the commercial network under uniform distribution of PV. At about 50 % of PV capacity, the voltage unbalance factors

of the feeders are about 1.0 which is the upper limits for the allowable VUF in Malaysia. This means that the allowable volume of PV to be accommodated by the commercial network is 50 % for maintaining the VUF below the upper limit. Figure 4.5 shows the voltage unbalance factor for non-uniform distribution of PV. Non-uniform distribution PV on LV distribution network has greater impact on the VUF. It is shown that non-uniform distribution of PV can cause the allowable volumes of PV to reduce by 40% in the commercial networks compared to that of the uniform distribution of PV. Table 4.4 shows the allowable uniform and non-uniform distribution of PV volumes that can be accommodated by the commercial networks before violating the limit of voltage unbalance factor.

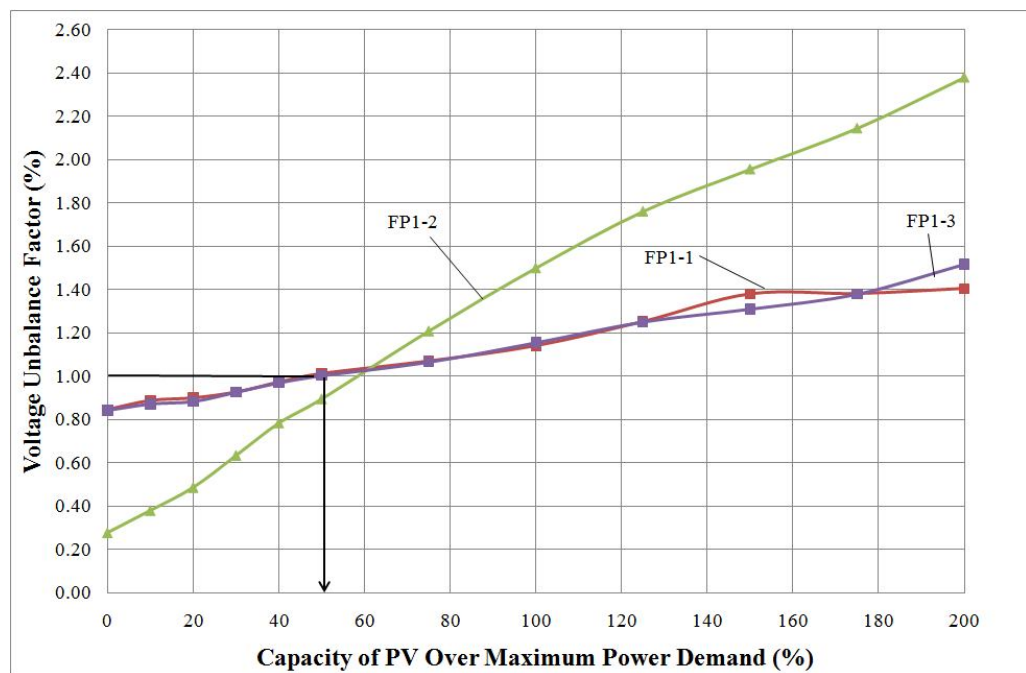


Figure 4.4 Voltage unbalance factor at feeders versus the capacity of PV for uniform distribution of PV for commercial network

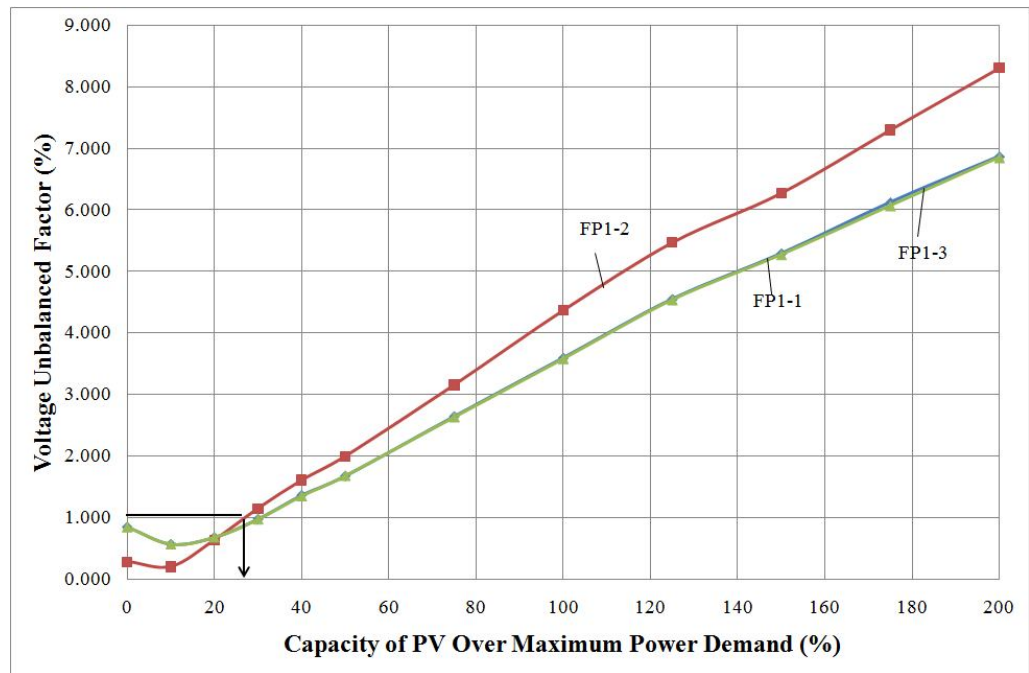


Figure 4.5 Voltage unbalance factor at feeders versus the capacity of PV for non-uniform distribution of PV for commercial network

Scenarios	Uniform distribution of PV	Non-uniform distribution of PV
Allowable PV Volume Before Violation of Voltage Unbalance Factor	265 kW (50%)	159 kW (30%)

Table 4.4 Allowable PV volumes (kW) on the commercial networks before exceeding the limit of the voltage unbalance factor

Figure 4.6 and figure 4.7 show the network power losses for each feeder under uniform and non-uniform distribution of PV for commercial area LV distribution network. The network power losses at each feeder are contributed by the impedance losses of all four cores conductors. Figure 4.8 shows the change in the total power loss as the PV capacity grows from 0 % to 200 % on

the commercial network under uniform and non-uniform distribution of PV. It is noticed that under the uniform distribution of PV, the power loss reduces as PV capacity increases from 10 % to 75 %. As the PV capacity grows, the amount of PV electricity available for the customers increases, hence minimising the electricity flow from the grid and the total power loss. However, the total network loss begins to rise as the PV capacity grows from 75 %. This is because the output of PV starts to be higher than the customer demands. This causes the PV electricity to be exported to the grid. As a result, 75 % of PV capacity is the allowable PV volumes that the network can accommodate before the increase in network loss.

As for non-uniform distribution of PV, it is shown that the allowable PV volumes on both networks under uniform distribution of PV are higher than that under non-uniform distribution of PV. This is because, under non-uniform distribution of PV, additional power losses occur due to the unbalance current flow through the neutral lines, hence making network losses to rise even at the low capacity of PV on the networks.

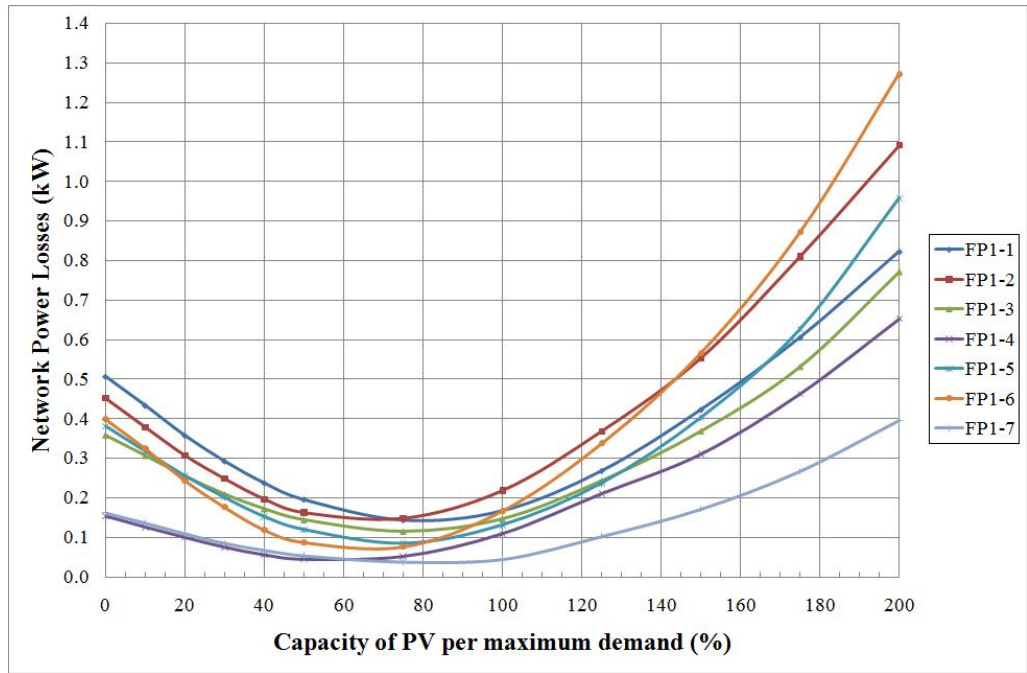


Figure 4.6 Network power losses for each feeder under uniform distribution of PV for commercial network

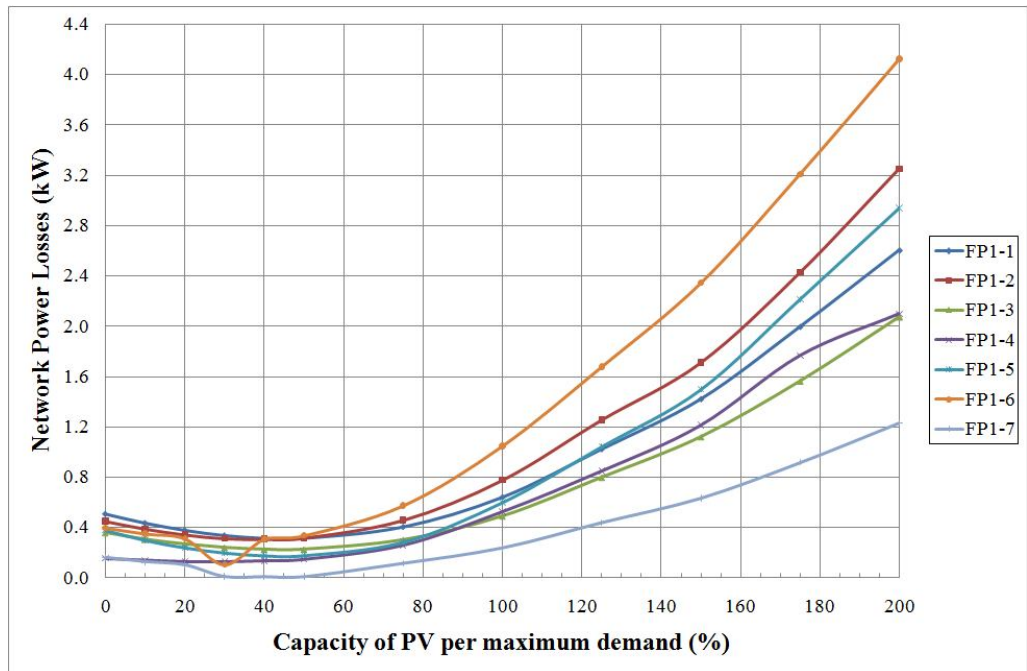


Figure 4.7 Network power losses for each feeder under non-uniform distribution of PV for commercial network

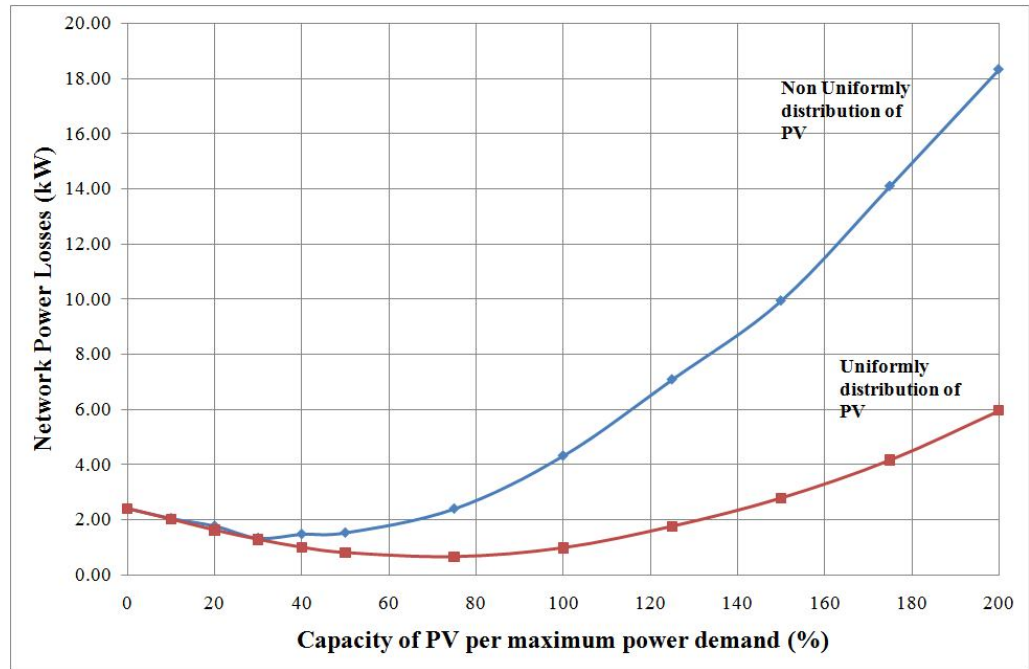


Figure 4.8 Total network power losses for uniform versus non uniform distribution of PV for commercial network

The current ratings of transformers Tx1 and Tx2 of the commercial network are 1.083 kA and 1.165 kA respectively. The ratings of Tx1 and Tx2 in the commercial network are 1000 kVA. It is shown in table 4.5 that the non-uniform distribution of PV results in the allowable PV volumes being higher than that of the uniform distribution of PV before violating the power rating of the transformers. This is because the network loss under non-uniform distribution of PV is higher than that under uniform distribution of PV. Therefore, a large volume of PV can be accommodated on the networks of non-uniform distribution of PV before the transformers are overloaded.

The current rating of the 70MMP 4C XLPE AL cable is 0.161 kA. The current rating of the 300MMP 4C XLPE AL cable is 0.434 kA. Table 4.6 shows that

uniform distribution of PV allows the networks to accommodate higher volumes of PV than that of the non-distribution of PV. This is because uniform distribution of PV enables PV current to be evenly distributed across three phases leading to reduced phase current. However, in both networks, such cables are used as double circuits for improving the reliability of electricity supply. Therefore, the current rating of the double circuits is 0.868 kA.

Scenarios	Transformers	Allowable PV Volume Before	
		Violation of Current Ratings	Violation of Power Ratings
Uniform Distribution of PV	Tx 1	1609.9 kW (300%)	1472.3 kW (277.8%)
	Tx 2	1499.3 kW (283%)	1509.1 kW (284.7%)
Non-Uniform Distribution of PV	Tx 1	794.9 kW (150%)	1765.5 kW (333.1%)
	Tx 2	515.4 kW (97.3%)	1866.4 kW (352.2%)

Table 4.5 Allowable PV volumes (kW) in the commercial networks before exceeding the current and power ratings of transformers

Scenarios	Cables	Uniform Distribution of PV	Non-Uniform Distribution of PV
Allowable PV Volume Before Exceeding the Current Rating of Any Cables	300MMP 4C XLPE AL	4858.3 kW	2484.6 kW
	70MMP 4C XLPE AL	4657.1 kW	2317.3 kW

Table 4.6 Allowable PV volumes (kW) in the commercial networks before exceeding the current rating of any cables

4.3.2 Residential Area LV Distribution Network

The introduction of PV on a residential distribution network can interfere with the standard regulation. As in the case of the earlier simulation, the allowable PV volumes that can be accommodated on the residential area LV distribution networks before violating any limit of the voltage magnitude, voltage unbalance factor and thermal limit of the underground and transformer rating are determined. The differences between commercial and residential area LV distribution networks have been mentioned in the previous chapter. Figure 4.9 shows the increase in the voltage magnitude at several buses of the residential network when the capacity of PV is increased. Table 4.7 shows the allowable PV volumes on the network before exceeding the voltage rise and voltage regulation limit. It was observed that under uniform distribution of PV, the allowable PV volume always higher than the non uniform distribution of PV, even though during period of low demand.

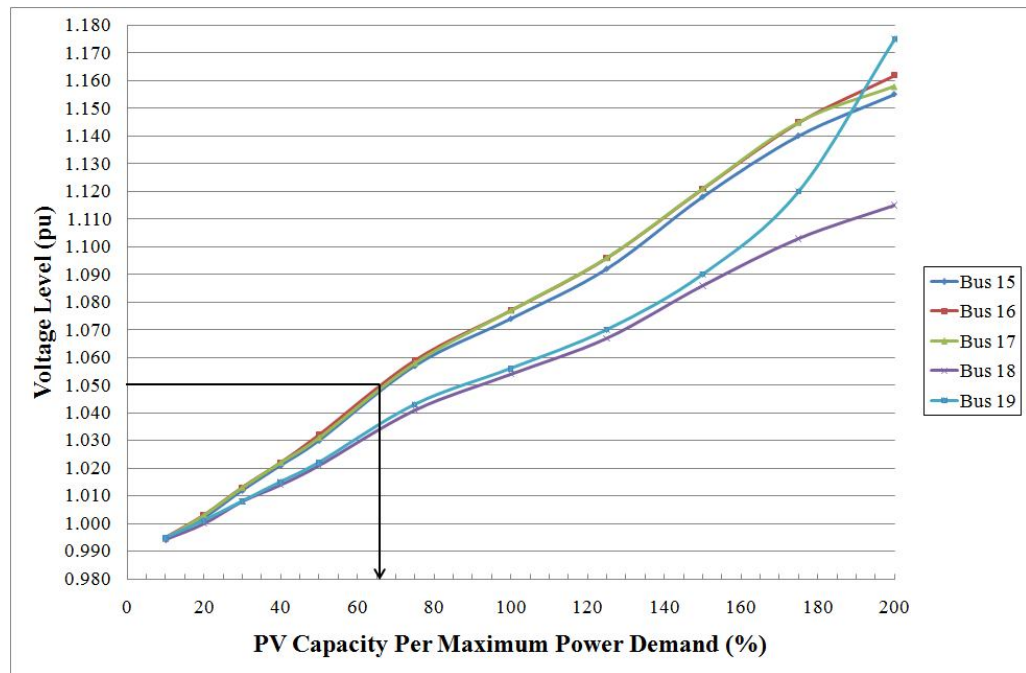


Figure 4.9 Voltage magnitude (pu) with the increase in PV capacity in the residential network under uniform distribution of PV

Scenarios	Uniform distribution of PV	Non-uniform distribution of PV
Allowable PV Volume Before Violation of Voltage Rise	9.45 kW (50%)	3.78 kW (20%)
Allowable PV Volume Before Violation of Voltage Regulation	14.17 kW (75%)	5.67 kW (30%)

Table 4.7 Allowable PV volumes (kW) on the residential networks before the violation of the voltage rise limit

Asymmetrical impedances, the connection of PV in single-phase, and uneven distribution of load have been postulated in chapter two as the major causes of voltage unbalance in the LV distribution network. The %VUF at the load end of the network under uniform distribution of PV is shown in figure 4.10. It is

seen from the figure that the %VUF increases as the capacity of PV increases. It is shown that the allowable volume of PV to be accommodated by the commercial network is 78 % for maintaining the voltage unbalanced factor below the upper limit of 1%. Figure 4.11 shows the voltage unbalance factor at the feeders for non-uniform distribution of PV for residential network. It is evident that non uniform distribution of PV has greater impact for voltage unbalance factor. The simulation has demonstrated that the inclusion of PV in the same phase of the network results in the flow of asymmetrical sequence currents, which causes the %VUF to increase gradually. Table 4.8 shows the allowable uniform and non-uniform distribution of PV volumes that can be accommodated by the residential networks before the violating the limit of voltage unbalance factor.

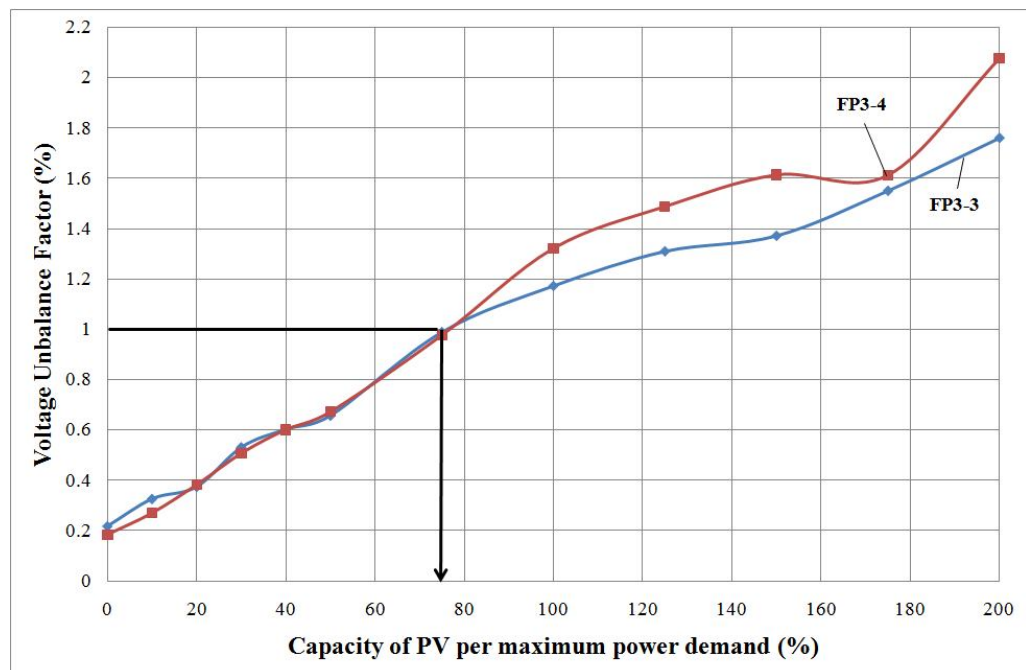


Figure 4.10 Voltage unbalance factor at feeders versus the capacity of PV for uniform distribution of PV for residential network

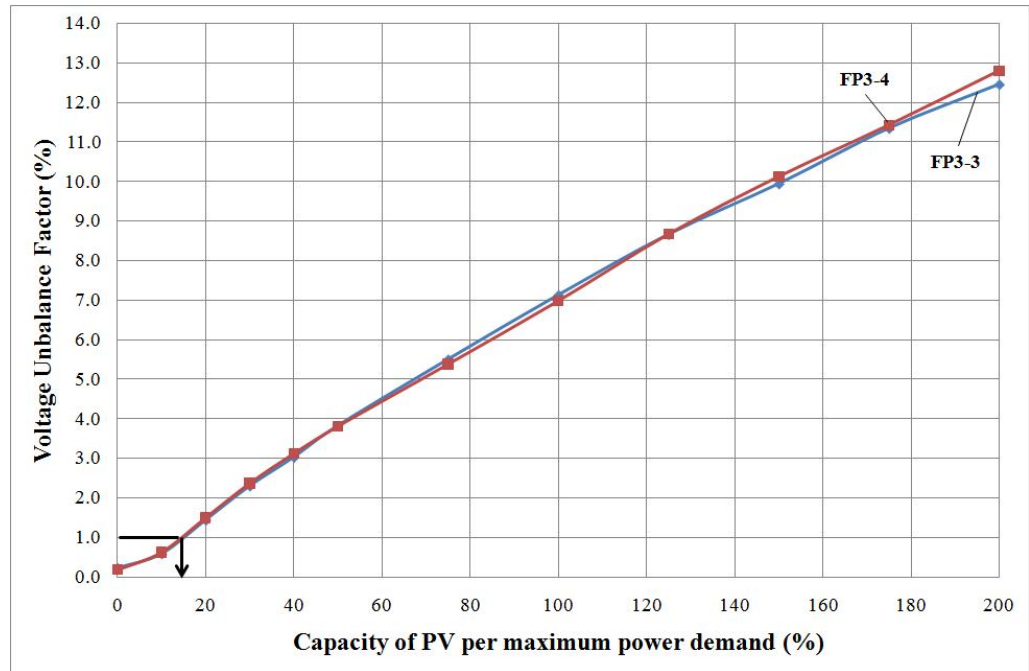


Figure 4.11 Voltage unbalance factor at feeders versus the capacity of PV for non-uniform distribution of PV for residential network

Scenarios	Uniform distribution of PV	Non-uniform distribution of PV
Allowable PV volume before violation of voltage unbalance factor	14.74 kW (78%)	1.89 kW (10%)

Table 4.8 Allowable PV volumes (kW) on the residential networks before exceeding the limit of the voltage unbalance factor

The total network power losses in the distribution networks are due to the resistance of the underground cables and overhead lines. Figure 4.12 and figure 4.13 show the network power losses for each feeder under uniform and non-uniform distribution of PV for residential area LV distribution network. Figure 4.14 shows the total network power losses for residential area LV distribution

network under uniform and non-uniform distribution of PV. When PV capacity grow from 0% to 200%, total network losses under non-uniform distribution PV can increase up to 300% as compared with uniform distribution of PV. Future distribution networks in Malaysia are likely to have high penetration of PV. High network power losses are contributed by the neutral wire when asymmetrical current flows through the neutral line. Inappropriate PV allocation can cause low or over-voltages in the network, furthermore, when PV generates higher power than the demand, reversed power flows may occurs and interfere with the traditionally used regulation practises (Baker PP, 2000).

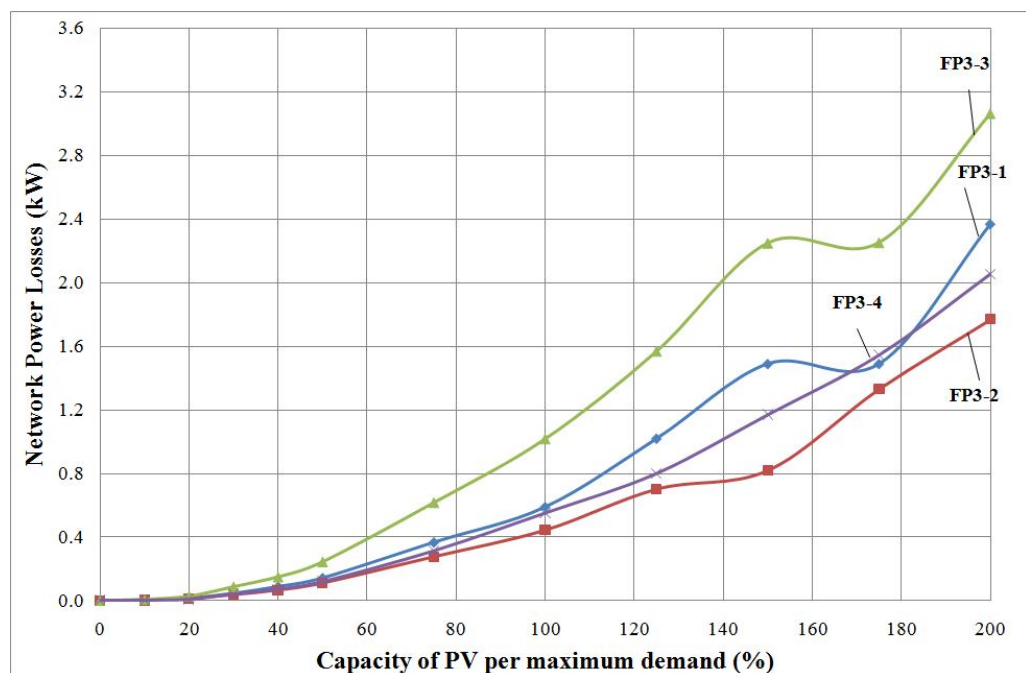


Figure 4.12 Network power losses for each feeder under uniform distribution of PV for residential network

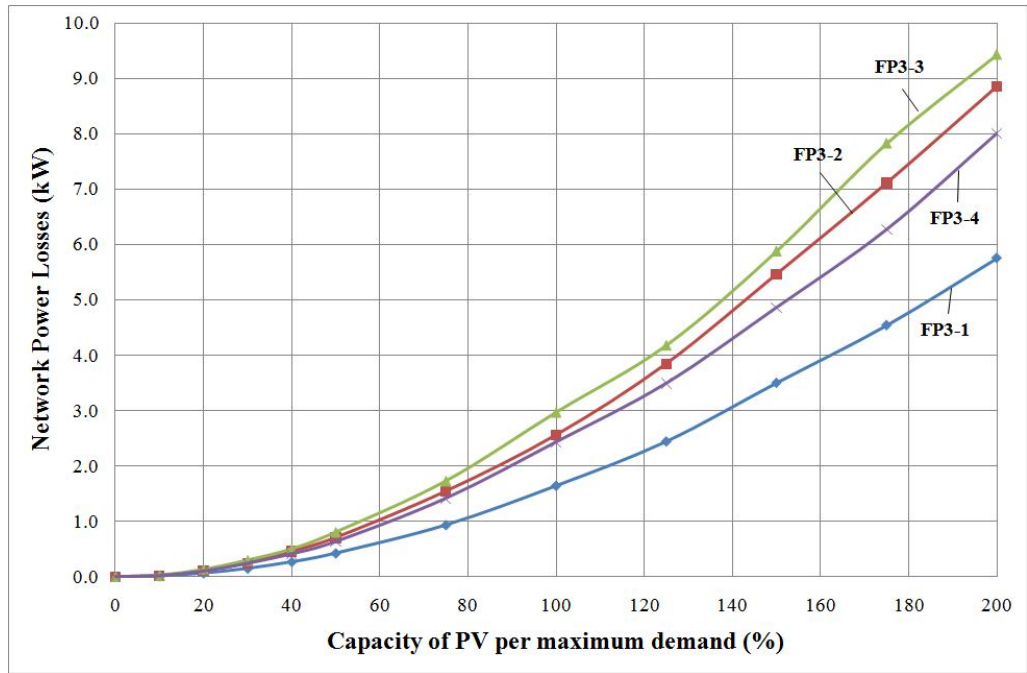


Figure 4.13 Network power losses for each feeder under non-uniform distribution of PV for residential network

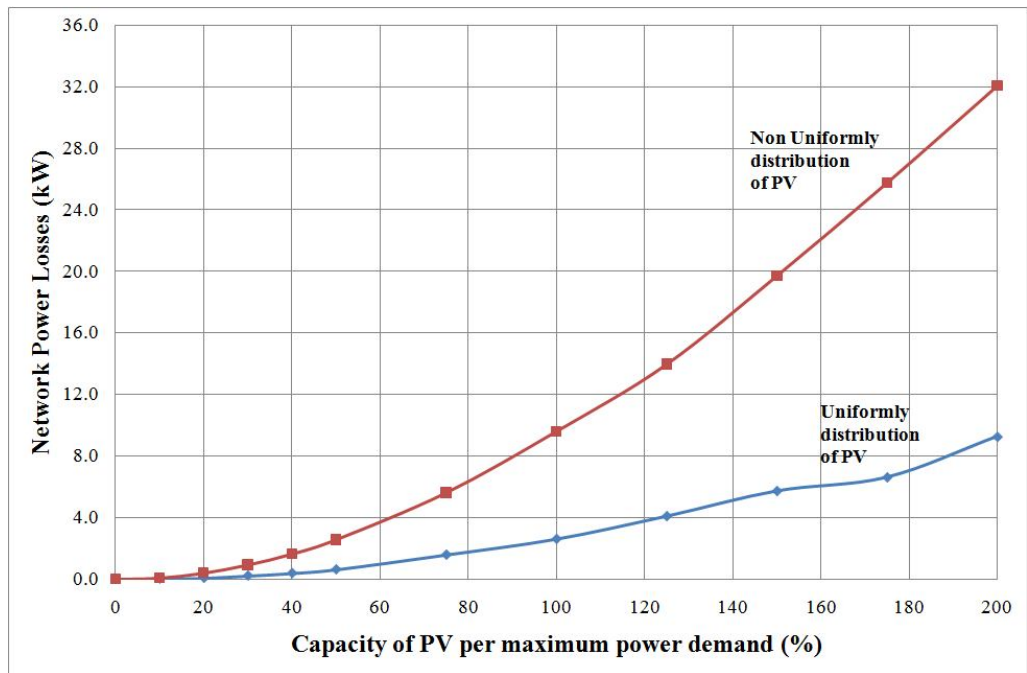


Figure 4.14 Total network power losses for uniform versus non-uniform distribution of PV for residential network

Table 4.9 and table 4.10 show the allowable PV volumes to be accommodated on the residential area LV distribution networks before exceeding the power and current ratings of transformers and cables. The current ratings of Tx1 and Tx2 of the residential network are 0.825 kA and 0.782 kA respectively. While the power ratings of transformers Tx1 and Tx2 in the residential network are 750kVA. Residential area LV distribution network utilize only 300MMP 4C XLPE AL cable to distribute electricity to end user. In order to improve the reliability of electricity supply, double circuit configuration is used for the cables so that the system can accommodate higher current flows to end users.

Scenarios	Transformers	Allowable PV Volume Before	
		Violation of Current Ratings	Violation of Power Ratings
Uniform Distribution of PV	Tx 1	38.74 kW (205%)	87.6 kW (463.5%)
	Tx 2	24.9 kW (131.7%)	58.1 kW (307.4%)
Non-Uniform Distribution of PV	Tx 1	12.0 kW (63.5%)	88.4 kW (467.7%)
	Tx 2	8.13 kW (43%)	59.6 kW (315.3%)

Table 4.9 Allowable PV volumes (kW) in the residential networks before exceeding the current and power ratings of transformers

Scenarios	Cables	Uniform Distribution of PV	Non-Uniform Distribution of PV
Allowable PV Volume Before Exceeding the Current Rating of Any Cables	300MMP 4C XLPE AL	32.13 kW	8.5 kW

Table 4.10 Allowable PV volumes (kW) in the residential networks before exceeding the current rating of any cables

4.4 Conclusions

With the use of these 2 three-phase four wire PSCAD models of the commercial and residential networks, studies were carried out to investigate the response of voltage, network losses, current and power flow of both networks with respect to the penetration of PV systems. The differences in the characteristics and parameters of the commercial and residential networks make these networks respond differently to the penetration of PV systems. The response of the networks was studied under two conditions; i) Uniform distribution of PV and ii) Non-uniform distribution of PV. It was shown that non uniform distribution of PV can cause the commercial and residential networks to reduce the amount of PV volumes as compared to the uniform distribution of PV under most of the technical constraints. It was also noticed that the commercial and residential networks suffered from voltage unbalance problems which could limit the growth of PV systems. This is mainly because of the tight voltage unbalance limit imposed by the utility companies in

Malaysia and the type of earthing arrangement used. T-T arrangement may not be an effective means of maintaining balanced networks in the presence of significant levels of single phase PV.

The allowable PV volumes that can be installed on the commercial and residential networks without violating any of the technical limits were found to be 318.58 and 14.74 kW respectively, for uniform distribution of PV systems. With such capacities of PV systems, the total amount of electricity that can be generated by the PV systems are 350 MWh and 16 MWh per year respectively. These amounts of solar electricity can reduce the emission of greenhouse gas by 6476 and 299 tonnes respectively. The PV owners can generate additional incomes by selling their “Certified Emission Reduction (CERs)”.

CHAPTER 5

MODELING OF ENERGY STORAGE UNIT INTEGRATED WITH FOUR QUADRANT CONVERTERS

5.1 Introduction

As discussed in Chapter 4, voltage unbalance has been identified as the main barrier to the penetration of distribution generation because the statutory limit of the voltage unbalance in Malaysia is 1% which is much stringent as compared to 1.3% in the UK and 2% in EU. The MBIPV project was aimed to induce the growth of BIPV installations by approximately 400% from 470 kW in 2006 to approximately 2,000 kW by 2010, with a unit cost reduction in the region of 20%. Up to date, the MBIPV Project leader has announced an achievement of 25% cost reduction in BIPV system. Currently, the government is considering a new feed-in tariff scheme allowing the owners of BIPV systems to make profits after several years of their generating system operations.

In order to allow the required penetration of renewable energy sources to be achieved with minimum power quality issues, it is proposed to use energy

storage unit integrated with a four quadrant converter. This energy storage unit is installed at the appropriate point of the low voltage distribution network in order to control the export or import of its real and reactive power depending on the network conditions.

In this chapter, two simple low voltage distribution networks used to study the interaction between the energy storage unit and the renewable energy sources in PSCAD/EMTDC are to be described. Then the concept of integrating the energy storage unit with the four quadrant converter is to be introduced. The control algorithm implemented in the converter to control the flow of its real and reactive power is to be described.

5.2 Development of Simplified LV Distribution Networks

Two simplified LV distribution networks as shown in figure 5.1 and figure 5.2 are modelled in PSCAD/EMTDC. These networks are established based on the Malaysian and UK LV distribution networks (P. F. Lyons, P. Trichakis, P. C. Taylor, G. Coates, 2009; Padraig Lyons, 2009; Lim Yun Seng, G. Lalchand and Gladys Mak, 2008). The distribution network models described in this section are modeled as TT grounded and TT multi-grounded three-phase four wire system. The secondary side of the substation transformer is wye connected and solidly grounded along with the neutral line.

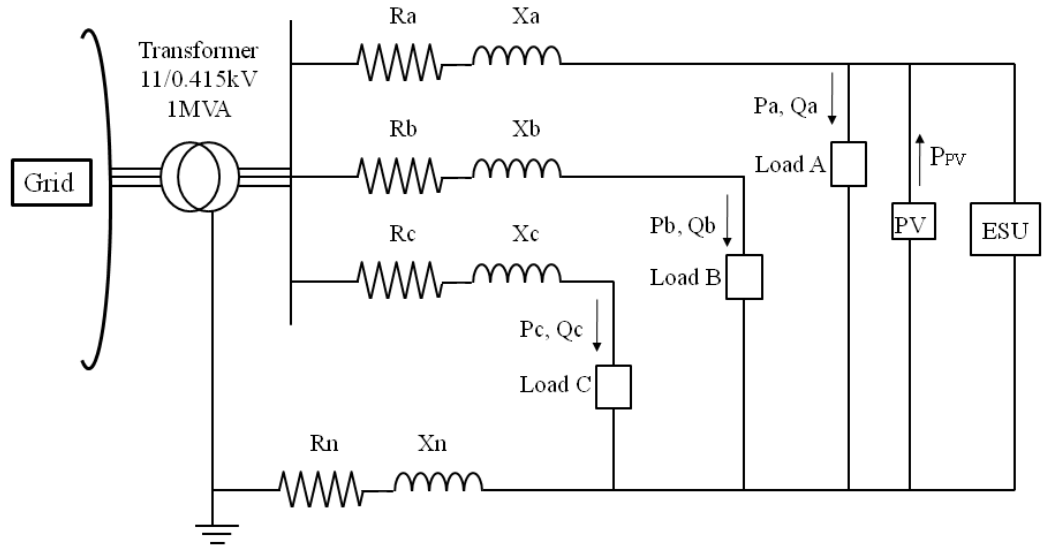


Figure 5.1 Layout of the simplified LV distribution network 1

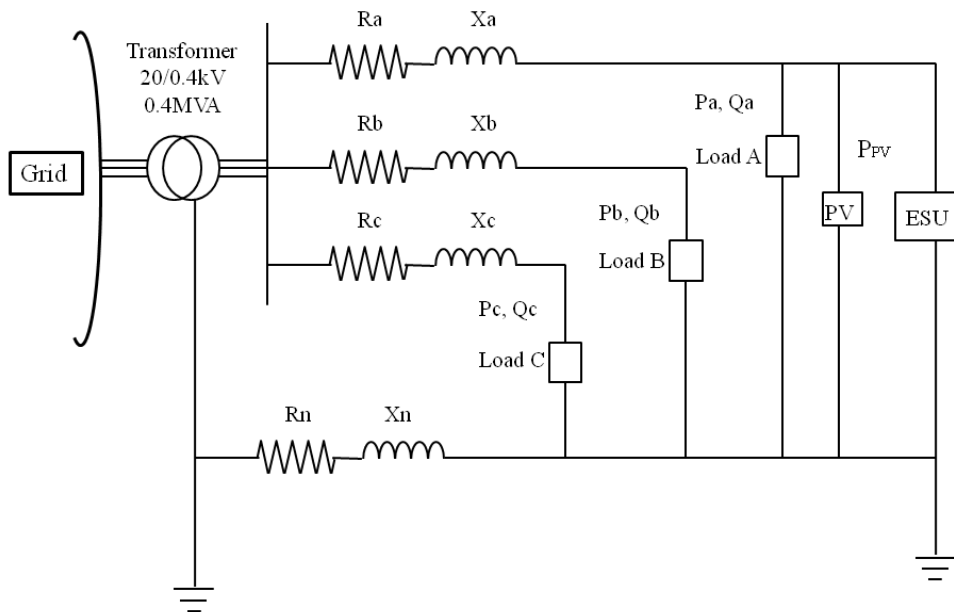


Figure 5.2 Layout of the simplified LV distribution network 2

Single and three-phase loads are modelled as constant active and reactive power consumers connected to the distribution network. Static load models are used. The load power factor under normal operation is within the range of 0.98 lagging to 0.98 leading. In these case studies, the loads were assumed to be balanced at all three-phases. The level of voltage unbalance would be solely

affected by the capacity of PV systems.

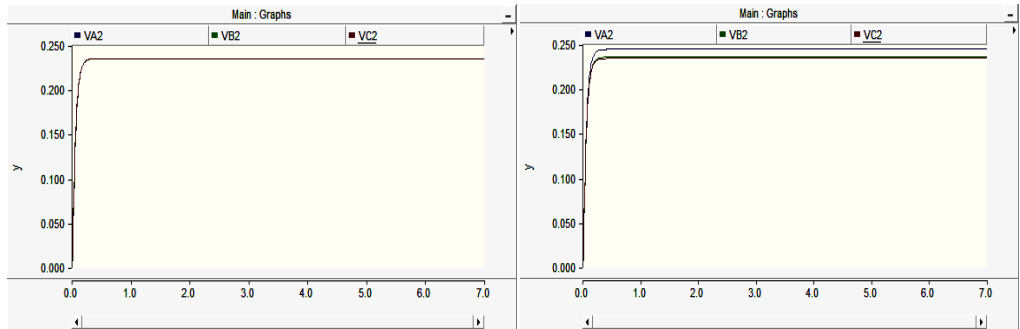
The inverter circuit of PV system is built by 4 insulated-gate bipolar transistors (IGBT). These IGBT models are normally used as controlling switches in high voltage devices with large power ratings. Appropriate gate triggering pulses are generated and applied to the terminals of the thyristors which results in a square wave output. The triggering pulses are generated by programming the components in the required manner. The inverter is then connected to one of the three phases at the customers' side via a coupling circuit consisting of a resistor of 0.001ohms and an inductor of 67.35mH. Two networks namely network 1 and 2 with different characteristics are modelled in PSCAD. The characteristics of both networks are shown in table 5.1.

No	Characteristic	Network 1	Network 2
1	3 Phase Transformer Rating	1 MVA	0.4 MVA
2	Base Operation Frequency	50 Hz	50 Hz
3	Primary Winding #1 Type	Delta	Delta
4	Secondary Winding #2 Type	Y	Y
5	Winding Voltage (#1/#2)	11kV/ 0.415kV	20kV/ 0.4 kV
6	Grounding type	TT	TT with multiple grounding
7	Phase Resistance R_a, R_b, R_c (ohms)	0.0544	0.03783

8	Phase Reactance (ohms) X_a , X_b , X_c	0.01815	0.00688
9	Neutral Resistance (ohms) R_n	0.0544	0.03783
10	Neutral Reactance (ohms) X_n	0.01815	0.0028

Table 5.1 Characteristics of LV distribution networks 1 and 2.

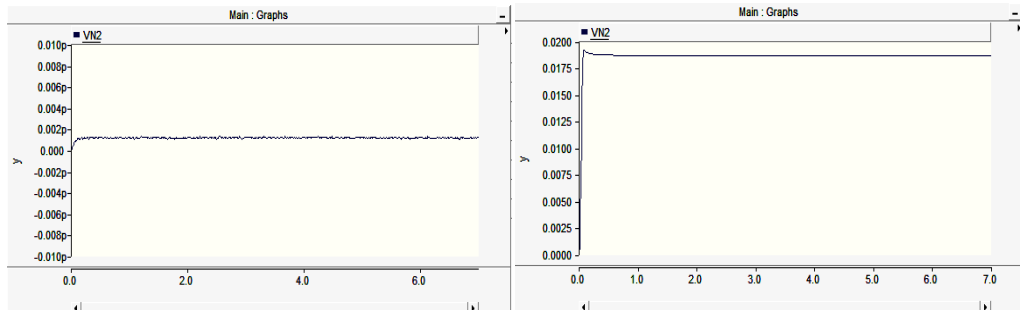
Figure 5.3 and figure 5.5 show the voltage level at the feeder end before and after the connection of PV onto phase A for networks 1 and 2. Initially, the three-phase voltages have the same magnitude. When PVs are connected onto phase A, it is obvious that phase A voltage is higher than the other 2 phases. Figure 5.4 and figure 5.6 show the voltage across the neutral line. The network is balanced when there's no PV connected. Hence, the voltage across the neutral line can be negligible. When the PVs are connected only at phase A, resulting in an unbalanced system, there are unbalanced voltages across the neutral line. Figure 5.7 shows the power flow at the feeder end for phase A, B, C and also neutral for both networks 1 and 2 with PVs connected only at phase A. It is obvious that, power flow in phase A has been affected. Reversed power flow is possible if the power generated by the distributed generator is greater than demand.



(a)

(b)

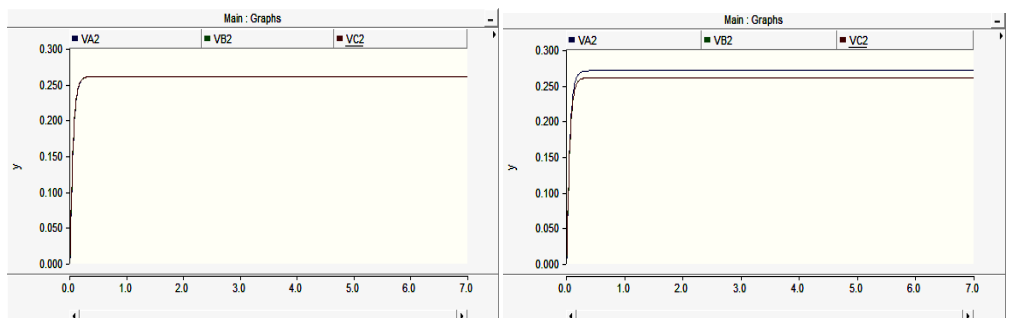
Figure 5.3 RMS phase voltage at the feeder end for network 1 (a) without PV system and (b) with PV system connected on Phase A



(a)

(b)

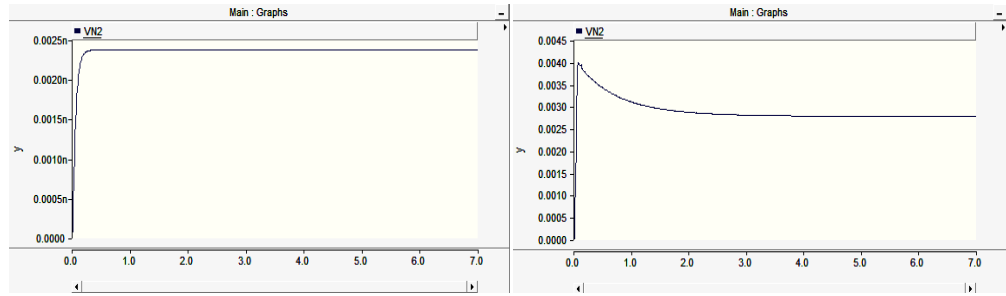
Figure 5.4 RMS value of neutral voltage at the feeder end for network 1 (a) without PV system, at $t=3.0s$, $V_n \approx 0kV$ and (b) with PV system connected on Phase A, at $t=3.0s$, $V_n=0.018kV$



(a)

(b)

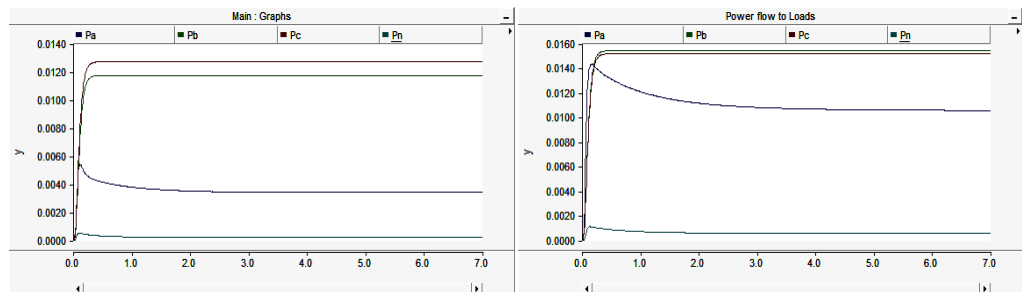
Figure 5.5 RMS phase voltage at the feeder end for network 2 (a) without PV system and (b) with PV system connected on Phase A



(a)

(b)

Figure 5.6 RMS value of neutral voltage at the feeder end for network 2 (a) without PV system, at $t=3s$, $V_n \approx 0kV$ and (b) with PV system connected on Phase A, at $t=3s$, $V_n = 0.026kV$



(a)

(b)

Figure 5.7 Power flow at the feeder end for (a) network 1 and (b) network 2 with PV connected at phase A

5.3 Computer Modeling of Energy Storage Unit Integrated with Four Quadrant Converter

Conventional distribution systems are designed to accept power transmitted from the supply transformer and to distribute it to customers. Hence, the flow of both real and reactive power is always from the high to low voltage levels. However, with significant penetration of the renewable energy sources, power flow tends to reverse and the network will no longer be a passive circuit

supplying power to the loads but an active system with power flowing to the loads and to the transformer (N. Jenkins, R. Allan, P. Crossley, D. Kirschen and G. Strbac, 2000). FACTS (Flexible AC Transmission Systems) devices were investigated for voltage correction by reactive power compensation in an LV distribution network. However, it has limited effect because the distribution network has rather low X/R ratios. Therefore, the concept of energy storage unit integrated with four quadrant converter is introduced to the LV distribution system as it is capable of controlling the flow of real and reactive power from the converter according to the voltage magnitude level and the phase angle at the point of common coupling between the converter and the grid. Voltage rise and phase angle rise at the point of common connection between the converter and the grid can be represented as the following:

$$\Delta V = \frac{(P_G - P_L)R + (Q_G - Q_L)X}{|V|} \quad (5.1)$$

Where

P_G, Q_G = Real and Reactive power of VSC, respectively

P_L, Q_L = Real and Reactive power of Load, respectively

R, X = Line Resistance and Reactance, respectively

V = Line voltage

Since the distribution network has rather low X/R ratio, the resistance, R is always higher than reactance, X. We can conclude that reactive power has lesser influence to the distribution network than real power. Furthermore, it is not possible to decouple both real and reactive power compensation in distribution networks. Hence, a four quadrant converter with 4 different

conditions as shown in figure 5.8 is designed to compensate both real and reactive power and also to control the voltage and phase angle at the point of connection.

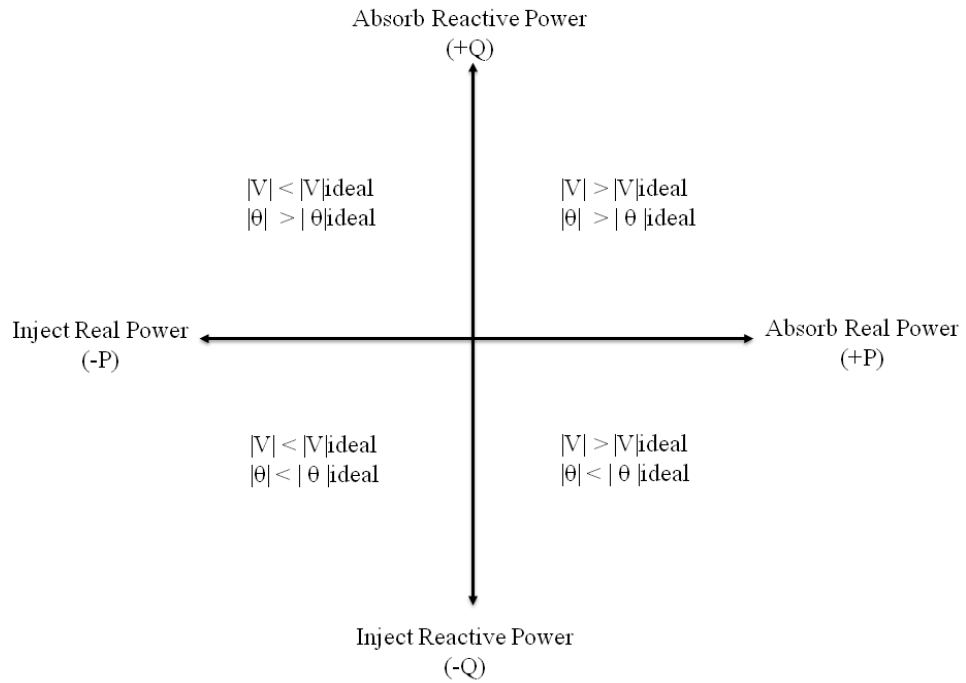


Figure 5.8 Conditions for controlling real and reactive power flow from the four quadrant converter

Figure 5.9 shows the block diagram of the energy storage system integrated with a four quadrant converter. It consists of a bi-directional inverter that converts AC to DC or DC to AC from the network to batteries or vice versa. A measurement unit measures the real and reactive power flows at the point of connection and sends signals to the controller that can be used to control the inverter. Real time values of voltage magnitude and phase angle will be determined by the measuring unit in order to select appropriate reference values of P and Q, to inject or absorb real and reactive power. PQ controller is used to determine the appropriate control algorithm in order to inject or absorb

the real and reactive power flow to/from the batteries.

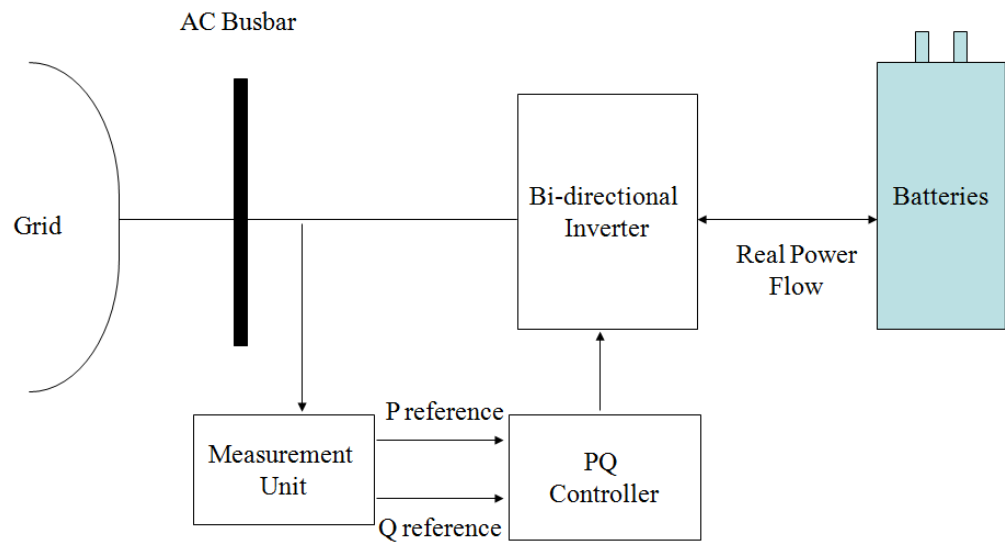


Figure 5.9 The block diagram of the energy storage system integrated with four quadrant converter

Figure 5.10 shows the PSCAD model of the energy storage system integrated with four quadrant converter in addition to the block diagram of figure 5.9. The system consists of 3 primary model elements: inverter system, battery and PQ controller. The measurement unit will send signals to the PQ controller in order to select the appropriate reference value to mitigate the power quality issues. Batteries provide storage for excess real power generated by the PVs and real power compensation in order to mitigate the voltage unbalance factor.

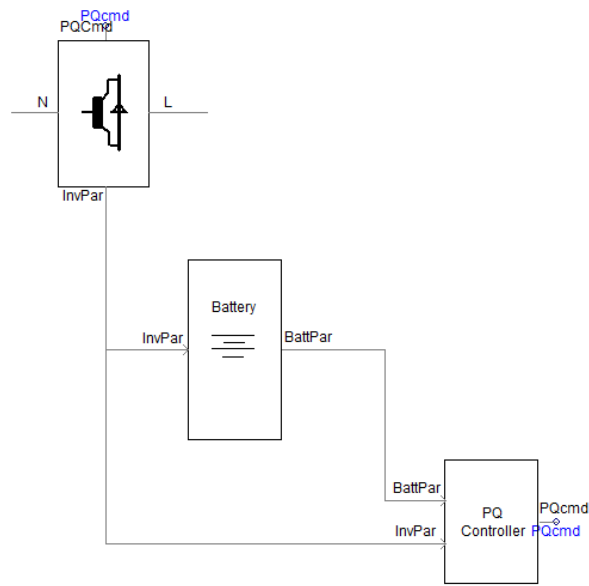


Figure 5.10 The PSCAD model of the energy storage system integrated with four quadrant converter

5.3.1 Battery Modeling

In order to investigate the active power control, an energy storage unit has been modelled in PSCAD. This enables import and export of real power flow from/to the LV distribution networks. Practically, there are many types of batteries and many factors which affect the battery performance. During the modeling, several factors need to be considered, these are listed as follows:

- State of charge and depth of discharge
- Battery storage capacity
- Rate of charging and discharging

Batteries are represented by Thevenin's equivalent circuit as shown in figure 5.11 while the PSCAD battery model is shown in figure 5.12.

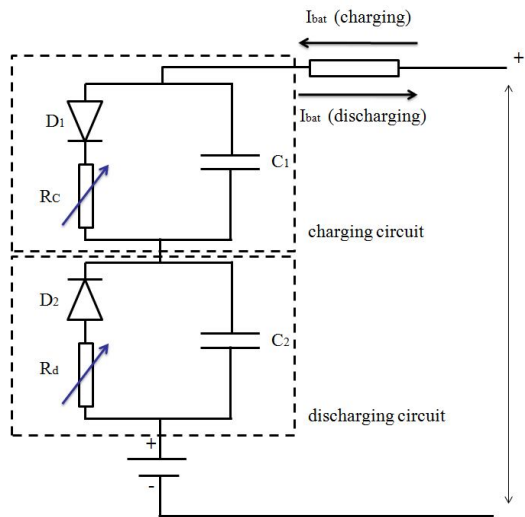


Figure 5.11 Thevenin's equivalent circuits for battery model

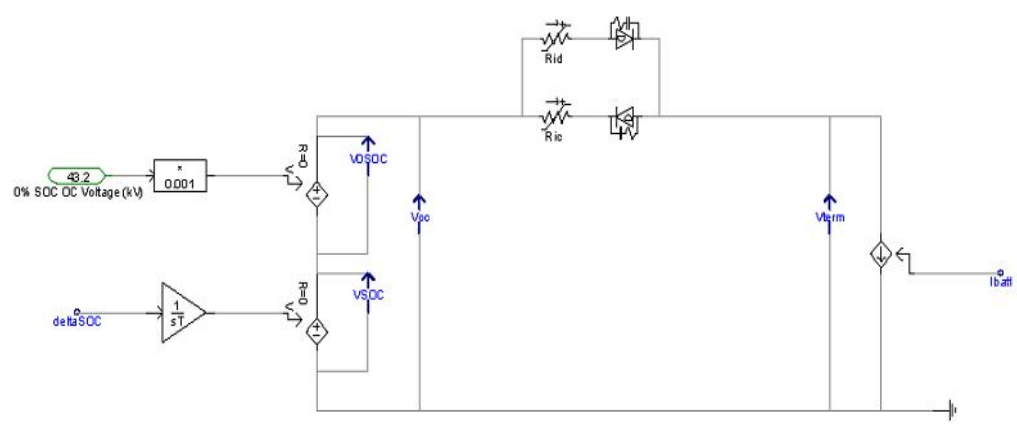


Figure 5.12 PSCAD model for battery (L. M. Cipcigan, P. C. Taylor, P. F. Lyons, 2009)

The equations for the described battery model are defined in two manners which are charging and discharging modes, as follows:-

For Charging:
$$V_{term} = V_{0\%soc} + V_{soc} + I_{batt}R_{ic} \tag{5.2}$$

For Discharging:
$$V_{term} = V_{0\%soc} + V_{soc} + I_{batt}R_{id} \tag{5.3}$$

Where

V_{term} = Terminal voltage for battery

$V_{0\% \text{soc}}$ = Open circuit voltage at 0% State of Charge, SOC

V_{soc} = Effect of battery SOC on open circuit voltage

I_{batt} = Internal current flow

$R_{\text{ic}}/ R_{\text{id}}$ = Variable resistance for charging/ discharging circuit

The variable resistances are dependent on the SOC of the battery and the charging/ discharging current. The SOC of a battery is checked in order to determine the condition of the individual cells. The nominal voltage of this battery is 12V and rated at 110Ah. Peukert equation is used to derive the capacity of the battery at a specific current, and can be represented as follows:-

$$I_i^n \tau_{ci} = \text{constant} \quad (5.4)$$

Where

I_i = discharge current

τ_{ci} = time to discharge the battery completely (hours)

n = constant, 1.35 for lead acid battery

Using this relationship, the battery ampere-hour (Ah) capacity at some discharge rate, say 20 hours rate, is now written as follows (Bumby et al., 1985) :-

$$C_1 = C_{20} \left(\frac{I_{20}}{I_1} \right)^{n-1} \quad (5.5)$$

Where

C = discharge rate

I = discharge current

As the battery SOC depends on the net discharge ampere-hours, by assuming a constant discharge current, the SOC is expressed as the following:

$$SOC = 1 - \frac{C_{Di}}{C_i} \quad (5.6)$$

Where

$$C_{Di} = I_i \tau_{Di}$$

I_i = the discharge current in ampere

τ_{Di} = the discharge time in hours

By manipulating (5.4), (5.5) and (5.6) the relationship of SOC at constant discharge rate is represented as the following (L. M. Cipcigan, P. C. Taylor, P. F. Lyons, 2009):

$$SOC = \frac{(1 - (I_i \tau_{Di}))}{C_{20} \left(\frac{I_{20}}{I_i} \right)^{n-1}} \quad (5.7)$$

Unfortunately, during discharging cycle, the discharge rate is not constant but varies from time to time, and therefore, a small change of SOC is considered. Consequently, equation (5.6) for non-constant discharge rate, ΔSOC can be written as follows:-

$$\Delta SOC = -\left(\frac{\Delta C_{Di}}{C_i}\right) = -\left(\frac{I_i \Delta t}{36000}\right) \left(\frac{1}{C_i}\right) = -\frac{I_i \Delta t}{3600 C_{20}} \left(\frac{I_i}{I_{20}}\right)^{n-1}$$

$$\frac{d(SOC)}{dt} = \frac{-i(t)}{(3600)(C_{20})\left(\frac{I_{20}}{I_i}\right)^{n-1}} \quad (5.8)$$

During constant charging, an expression for the rate of change of SOC is formed by the following (Bumby et al., 1985):

$$\frac{d(SOC)}{dt} = \frac{I_i n_c}{(3600)(C_{20})} \quad (5.9)$$

Where

n_c = constant charge efficiency

I_i = the discharge current in ampere

5.3.2 Modeling the Four-quadrant Converter

Voltage and frequency droop control method (K. De Brabandere and et. al., 2004) for inverter is a methodology without the need for any common control circuitry or communication between the inverters. In LV distribution network, the active resistance R is always larger than the reactance of the line, $R \gg X$. Therefore, the control principles are different from the high voltage network. The implemented droop method is applied to control both active and reactive power. It is efficient in controlling both voltage and phase angle in proportion to the needed active and reactive power flows. Figure 5.13 shows the power flowing from point A (connected to the grid) to point B (connected to the

inverter). The apparent power, S can be written as follows:-

$$S = P + jQ = EI^* \quad (5.10)$$

$$\begin{aligned} S &= E \left(\frac{E - V}{Z} \right)^* \\ &= E \left(\frac{E - Ve^{j\delta}}{Ze^{j\delta}} \right) \\ &= \frac{E^2}{Z} e^{j\delta} - \frac{EV}{Z} e^{j(\theta+\delta)} \end{aligned} \quad (5.11)$$

S is the apparent power, P and Q are the real and reactive power respectively and δ , θ , and ϕ are the corresponding angle of the load voltage phasor, complex impedance and current phasor taking the source voltage V as reference. Total apparent power flowing from point A to point B from equation (5.11) can be further written as the follows:-

$$\begin{aligned} S &= \frac{E^2}{Z} (\cos \theta + j \sin \theta) - \frac{EV}{Z} [\cos(\theta + \delta) + j \sin(\theta + \delta)] \\ &= \frac{E^2}{Z} \cos \theta - \frac{EV}{Z} \cos(\theta + \delta) + j \left[\frac{E^2}{Z} \sin \theta - \frac{EV}{Z} \sin(\theta + \delta) \right] \end{aligned} \quad (5.12)$$

Thus, the active and reactive power components can be decoupled as follows:-

$$P = \frac{E^2}{Z} \cos \theta - \frac{EV}{Z} \cos(\theta + \delta) \quad (5.13)$$

$$Q = \frac{E^2}{Z} \sin \theta - \frac{EV}{Z} \sin(\theta + \delta) \quad (5.14)$$

With $Ze^{j\theta} = R+jX$, thus $Z=\sqrt{(R^2+X^2)}$; $\cos \theta = \frac{R}{Z}$; $\sin \theta = \frac{X}{Z}$ and using the trigonometri identities $\{ \cos (\theta+\delta)= \cos \theta \cos \delta- \sin \theta \sin \delta ; \sin (\theta+\delta)= \cos \theta \cos \delta+ \sin \theta \sin \delta \}$

$$P = \frac{E^2}{Z} \left(\frac{R}{Z} \right) - \frac{EV}{Z} \left[\frac{R}{Z} \cos \delta - \frac{X}{Z} \sin \delta \right]$$

$$P = \frac{E}{R^2 + X^2} [R(E - V \cos \delta) + XV \sin \delta] \quad (5.15)$$

And

$$Q = \frac{E^2}{Z} \left(\frac{X}{Z} \right) - \frac{EV}{Z} \left[\frac{R}{Z} \cos \delta + \frac{X}{Z} \sin \delta \right]$$

$$Q = \frac{E}{R^2 + X^2} [-RV \sin \delta + X(E - V \cos \delta)] \quad (5.16)$$

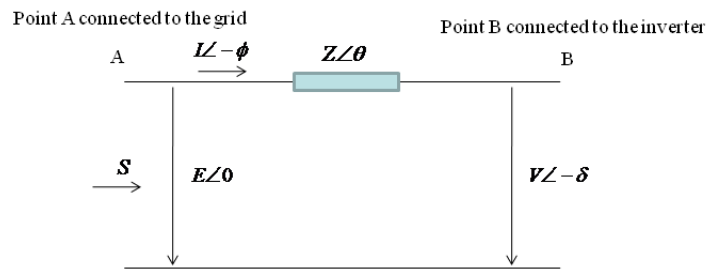


Figure 5.13 Power flow from the grid to the inverter

As mentioned above, the active resistance R in LV distribution networks is always larger than the reactance of the line, $R \gg X$. In this case, assuming $X=0$ and the power angle δ is so small, $\cos \delta =1$ and $\sin \delta =\delta$. Equation 5.15 and 5.16 can be further written as follows:-

$$P = \frac{E}{R}(E - V) \quad (5.17)$$

$$Q = \frac{EV}{R} \delta \quad (5.18)$$

It is noticed that adjusting active power P will influence the voltage magnitude (E-V), while adjusting the reactive power Q influences the power angle δ . Figure 5.14 shows the single - phase current source inverter control circuit for both real and reactive power flow injection in to the LV distribution network. The inverter uses a pair of PI controllers to regulate the real and reactive power flow of the current source (Akagi. H., Kanazawa Y., Nabae A., 1984). The current flows of the inverter model is sinusoidal and do not consider semi-conductor switching effects. Figure 5.15 is the PSCAD model for bi-directional inverter including the control circuit shown in figure 5.14. The inverter uses a phase detector that works similar to the phase locked loop (PLL). The phase detector measures the absolute phase of the phase-neutral voltage.

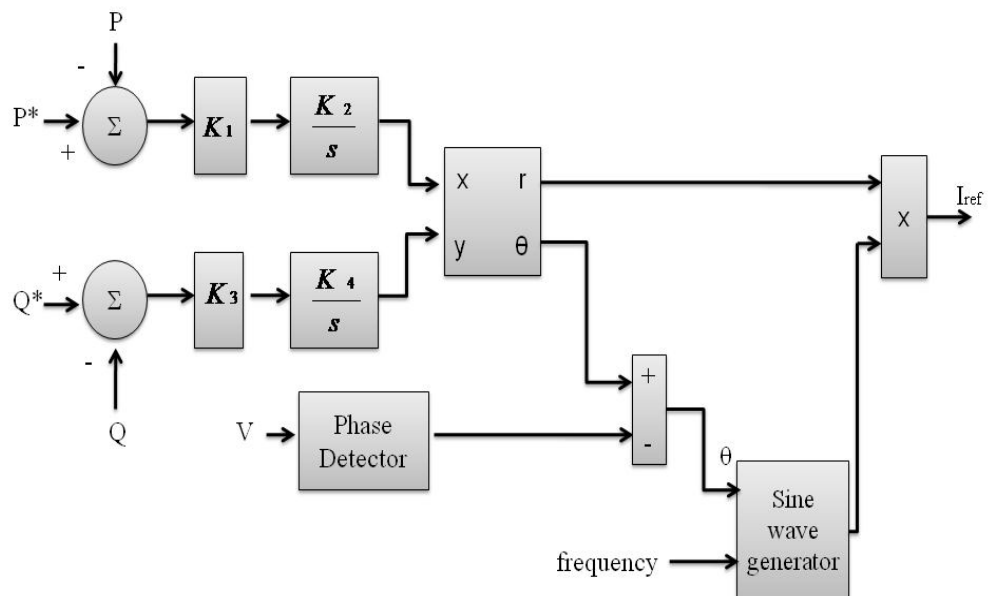


Figure 5.14 Single-phase current source inverter control circuit for power flow injection into the secondary distribution transformer model

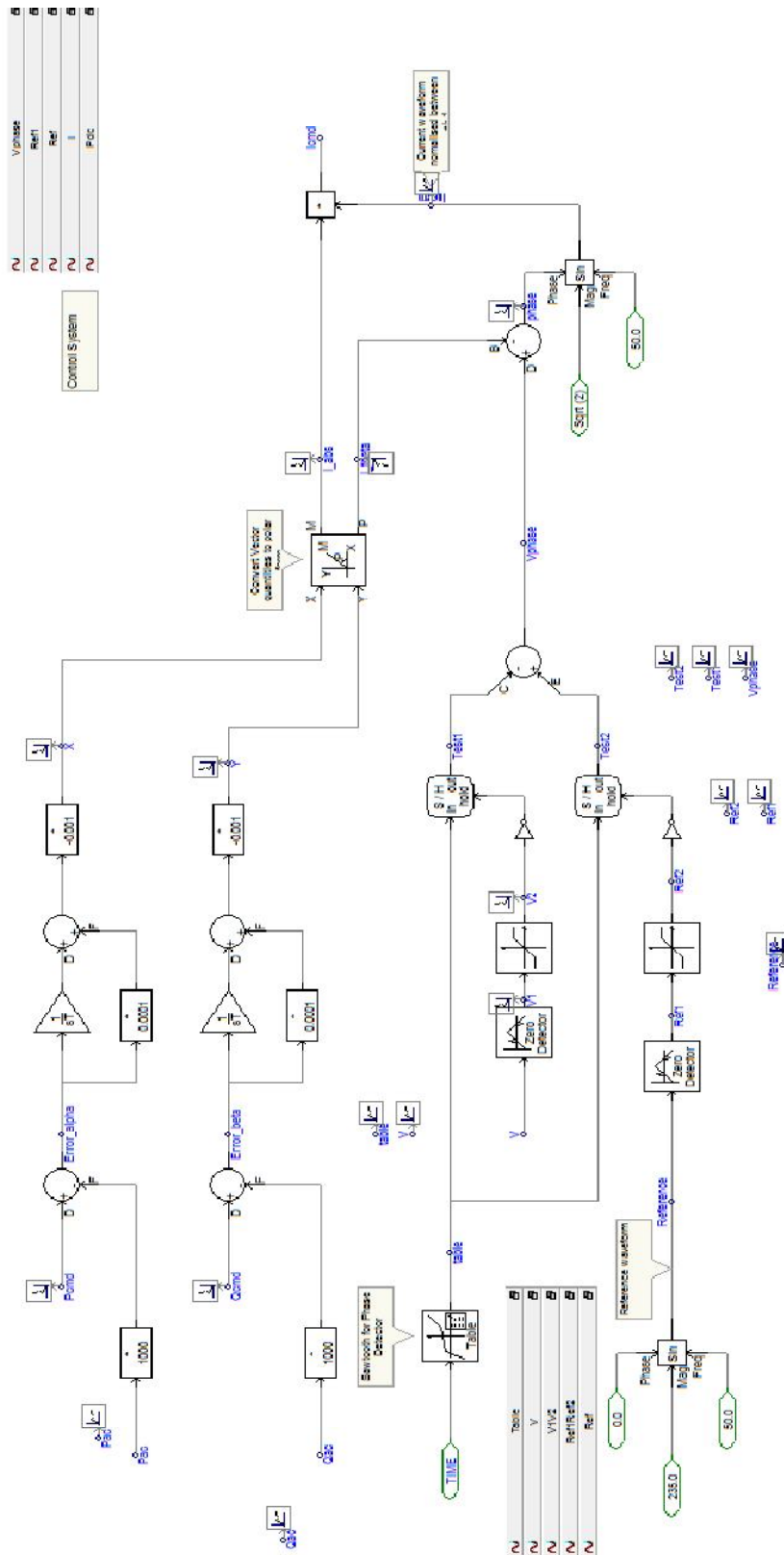


Figure 5.15 Single-phase current source inverter control circuit for power flow injection into the secondary distribution transformer model in PSCAD

5.3.3 Proposed Control Algorithm for Mitigating Voltage Unbalance and Network Losses

An integrated energy storage unit with four quadrant converter is proposed to mitigate the voltage unbalance factor and increase the network efficiency of the distribution system. Figure 5.16 shows the flow chart of the controller's operation. There are 2 conditions as follows:-

- Normal condition: All measured parameters, such as phase voltage and phase angle are within the permissible limit. No operation is needed.
- Alert condition: One or more parameters exceed their permissible limit. The controller will determine the required real and reactive power to be injected/ absorbed in order to restore the system to normal condition.

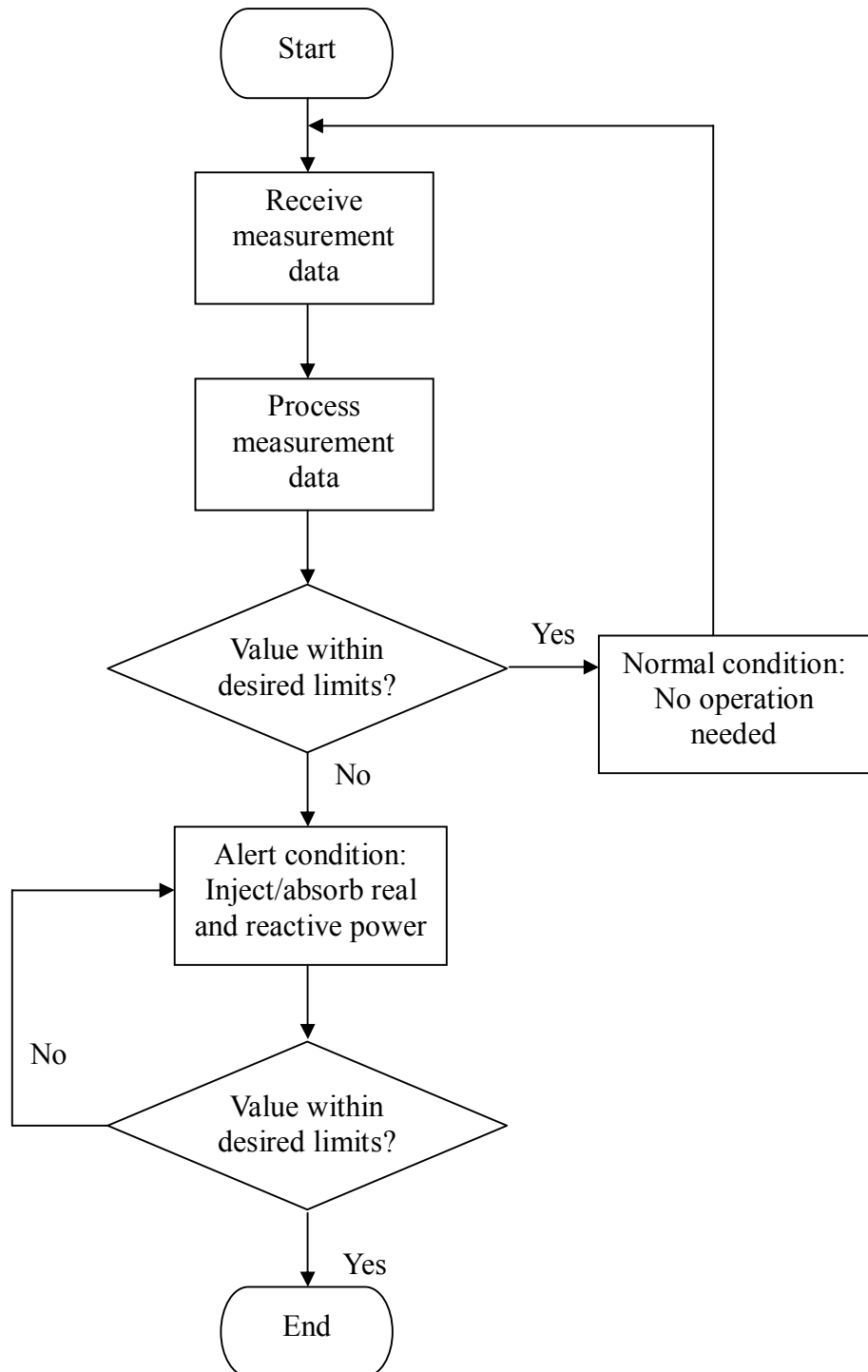


Figure 5.16 Flow chart of the controller's operation

Figure 5.17 shows the control algorithm of the energy storage unit. The algorithm controls the voltage level at each phase in order to make the network to be balanced, hence reducing the neutral current flowing through the neutral

line. As a result, this reduces the total network power losses of the distribution network. The integrated energy storage unit with the four quadrant converter has extended its performance to generate a balanced three phase voltage whose magnitude and phase angle can be adjusted rapidly to either draw/absorb real or reactive power from/to the power system.

The PQ controller as shown in figure 5.17 uses a pair of PI controller to control the voltage magnitude and phase angle of the connected phase. The PI controller is a feedback controller than uses the difference between the set point voltage (V^*) and the measured voltage (V) to generate error and hence the integral and proportional gain system change the output value till error is zero. If the measured voltage is greater than set point voltage, voltage rise situation occurs. This results the controller output to remain positive until the negative error reduces the value of the integrator. Eventually, the output of the PI controller is limited at the maximum exportable active power of the PV, hence reducing the voltages at the point of connection. Similarly, the mechanism of phase angle adjustment uses the difference between the set point phase angle (θ^*) and the measured phase angle (θ) can be used to control the reactive power generation.

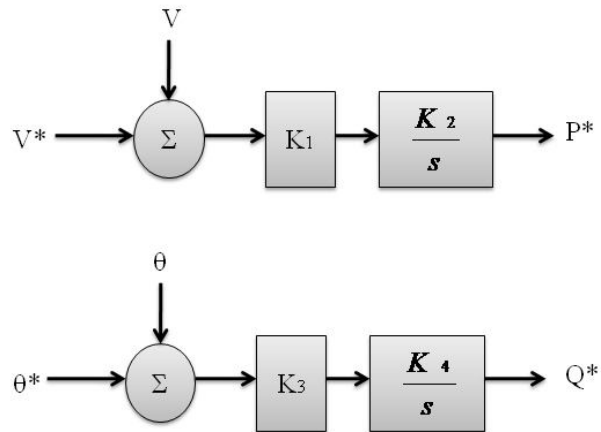


Figure 5.17 PI controller block diagram

Figure 5.18 shows the PSCAD model of the proposed control algorithm in addition to figure 5.17. The control algorithm determines whether to inject or absorb real or reactive power by looking at the voltage magnitude and the phase angle. By controlling the voltage level and phase angle, the voltage unbalance factor is reduced, hence reducing the current flowing through the neutral phase. As a result, the network power losses can be further minimised.

A SOC monitor has been included in order to stop charging and discharging the battery whenever the threshold level of the SOC is reached. The battery operates if and only if the SOC is within 10% to 95%. The battery charge up to 95% in this case. The control system then provides a proper control signal to the PQ controller as shown in figure 5.14.

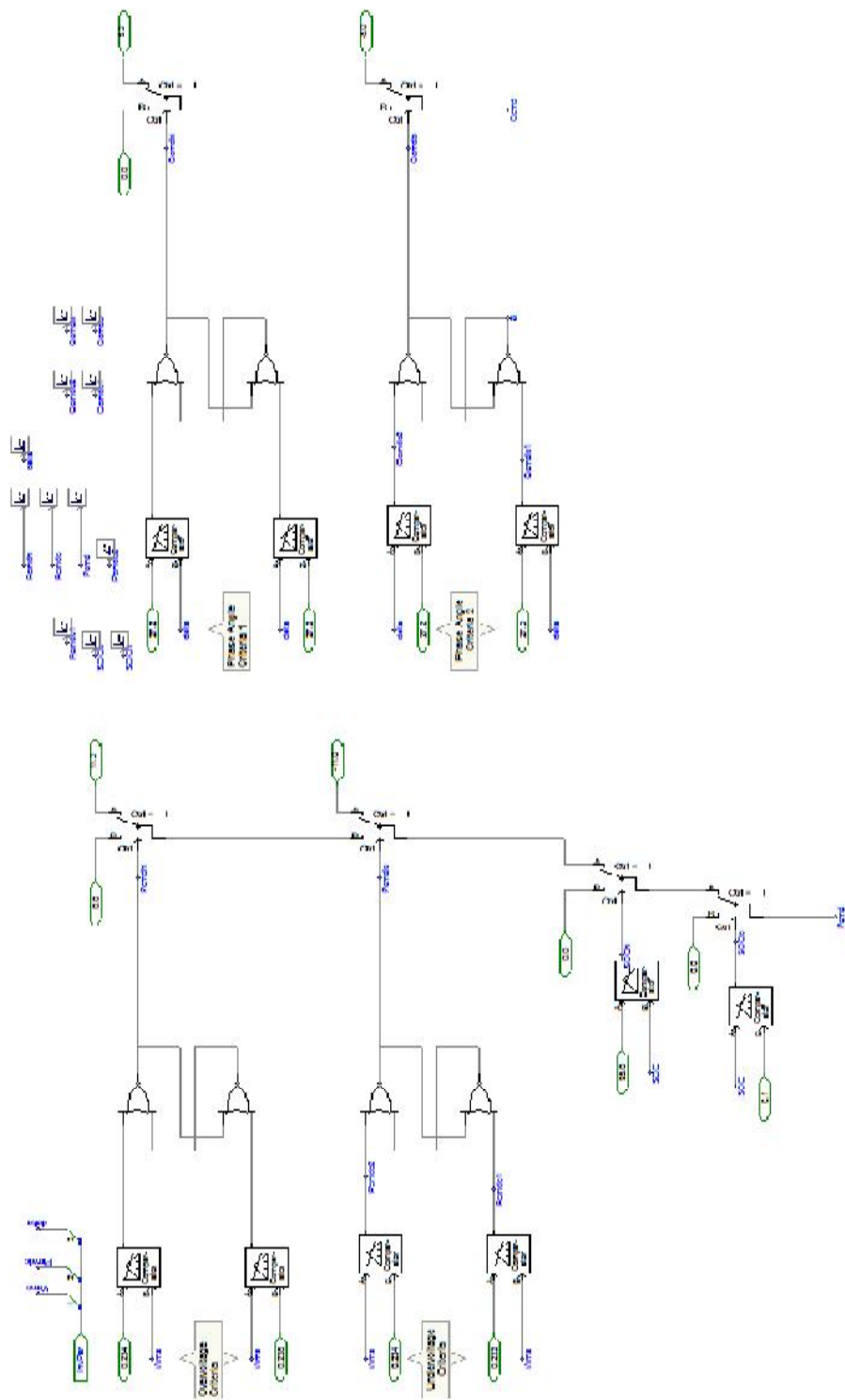


Figure 5.18 PI controller block diagram in PSCAD

5.4 Conclusions

Two generic distribution networks were described in this chapter such that they can be used to study the interaction between various penetration of PV and the energy storage system. The energy storage unit integrated with the four quadrant converter was also described. It was shown that the converter manipulates the phase difference to control the export and import of real power from the battery. The converter manipulates the voltage magnitude difference to control the flow of reactive power. The control algorithm was also described to show how the converter exports power based on the voltage conditions on the distribution networks. To show the effects of the energy storage unit on the network, a number of case studies are developed and to be described in the following chapter.

CHAPTER 6

EVALUATION OF ENERGY STORAGE UNIT FOR IMPROVING %VUF & EFFICIENCY OF LV DISTRIBUTION NETWORKS WITH PV SYSTEM

6.1 Introduction

The previous chapter detailed the design and development of energy storage unit integrated with four quadrant converter. The energy storage system monitors and controls voltage and current on each phase independently. In this chapter, three case studies are to be presented to show the effectiveness of energy storage system in mitigating the voltage rise, voltage unbalance and network power losses on the two simplified distribution networks.

6.2 Case Study 1:

6.2.1 General

In this case study, it is assumed that the three-phase load in the network 1 and 2 are balanced. PVs are connected only to phase A of network 1 and 2. Each

energy storage system is installed at phase A at the end of the feeders in networks 1 and 2.

6.2.2 Simulation Results:

Figure 6.1 shows the voltage phasor of network 1 at feeder end. The voltage magnitude and angle at phase A have been altered due to the connection of PVs, while the other two phases B and C remained at the nominal value of voltage magnitude and phase angle, due to the absence of generation.

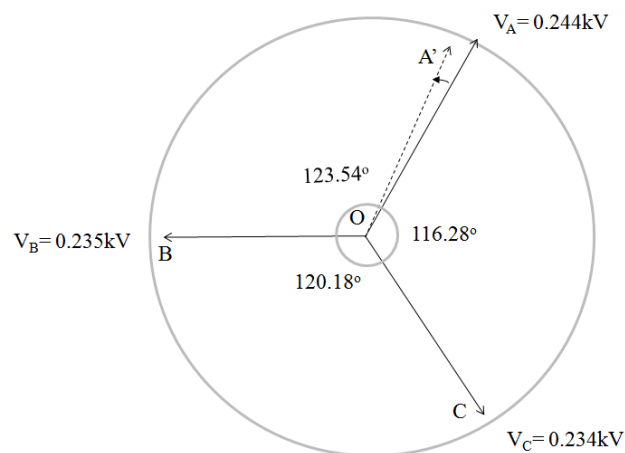


Figure 6.1 Unbalanced instantaneous voltage phasors at the remote end of 415V feeder for network 1 with PV connected only at Phase A

Figure 6.2 and figure 6.3 illustrate the voltage variation at feeder end for each phase before and after the connection of energy storage unit at phase A of networks 1 and 2. Initially, the PVs export active power to phase A and the controller of the energy storage unit receives the measured data at the point of its connection. It detects that the measured voltage is higher than the threshold. Therefore, action is taken to reduce the voltage level at the affected phase by

absorbing the excess active power from the network.

The voltages measured on phases B and C as shown in figure 6.2 and figure 6.3 during the simulation are similar, which is as expected, as there is no distributed generator connected on these phases. However, small differences do exist and this is due to the effect of neutral voltage displacement which is due to the return current along the neutral wire.

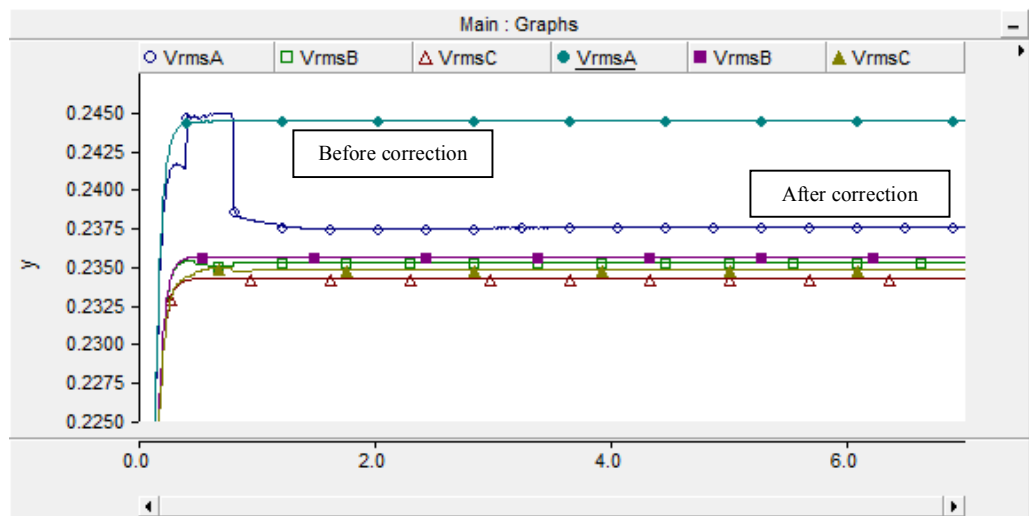


Figure 6.2 Voltage level at the feeder end before and after the correction of energy storage unit for network 1

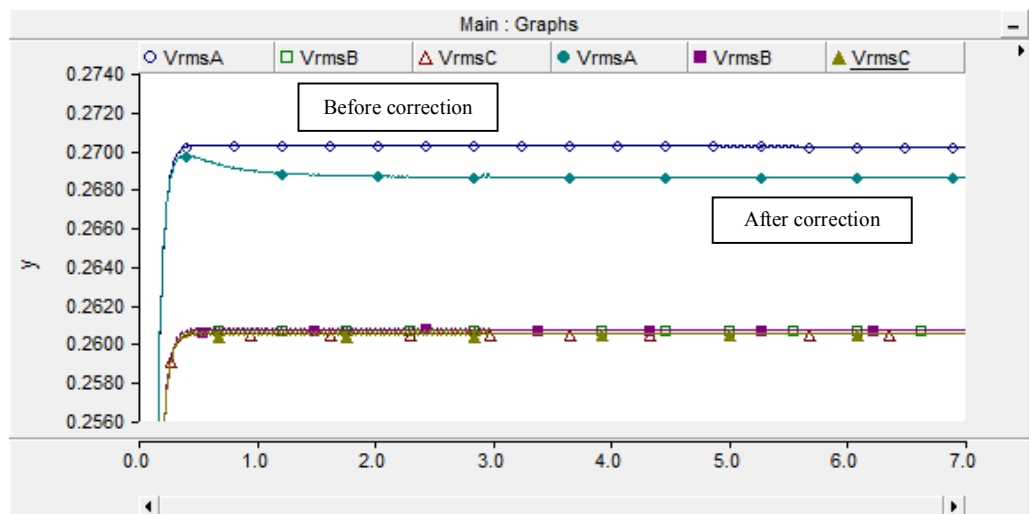


Figure 6.3 Voltage level at the feeder end before and after the correction of energy storage unit for network 2

Figure 6.4 shows the phase angle at the feeder end before and after the correction by the energy storage unit for both networks 1 and 2. The energy storage unit will either inject or absorb reactive power in order to mitigate the phase angle, so that the unbalance factor will be further reduced.

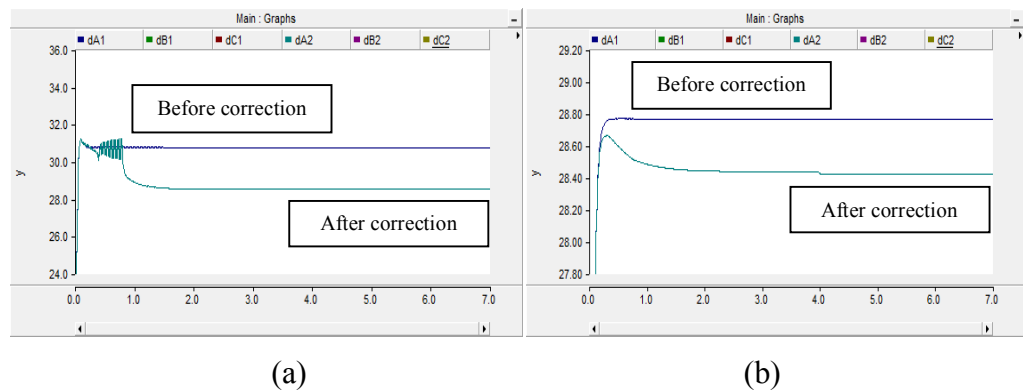
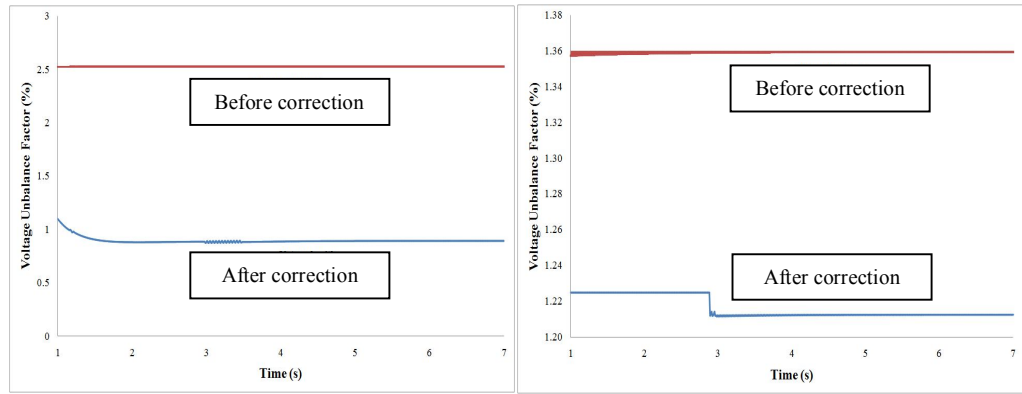


Figure 6.4 Phase angle at the feeder end before and after the correction by the energy storage unit for (a) network 1 (b) network 2

Table 6.1 shows the %VUF and network power losses of networks 1 and 2 before and after the correction. It is shown that the %VUF has gradually reduced from 2.5% to 0.88% when the energy storage unit is connected at the affected phase to mitigate the excess active power flow by the PV. It is seen that the voltage unbalance factor of network 2 is reduced from 1.36% to 1.21%. This shows that the energy storage unit is capable of reducing the unbalance factor even if it is connected to a network with different characteristics. Figure 6.5 and figure 6.6 show the graphs of %VUF and network power losses before and after the correction for both networks 1 and 2, when PVs are connected only at phase A.

	Network 1		Network 2	
	Voltage unbalance factor (%)	Network power losses (KW)	Voltage unbalance factor (%)	Network power losses (KW)
Before correction	2.52	0.48	1.36	2.6
After correction	0.89	0.32	1.21	2.0
Percentage Reduction (%)	64.68	33.33	11.03	23.07

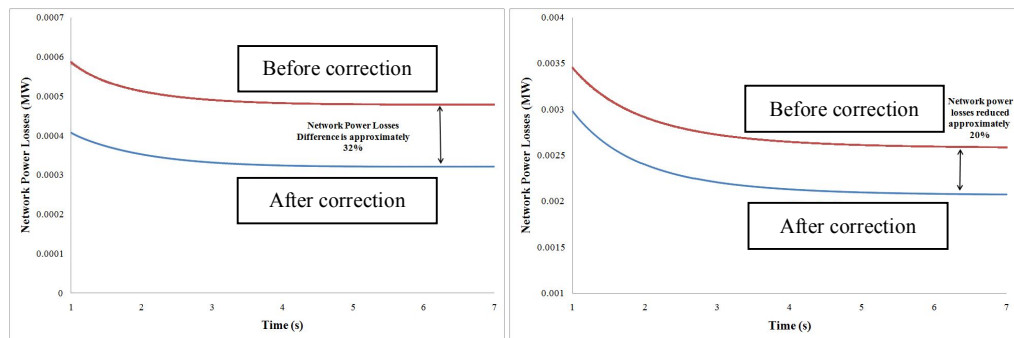
Table 6.1 Voltage unbalance factor and network power losses due to connection of PV on one phase for network 1 and 2 before and after the correction



(a)

(b)

Figure 6.5 Voltage unbalance factor of the feeder end due to connection of PV on phase A for (a) network 1 and (b) network 2



(a)

(b)

Figure 6.6 Total network power losses due to connection of PV on phase A for (a) network 1 and (b) network 2

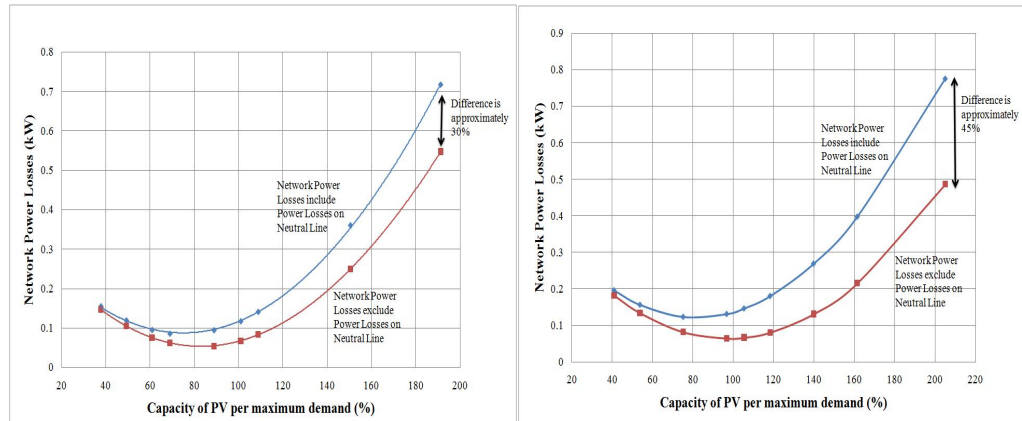
The network power losses are contributed by the resistance losses at all wires. It is noted that the unbalanced current increases as the system become unbalanced. Therefore, it increases the I^2R value of the neutral wire when the unbalance level of the network increases. To reduce the network power losses, one must reduce the unbalance level of the system. It has been proven in figure 6.6 that the network power losses reduce gradually as the voltage unbalance factor is reduced. Moreover, it is shown in table 6.1 that network power loss has been reduced by 33.33% and 23.07% respectively for both networks 1 and 2. Figure 6.7 shows the total network power losses for both networks 1 and 2. The graphs show the network power losses with and without considering the neutral line losses. The neutral line losses contribute a significant amount when the network becomes unbalanced, as the unbalanced current flowing through the neutral line tends to increase. Referring to the equation 6.1, it is seen that the total network power losses are contributed by the I^2R of each phase. Considering the network to be unbalanced, the unbalance current I_n tends to flow through the neutral line causing the $I_n^2 R_n$ losses to increase. It is shown in figure 6.7 that the neutral line losses of networks 1 and 2 have a contribution of 30% and 45%, respectively, with respect to the total network power losses.

$$P_{loss} = I_a^2 R_a + I_b^2 R_b + I_c^2 R_c + I_n^2 R_n \quad (6. 1)$$

Where,

I_a, I_b, I_c, I_n = Line current for phase A, B, C, and the neutral respectively

R_a, R_b, R_c, R_n = Line resistance in phase A, B, C and the neutral respectively

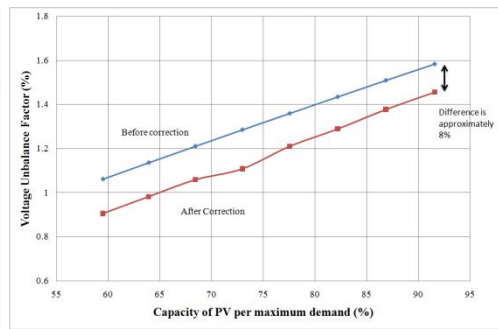
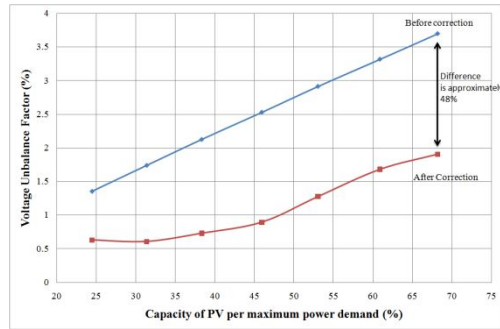


(a)

(b)

Figure 6.7 Total network power losses with and without considering the neutral line losses versus different capacity of PVs on Phase A for (a) network 1 and (b) network 2

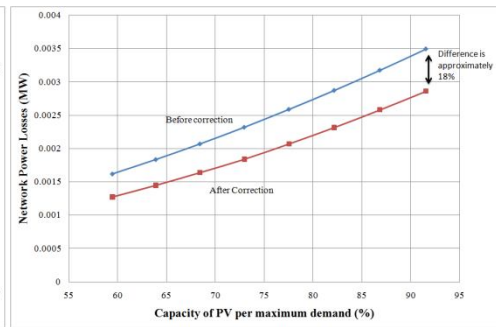
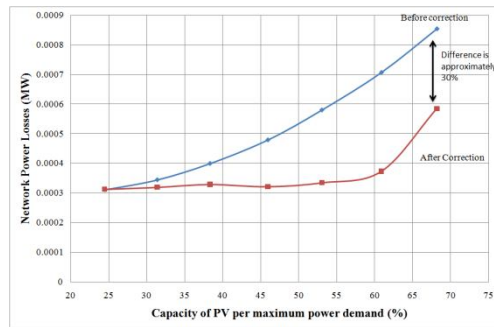
The simulation was extended to increase the capacity of PV so as to verify the effectiveness of the energy storage unit in mitigating the %VUF and the network power losses. Figure 6.8 and figure 6.9 show the %VUF and network power losses of networks 1 and 2 with respect to different capacity of PVs before and after the correction, by using energy storage unit. It is seen that the %VUF increases as the generation of PV increases. It is shown in the graphs that the overall %VUF and network power losses have been reduced when the energy storage unit is connected at the affected phase. With the installation of energy storage units, the %VUF on networks 1 and 2 have been reduced by 48% to 65% and 8% to 14% respectively as the capacity of PV is increased, whereas, the network power losses on networks 1 and 2 have been reduced from 7% to 47% and 18% to 21%, respectively.



(a)

(b)

Figure 6.8 Voltage unbalance factor versus different capacity of PV for (a) network 1 and (b) network 2 before and after correction by using the energy storage unit



(a)

(b)

Figure 6.9 Network power losses versus different capacity of PV for (a) network 1 and (b) network 2 before and after correction by using the energy storage unit

6.3 Case Study 2:

6.3.1 General

In this second case study, PVs are evenly distributed on two phases, say, phase A and B in order to violate the limit of %VUF. The ideal %VUF limit is assumed to be 1.0% for network 1 and 1.3% for network 2.

6.3.2 Simulation Results

Figure 6.10 shows the unbalanced instantaneous voltage phasors at the remote end of network 1 with PVs connected at phases A and B. This case study is similar to case study 1 except that, PVs are evenly distributed on two phases. Each energy storage unit integrated with four quadrant converter is connected at the affected phases in order to mitigate the excess active power flow, hence to reduce the voltage unbalance factor and increase the effectiveness of the LV distribution network.

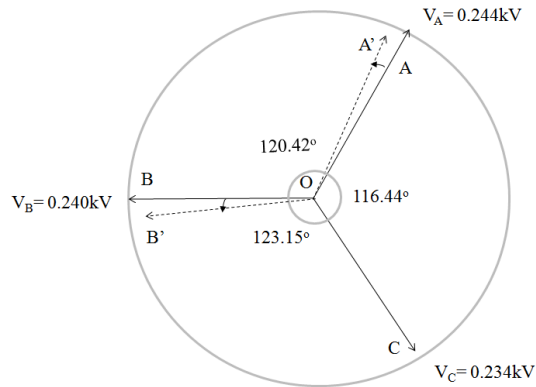


Figure 6.10 Unbalanced instantaneous voltage phasors at the remote end of 415V feeder for network 1 with PV connected at Phases A and B

Figure 6.11 and figure 6.12 show the voltage magnitude of networks 1 and 2 before and after correction by using the energy storage unit. It is shown that voltage level at phases A and B are affected by the PVs connected on these phases. While phase C has no generation, there is no changes in phase C. Two numbers of energy storage units integrated with four quadrant converter are connected individually at the affected phases A and B. The energy storage units mitigate the voltage rise at the affected phases in order to bring to the nominal value. This could help to reduce the %VUF in the LV distribution network.

Figure 6.13 and figure 6.14 show the phase angle of the affected phases A and B for networks 1 and 2 before and after the correction, using energy storage unit integrated with four quadrant converter.

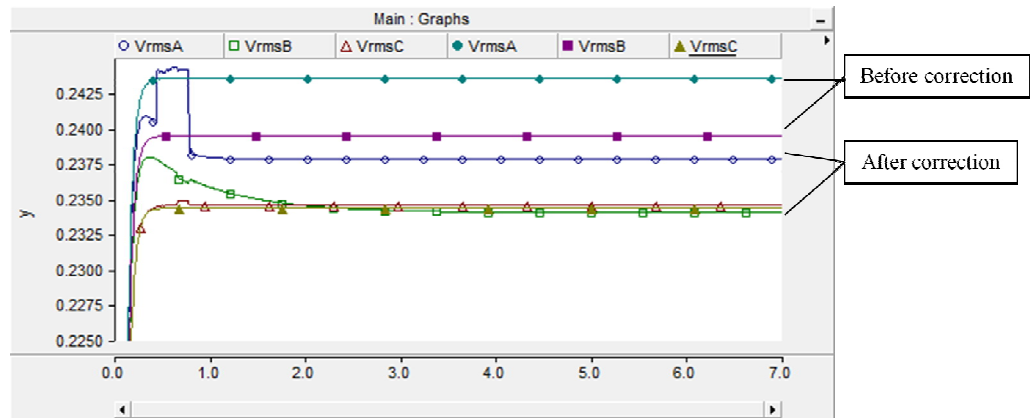


Figure 6.11 Voltage level at the feeder end before and after the correction of energy storage unit at network 1

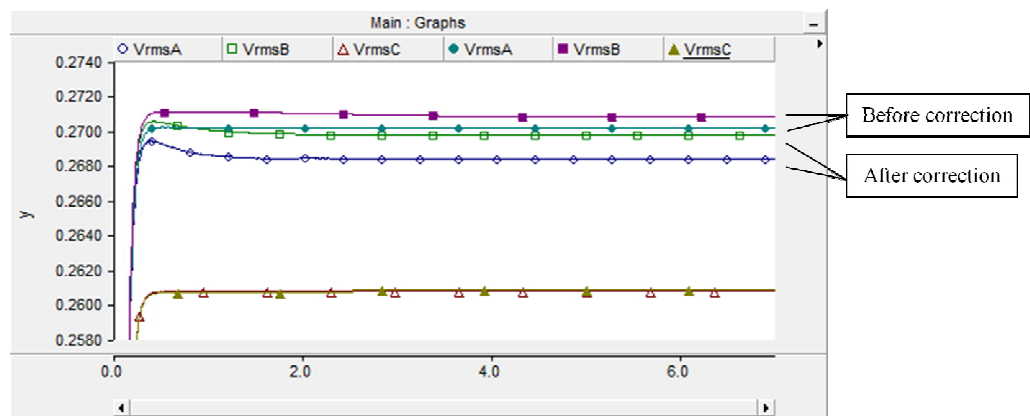
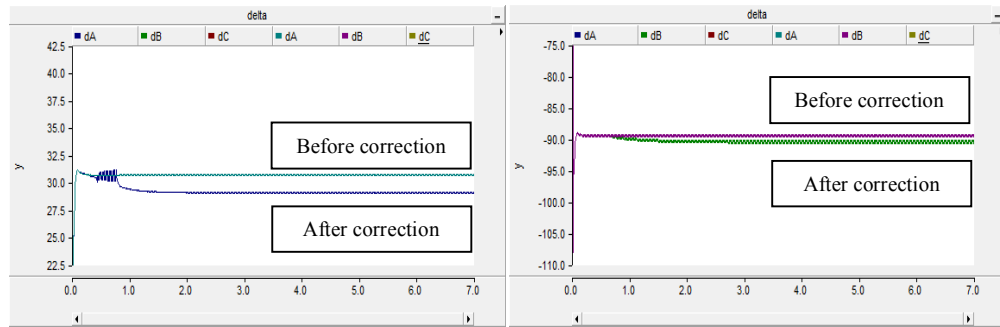


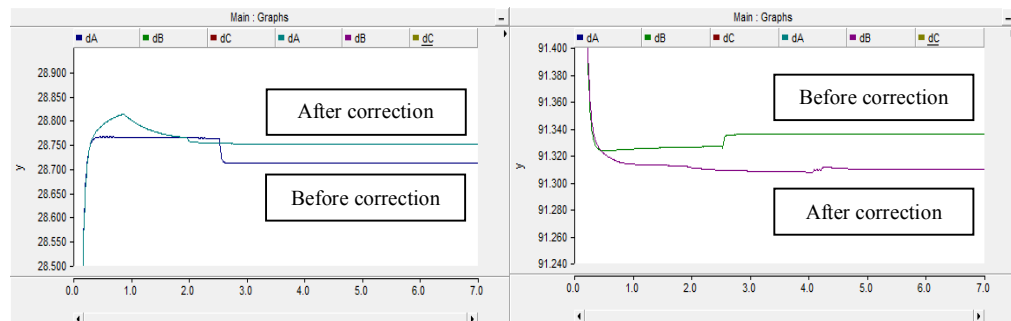
Figure 6.12 Voltage level at the feeder end before and after the correction of energy storage unit in network 2



(a)

(b)

Figure 6.13 Phase angle of the feeder end for network 1 at the affected (a) phase A and (b) phase B



(a)

(b)

Figure 6.14 Phase angle of the feeder end for network 2 at the affected (a) phase A and (b) phase B

Table 6.2 shows the %VUF and network power losses of networks 1 and 2 before and after the correction. With the installation of energy storage units, the %VUF on networks 1 and 2 have been reduced by 50% and 15% respectively, whereas, the network power losses on networks 1 and 2 have been reduced by 27% and 17%, respectively. As we can see, the energy storage unit gives different results in different networks. The differences of both networks have been discussed earlier in chapter 5. Figure 6.15, figure 6.16 and figure 6.17 show %VUF, network power losses and voltage level of both networks 1 and 2 before and after the correction using energy storage units, in addition to the data listed in table 6.2.

	Network 1		Network 2	
	Voltage unbalance factor (%)	Network power losses (KW)	Voltage unbalance factor (%)	Network power losses (KW)
Before correction	1.79	0.44	1.31	4.2
After correction	0.89	0.32	1.12	3.5
Percentage Reduction (%)	50.28	27.27	14.50	16.67

Table 6.2 Voltage unbalance factor and network power losses of network 1 and 2 before and after the correction

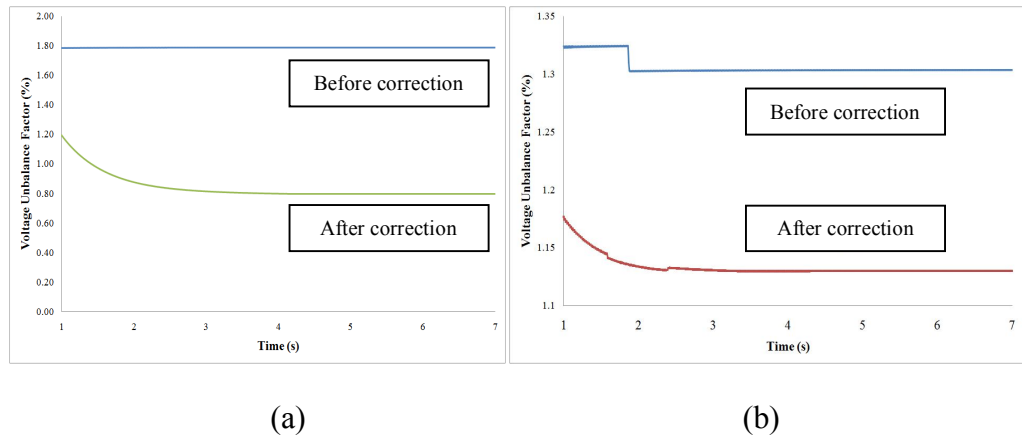


Figure 6.15 Voltage unbalance factor of the feeder end for (a) network 1 and (b) network 2 with PV connected at phase A & B

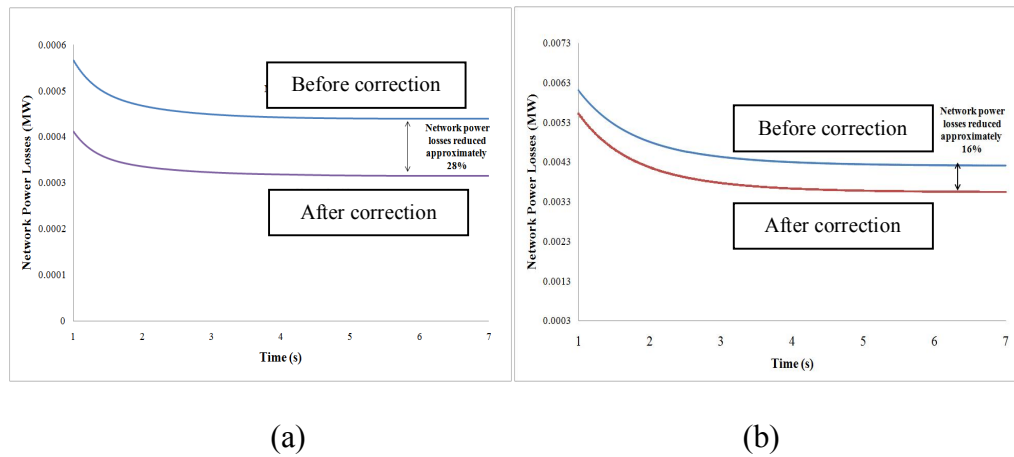
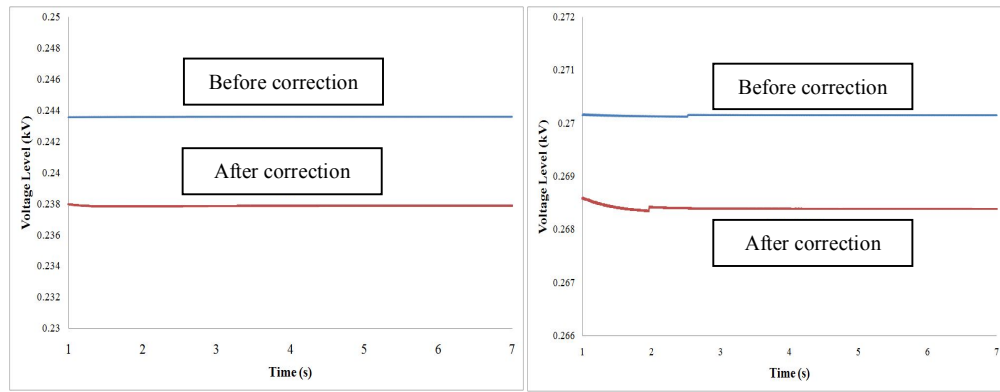


Figure 6.16 Total network power losses of (a) network 1 and (b) network 2 with PV connected at phase A & B



(a)

(b)

Figure 6.17 Voltage level at the feeder end of (a) network 1 and (b) network 2 with PV connected at phase A & B

6.4 Case Study 3:

6.4.1 General

In this case study, both leading and unity power factor loads were considered for investigation. Results are then compared with that of the lagging power factor loads.

6.4.2 Voltage Unbalance Factor Against the Capacity of PV

Figure 6.18 and figure 6.19 show the voltage unbalance factors before and after the correction by the energy storage unit, with respect to the capacity of PVs on networks 1 and 2 respectively under various PF at the loads. It is shown that the voltage unbalance factors of network 1 are higher than that of network 2 over the same increase in the capacity of PV. This is because the TT grounding system causes the majority of the network voltages to be floating or

uncontrolled. Therefore, the voltage magnitude and hence the voltage unbalance factors can be easily affected by the PV system. However, it is noticed that, after the correction of the energy storage unit, the voltage unbalance factors of network 1 are significantly reduced below that of network 2. It is also seen that the correction of voltage unbalance factor by the energy storage unit is much effective on the network with TT grounding system because, the voltage is more susceptible to the change of power flow on the network.

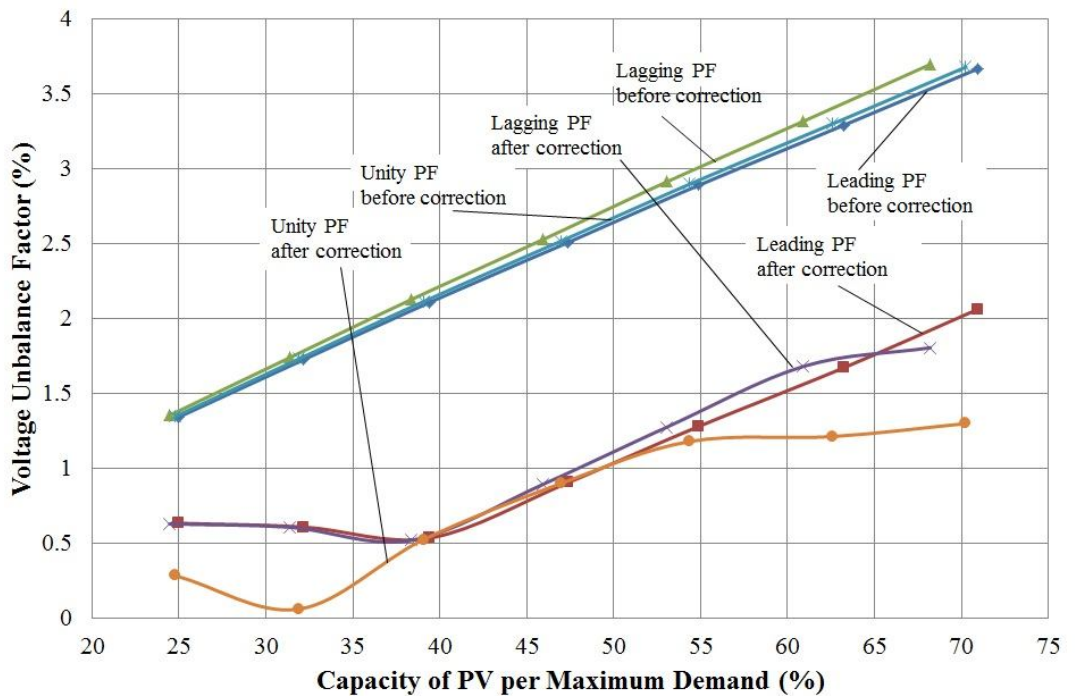


Figure 6.18 Voltage unbalance factor of network 1 against capacity of PV with and without energy storage unit for 0.98 leading, 0.98 lagging and unity power factor

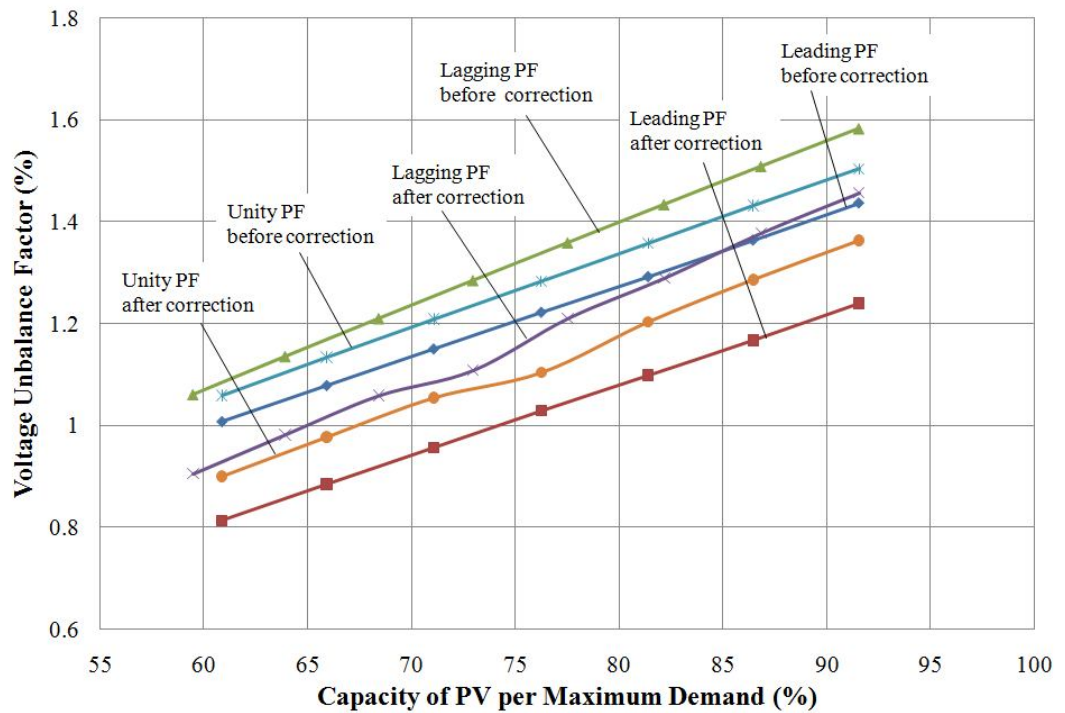


Figure 6.19 Voltage unbalance factor of network 2 against capacity of PV with and without ESU for 0.98 leading, 0.98 lagging and unity power factor

6.4.3 Network Power Losses Against the Capacity of PV

Figure 6.20 and figure 6.21 show the network power losses before and after the correction of the energy storage unit with respect to the growth of PVs on networks 1 and 2 respectively. It is shown that the power losses on any network is the highest under the leading power factor, followed by the unity and lagging power factors. Under leading power factor, current is leading voltage. The line power loss is higher than that of the lagging and unity power factors due to the leading current. The line power losses is calculated by square of line current multiplied by line resistor. It is noticed that the energy storage unit can effectively reduce the power losses on the two networks, hence improving the efficiency of the networks.

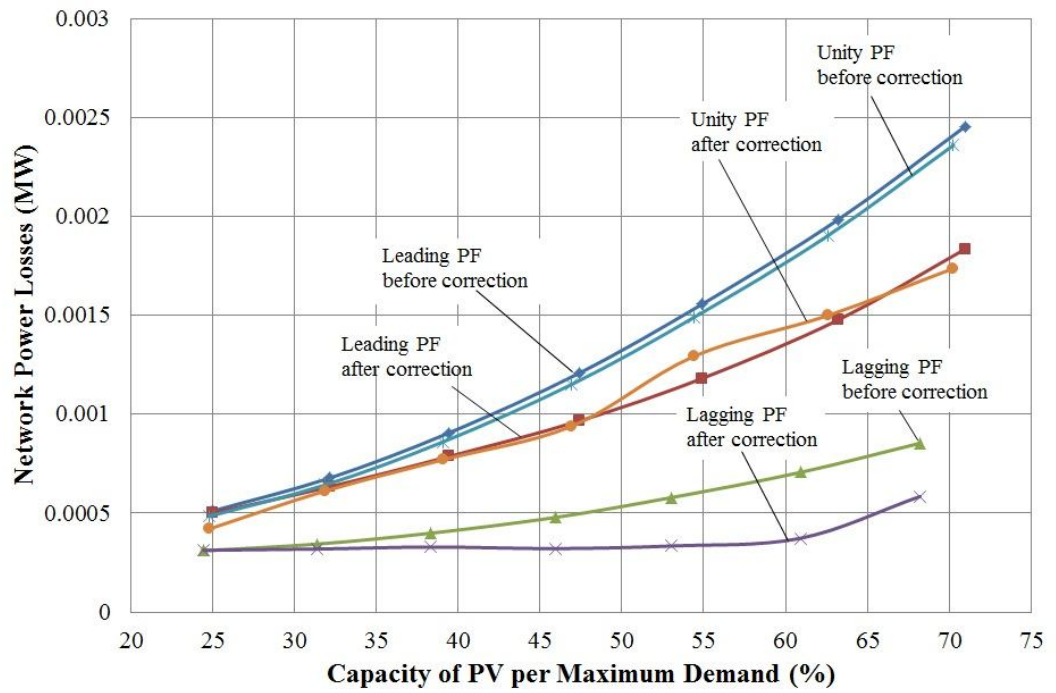


Figure 6.20 Network power losses of network 1 against capacity of PV with- and without ESU for 0.98 leading, 0.98 lagging and unity power factor

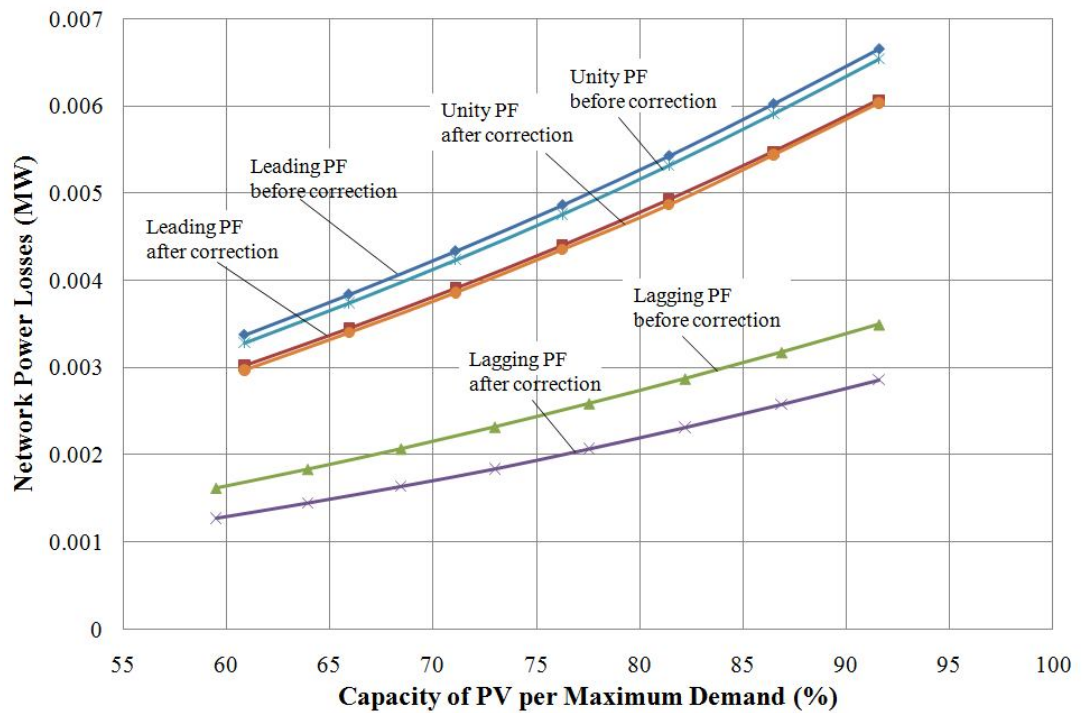


Figure 6.21 Network power losses of network 2 against capacity of PV with- and without ESU for 0.98 leading, 0.98 lagging and unity power factor

6.5 Conclusions

LV distribution networks should be operated with low voltage unbalance factor. In addition, the loads and generation should be evenly distributed throughout the LV network so that the system can maintain its voltage unbalance within the desired limits. However, if this is not possible, energy storage unit integrated with four quadrant converter is an active management solution to mitigate the voltage unbalance of the network and improve the efficiency of the network with high penetration of distributed generators.

PSCAD models of the energy storage unit, the simplified LV distribution networks and PV systems were developed to simulate the performance of the networks with different penetration levels of PV. Three simulation case studies were developed to show how effective of the energy storage systems can be in mitigate voltage rise, voltage unbalance factor and network power losses. The simulation results show the effectiveness of the energy storage unit to reduce the voltage unbalance factor and network power losses.

CHAPTER 7

EXPERIMENTAL VALIDATION OF ENERGY STORAGE SYSTEM

7.1 Introduction

An experimental set up was developed at University of Durham for the purpose of verifying the effectiveness of energy storage system in mitigating voltage unbalance factor and reducing power losses on the network. A Small-Scale Energy Zone (SSEZ), as shown in figure 7.2, is set up which consists of one load emulator, one wind turbine generator emulator, one PV generation emulator, one energy storage system with four quadrant converter and one LV network emulator. This chapter discusses the findings of the investigation on the effect of high DG penetrations on distribution networks.

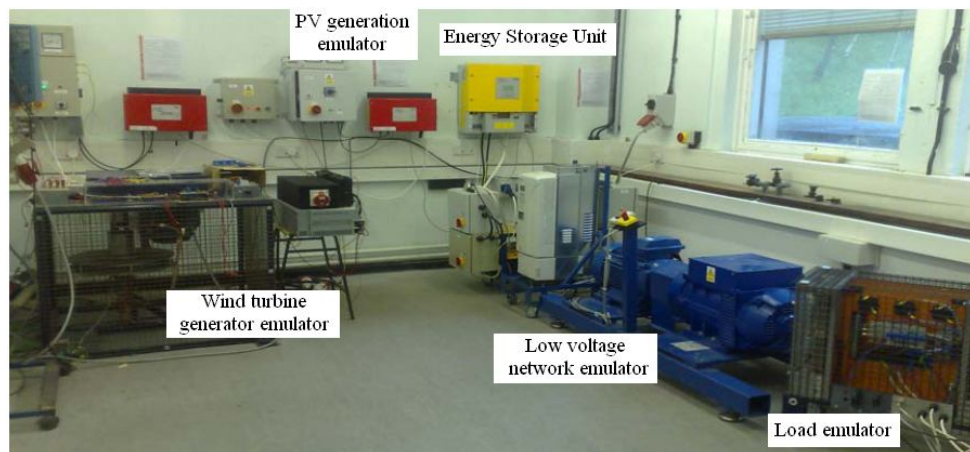


Figure 7.1 Experimental Small-Scaled Energy Zone (SSEZ)

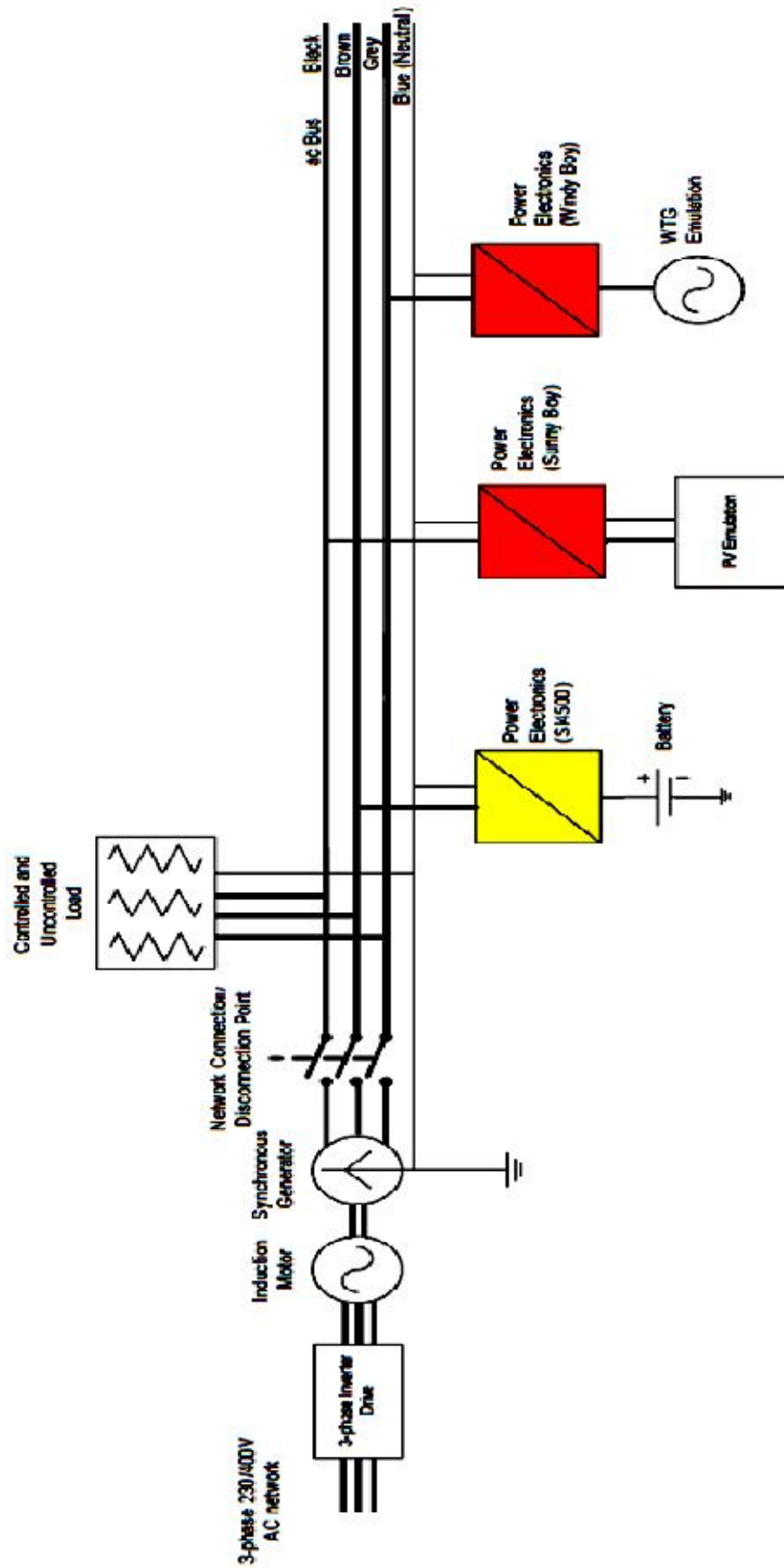


Figure 7.2 Electrical layout of the experimental SSEZ

7.2 Effect of Load Condition on Voltage Unbalance and Network Power Losses

The main objective of this experiment is to investigate the effects of various load conditions on the %VUF and network power losses. Voltages on phases A, B and C at the load end were measured under three different load conditions, namely load conditions 1, 2, and 3. In load condition 1, only phase A is loaded with a variable resistor varying from 0 to 2500 W. In condition 2, phase A is loaded with the variable resistor and phase B is loaded with a fixed resistor of 500 W. In condition 3, all the three phases are loaded equally with the variable resistors. Figure 7.3 shows the %VUF of the network under three load conditions. For the load conditions 1 and 2, the %VUF increases linearly with the load. For load condition 3, the %VUF stays at 0.23 irrespective of the load variation. Figure 7.4 shows the network power losses versus %VUF under load condition 1. It is shown that power loss increases together with the %VUF. When the %VUF is 0.23, the loss is negligibly small. However, the loss becomes 6% of the total demand when the %VUF is 2.3. The power losses are mainly caused by the line losses of the distribution network and the presence of unbalance current flows through the neutral line.

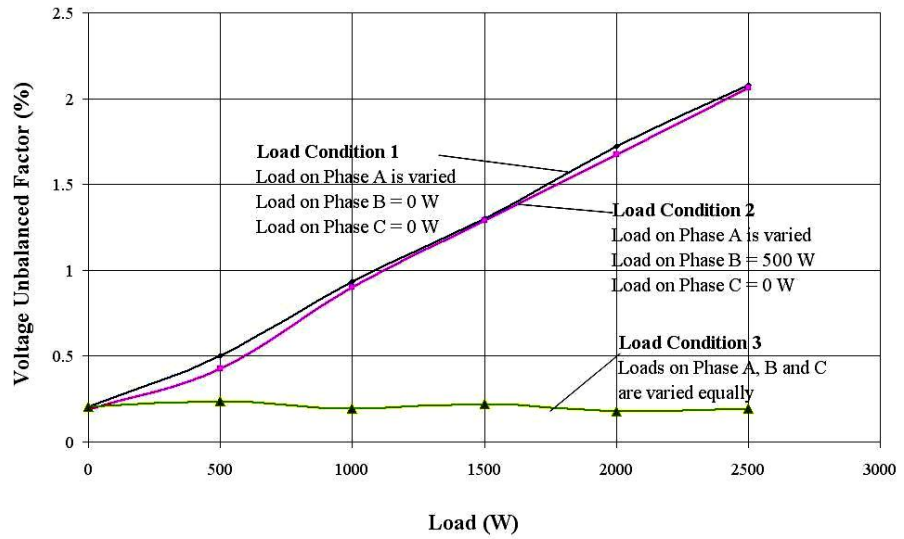


Figure 7.3 Voltage unbalance factor versus load under various load conditions

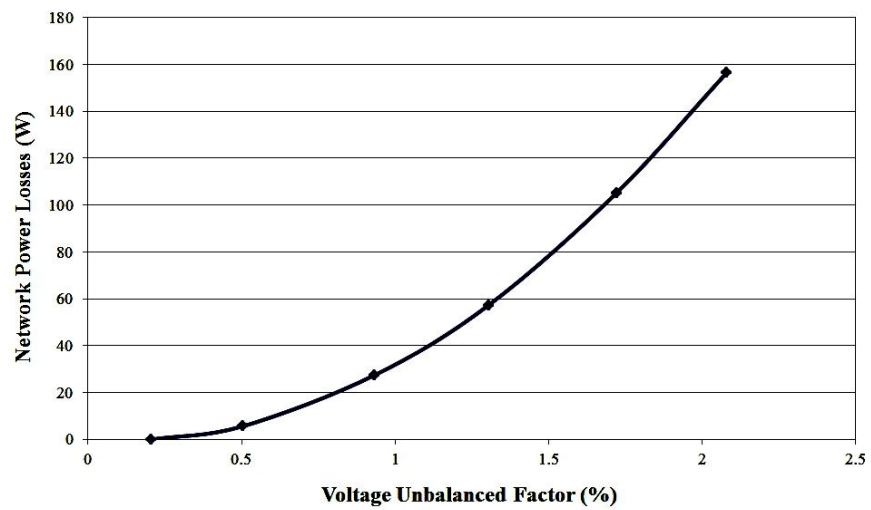
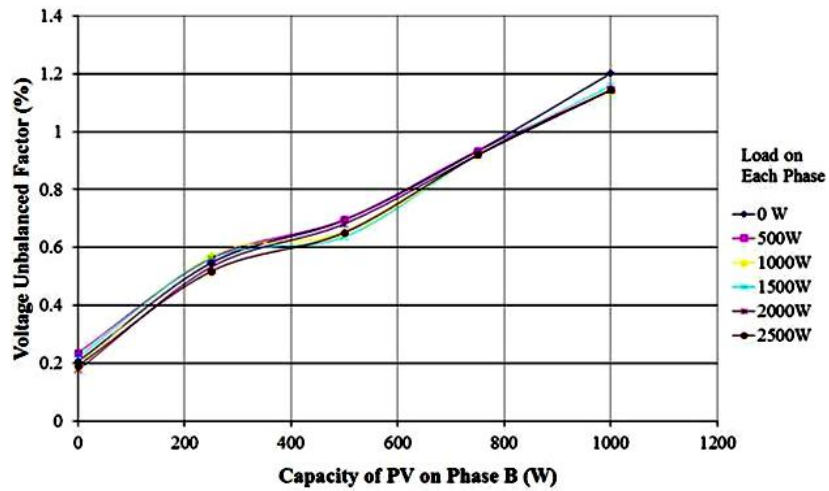


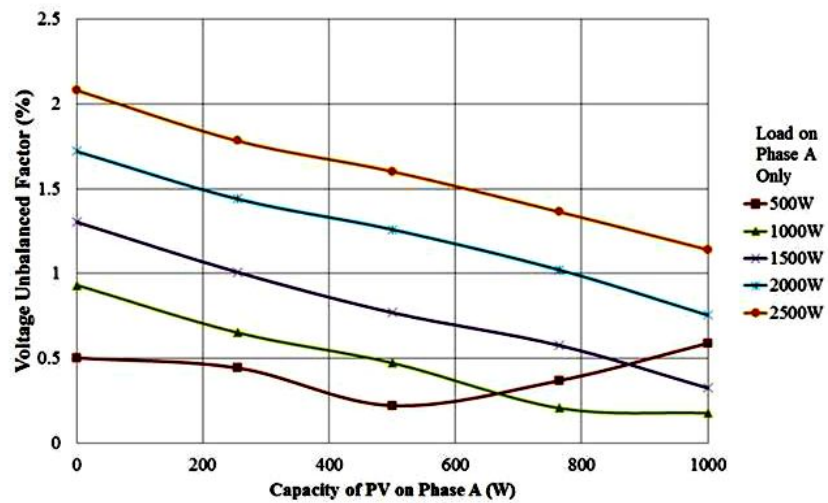
Figure 7.4 Network power loss against voltage unbalance factor under load condition 1

7.3 Effect of PV on Voltage Unbalance and Network Power Losses Under Balanced and Unbalanced Load Conditions

The purpose of this section is to investigate the effects of PV on the %VUF and network power losses under balanced and unbalanced load conditions. The %VUF and network losses are measured for various capacities of PV on phase B under the different load conditions. Figure 7.5(a) shows the results of %VUF under balanced load condition. It is shown that the %VUF increases approximately linearly as the capacity of the PV on phase B grows from 0 to 1000W for all the load values. This is due to the fact that the PV power has offset certain portion of the load in phase B and causes the network load condition to be unbalanced. Figure 7.5(b) shows that the %VUF decrease for all load values except for the load of 500 W. It was found that the graph for the load of 500 W is U-shaped. The minimum point occurs at the PV capacity of 500 W. This is due to the fact that the PV power has offset the load at phase A. Hence, the load profile of the network is more balanced. As the capacity of PV continues to increase, there will be an excess power in the phase A. Hence, the network becomes unbalanced. In fact, the placement of PV at the same phase as load can mitigate the %VUF in the balanced load conditions as long as the power generated by the PV does not exceed the load value.



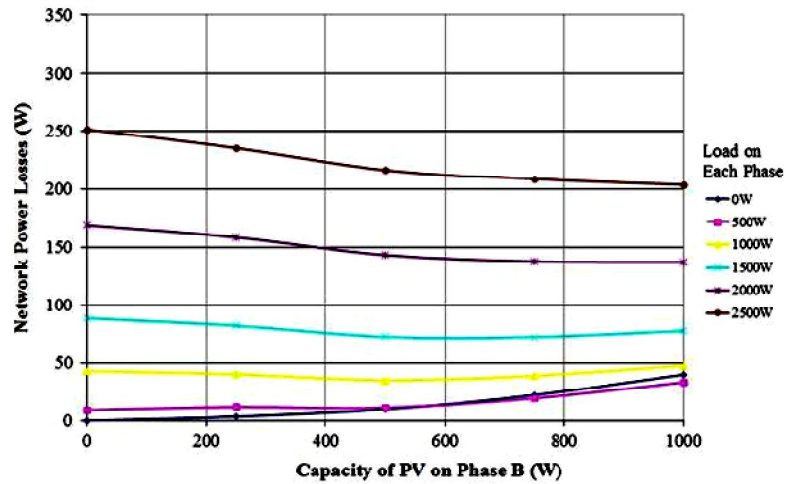
a) Balanced load condition



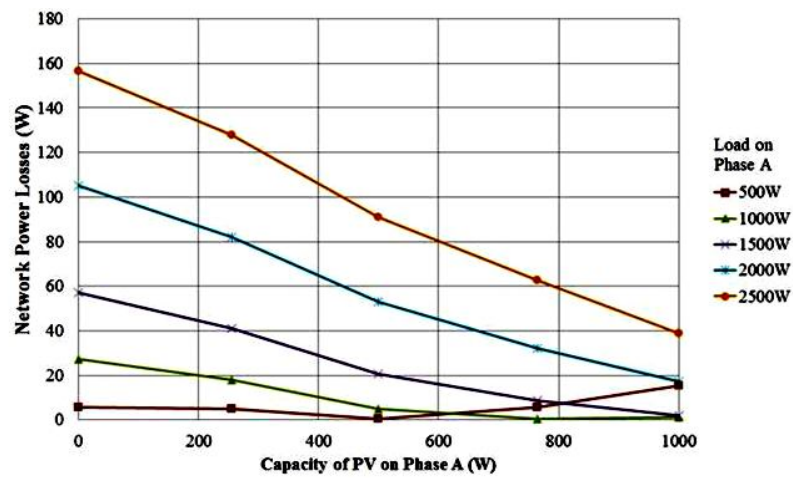
b) Unbalanced load condition

Figure 7.5 Voltage unbalanced factor against the capacity of PV on phase B under balanced and unbalance load conditions

Figure 7.6(a) shows that the network power losses decrease as the PV capacity increases under balanced load condition. When the %VUF decreases, the network power losses decrease as well. As the load increases, the power losses increase. Same concept is applied to unbalanced load condition.



a) Balanced load condition



b) Unbalanced load condition

Figure 7.6 Network power losses against capacity of PV on phase B under (a) balanced and (b) unbalanced load conditions

7.4 Effects of Energy Storage System on the Voltage Unbalance Factor and Network Power Losses

This section explained the effectiveness of energy storage unit on the %VUF and network power losses under various load conditions. Figure 7.7(a) shows the %VUF when the energy storage unit is installed on the same phase as PV

and the load. Figure 7.7(b), (c), and (d) show the %VUF of the network when the energy storage unit is placed on phases A, B and C respectively, while PV is fixed on phase B and the load on phase A. Figure 7.7(a) shows that when the energy storage unit is placed at the same phase as the PV and the load, the %VUF can be effectively reduced to lower than 0.8 %, regardless of the power output of PV and the load demand. The second best location of the energy storage unit is the phase of PV as shown figure 7.7(c). However, if the energy storage unit, PV and load are distributed across all different phases as shown in figure 7.7(b) and (c), then the %VUF cannot be maintained as low as that shown in figure 7.7(a).

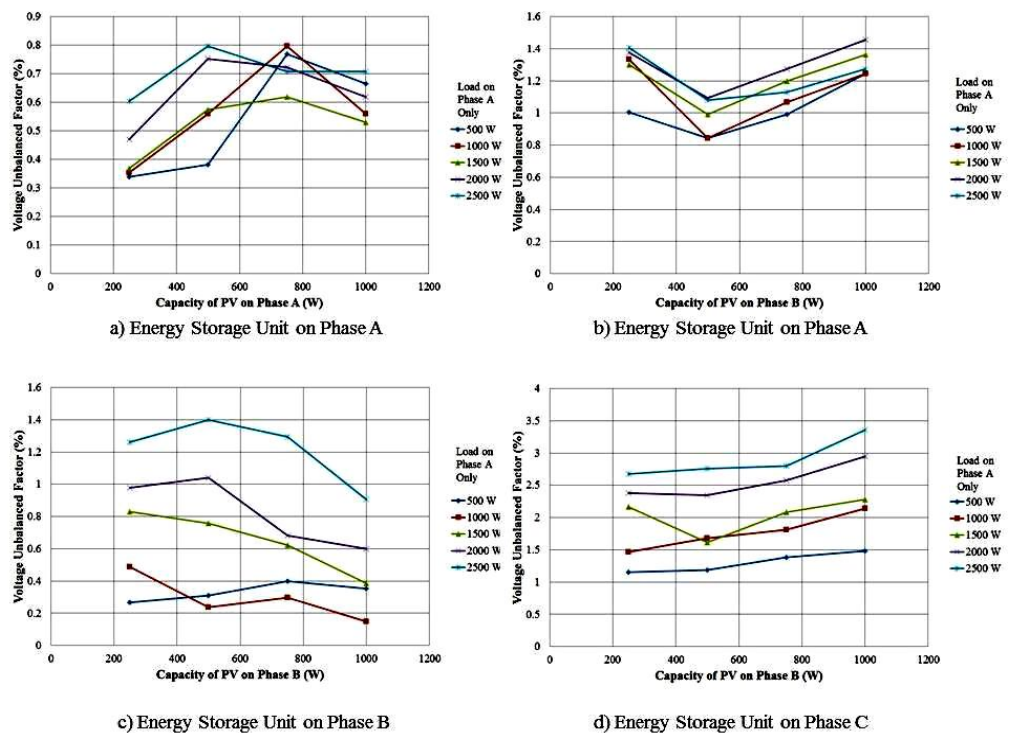


Figure 7.7 Voltage unbalance factor against capacity of PV with load on phase A and the placement of the energy storage unit at various locations

Figure 7.8 (a) shows the reduction in network power losses when the energy storage unit is placed at the same phase as the PV and the load. Figure 7.8 (b), (c) and (d) show the results of the energy storage unit, PV and load are distributed on different phases. Negative reduction in network power losses means that there is an increase in network power losses. The effectiveness of the energy storage unit to reduce network power losses relies on the reduction for phase and neutral current. As shown in figure 7.8 (a), there is a significant reduction in network power losses as long as the energy storage unit is on the same phase as PV and the load, and the load does not greater than the PV capacity. This is because the energy storage unit can reduce the phase and neutral current by injecting power to the load. If the load is smaller than the PV capacity, then PV reduces the phase and neutral current by injecting the power directly to the load, hence reducing the role of the energy storage unit.

Figure 7.8 (b) shows that when the energy storage unit is placed on the same phase as the load, there is a significant reduction in network power losses. The amount of reduction is directly proportional to the load demand. This is due to the loads are much greater than the PV capacity. The load current is very dominant on the network and it contributes to the majority of the network power losses. The energy storage unit can minimize the load current by providing power directly to the load. As a result, the power losses are reduced significantly. Figure 7.8 (c) shows that if the energy storage unit is placed on the same phase as PV, there is a significant increase in power losses under unbalanced load condition. This is because the voltage magnitude measured from the positive terminal of PV to the neutral point increases substantially due

to the fact that the neutral voltage deviates from the ground voltage. Therefore, the energy storage unit acts as a load for absorbing power from PV as well as the grid in order to reduce the voltage magnitude to be within the statutory voltage limits. As a result, the phase current on phase B becomes very large, hence causing the network power losses to increase. It is therefore not appropriate to place the energy storage unit at the same phase as PV. As shown in figure 7.8 (c), the energy storage unit does not contribute to the reduction of network power losses. This is because the phase of energy storage unit is different from that of PV and the load. Therefore, the effect on the reduction of phase and neutral currents is very minimal.

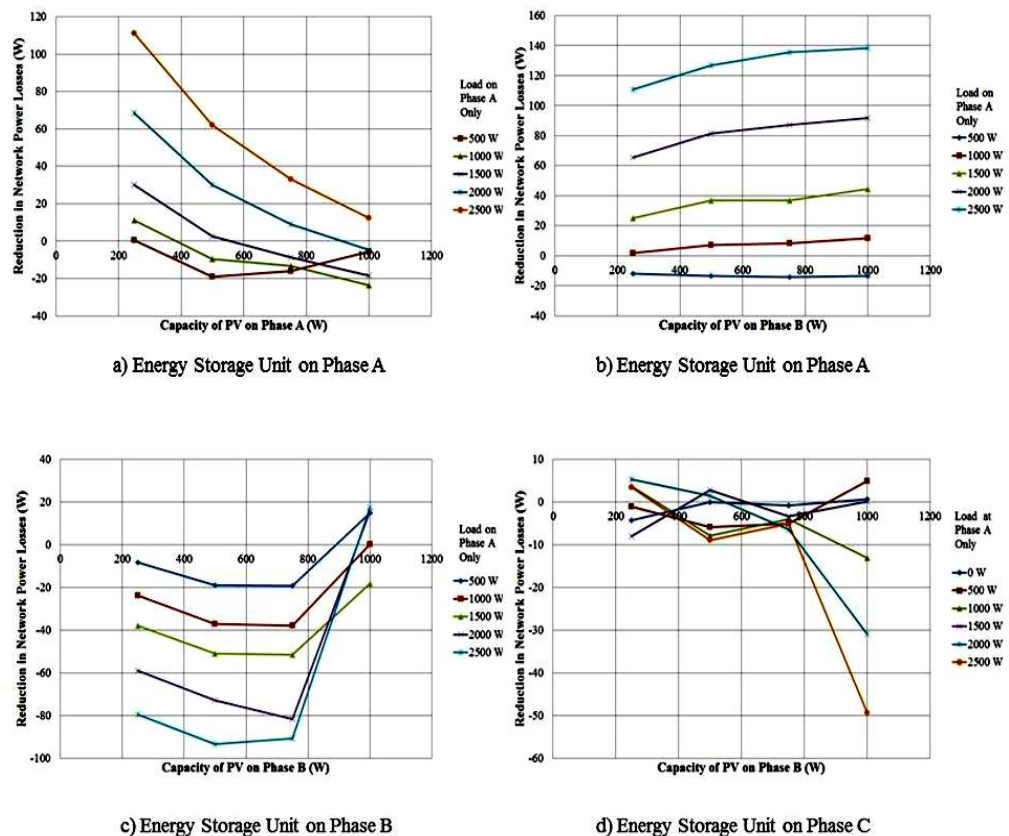


Figure 7.8 Reduction in network power losses against capacity of PV under unbalanced conditions with different locations of energy storage unit

7.5 Conclusions

Experimental studies were then carried out in the experimental small-scaled energy zone (SSEZ) at Durham University in the UK to validate the effectiveness of the energy storage system in improving the voltage unbalance and the efficiency of the network under various penetration levels of PV systems and load conditions. The experimental results show that the %VUF can be effectively reduced to less than 0.8 % if the energy storage unit is placed at the same phase as PV and the load. There is also a significant amount of reduction on power losses if the energy storage unit is at the same phase as the PV and load. The simulation and experimental studies prove that using energy storage unit is an effective means of mitigating %VUF and reducing power losses of low voltage distribution network integrated with a large amount of SSEG.

CHAPTER 8

DISCUSSION & CONCLUSIONS

8. 1 Discussion

With the continuous growth of load demand, climate change, increased fossil fuel consumption and emergence of green technology, PV is likely to be the dominant type of renewable energy source and plays a key role in Malaysian LV distribution network. With this current trends, initiatives and efforts are taken by the government to promote and embrace renewable energy technology. However, the intermittent nature and the uncertainties associated with the PV systems create technical challenges that have to be investigated in order to facilitate the utilisation of these PV units in the LV distribution system. Furthermore, the design of the LV distribution networks does not take into account the installation of anticipated growth of PV systems which allows bi-directional flow of current but only designed to accommodate unidirectional flow of current.

Voltage unbalance of the network has been identified to be the major concern in Malaysian LV distribution network. This is because the PV systems installed in the Malaysian networks are single phase and their growth on the LV

distribution networks is driven by the customers and is not centrally planned. The thesis has proposed a method to mitigate the voltage unbalance factor and enhance the efficiency of the network by reducing its network power losses.

In this research, the work has been divided into two stages in order to investigate the impacts of high penetration of PV on LV distribution networks in commercial and residential areas in Aman Jaya. Two PSCAD models of LV distribution networks in commercial and residential areas have been modeled.

The commercial area has a maximum load demand when the PV outputs maximum power while the residential area has a minimum load demand when the PV outputs maximum power. The performance of the LV distribution networks with respect to uniform and non-uniform distribution of PVs have been investigated through both commercial and residential LV distribution networks.

The active power management solution utilising the energy storage unit integrated with four quadrant converter is proposed. PSCAD models of the energy storage unit, generic LV distribution networks and PV systems were developed to simulate the performance of the networks with different penetration levels of PV systems. Installing the energy storage unit at the feeder end could absorb the excessive real power generated by the PV. The controller of the energy storage unit monitors the voltage level at each phase in order to reduce the voltage unbalance at the remote end of the LV networks and then determines the required real and reactive power to be absorbed/injected

from/onto the network. The simulation results show that the energy storage unit can effectively reduce the voltage unbalance factor and network power losses on the network integrated with PV systems.

An experimental SSEZ was set up at the University of Durham to validate the effectiveness of the energy storage system in improving voltage unbalance and efficiency of the network under various penetration levels of PV systems and load conditions.

8. 2 Conclusions

The key findings of the simulation are listed as follows:-

- Installing PVs into any one of the phases will improve the voltage profile and reduce the network power losses of the phases as long as the capacity of PV does not exceed the demand.
- The losses of the system may vary as the PV output changes. In general, the minimum losses occur when the size of the PV is equal to the feeder load.
- The voltage unbalance factor is proportional to the capacity of PV with respect to the maximum demand. As the capacity of PV increases, the voltage unbalance factor increases.
- As the distribution networks become unbalanced, unbalance current tends to flow through the neutral line. Consequently, the total network power losses will increase.
- Non-uniform distribution of PVs can cause the commercial and

residential networks to reduce the amount of PVs that can be installed as compared to the uniform distribution of PVs under most of the categories of technical constraints.

The experimental results show that the voltage unbalance factor can be effectively reduced to 0.8 % if the energy storage unit is placed at the same phase as PV and the load. There is also a significant amount of reduction on power losses if the energy storage unit is at the same phase as the PV and load. The simulation and experimental studies prove that using energy storage unit is an effective means of mitigating voltage unbalance factor and reducing power losses of low voltage distribution networks integrated with a large amount of PV.

8. 3 Future Work

Current work only focus on high penetration of PV onto weak network. In addition, study can include the investigation on the operation of energy storage unit when the DG is malfunction. Apart from this, the energy storage unit can be integrated to a more complex distribution network and observe the dynamic response of the energy storage unit to mitigate the voltage unbalance factor and network power losses.

The current design of the energy storage unit is based on single phase four quadrant converter. In future, energy storage unit integrated with a three phase four quadrant converter should be introduce in order for better improvement to oversee the three phase voltage level hence to mitigate the voltage unbalance factor.

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Appendix A

Line data for commercial area LV distribution network

No.	Type of Cable
1	70MMP 4C XLPE AL
2	300MMP 4C XLPE AL

Transformer	Subsystem	Line Data					Type of Cable
		Bus	Phase	Length	R _L ohms	X _L ohms	
TX1	FP1-1	4	-	200	0.02600	0.01440	2
		5	A	50	0.02840	0.00375	1
			B	50	0.02840	0.00375	1
			C	50	0.02840	0.00375	1
		6	A	45	0.02556	0.00338	1
			B	45	0.02556	0.00338	1
			C	45	0.02556	0.00338	1
		7	A	40	0.02272	0.00300	1
			B	40	0.02272	0.00300	1
			C	40	0.02272	0.00300	1
		8	A	35	0.01988	0.00263	1
			B	35	0.01988	0.00263	1
			C	35	0.01988	0.00263	1
		9	A	40	0.02272	0.00300	1
			B	40	0.02272	0.00300	1
	C	40	0.02272	0.00300	1		
	FP1-2	10	A	45	0.02556	0.00338	1
		B	45	0.02556	0.00338	1	
		C	45	0.02556	0.00338	1	
	11	-	150	0.01950	0.01080	2	
	12	A	60	0.03408	0.00450	1	
		B	60	0.03408	0.00450	1	
		C	60	0.03408	0.00450	1	
	13	A	55	0.03124	0.00413	1	
		B	55	0.03124	0.00413	1	
		C	55	0.03124	0.00413	1	
	14	A	50	0.02840	0.00375	1	
		B	50	0.02840	0.00375	1	
		C	50	0.02840	0.00375	1	
	15	A	35	0.01988	0.00263	1	

			B	35	0.01988	0.00263	1
			C	35	0.01988	0.00263	1
		16	A	30	0.01704	0.00225	1
			B	30	0.01704	0.00225	1
			C	30	0.01704	0.00225	1
		17	A	35	0.01988	0.00263	1
			B	35	0.01988	0.00263	1
			C	35	0.01988	0.00263	1
		18	A	40	0.02272	0.00300	1
			B	40	0.02272	0.00300	1
			C	40	0.02272	0.00300	1
	FP1-3	19	-	140	0.01820	0.01008	2
		20	A	70	0.03976	0.00525	1
			B	70	0.03976	0.00525	1
			C	70	0.03976	0.00525	1
		21	A	65	0.03692	0.00488	1
			B	65	0.03692	0.00488	1
			C	65	0.03692	0.00488	1
		22	A	60	0.03408	0.00450	1
			B	60	0.03408	0.00450	1
			C	60	0.03408	0.00450	1
		23	A	55	0.03124	0.00413	1
			B	55	0.03124	0.00413	1
			C	55	0.03124	0.00413	1
		24	A	50	0.02840	0.00375	1
			B	50	0.02840	0.00375	1
			C	50	0.02840	0.00375	1
		25	A	45	0.02556	0.00338	1
			B	45	0.02556	0.00338	1
			C	45	0.02556	0.00338	1
TX2	FP1-4	26	-	65	0.00845	0.00468	2
		27	A	75	0.04260	0.00563	1
			B	75	0.04260	0.00563	1
			C	75	0.04260	0.00563	1
		28	A	70	0.03976	0.00525	1
			B	70	0.03976	0.00525	1
			C	70	0.03976	0.00525	1
		29	A	65	0.03692	0.00488	1
			B	65	0.03692	0.00488	1
			C	65	0.03692	0.00488	1
		30	A	60	0.03408	0.00450	1
			B	60	0.03408	0.00450	1

			C	60	0.03408	0.00450	1
		31	A	55	0.03124	0.00413	1
			B	55	0.03124	0.00413	1
			C	55	0.03124	0.00413	1
		32	A	60	0.03408	0.00450	1
			B	60	0.03408	0.00450	1
			C	60	0.03408	0.00450	1
		33	A	65	0.03692	0.00488	1
			B	65	0.03692	0.00488	1
			C	65	0.03692	0.00488	1
	FP1-5	34	-	125	0.01625	0.00900	2
		35	A	80	0.04544	0.00600	1
			B	80	0.04544	0.00600	1
			C	80	0.04544	0.00600	1
		36	A	75	0.04260	0.00563	1
			B	75	0.04260	0.00563	1
			C	75	0.04260	0.00563	1
		37	A	70	0.03976	0.00525	1
			B	70	0.03976	0.00525	1
			C	70	0.03976	0.00525	1
		38	A	65	0.03692	0.00488	1
			B	65	0.03692	0.00488	1
			C	65	0.03692	0.00488	1
		39	A	60	0.03408	0.00450	1
			B	60	0.03408	0.00450	1
			C	60	0.03408	0.00450	1
		40	A	55	0.03124	0.00413	1
			B	55	0.03124	0.00413	1
			C	55	0.03124	0.00413	1
		41	A	50	0.02840	0.00375	1
			B	50	0.02840	0.00375	1
			C	50	0.02840	0.00375	1
		42	A	45	0.02556	0.00338	1
			B	45	0.02556	0.00338	1
			C	45	0.02556	0.00338	1
	FP1-6	43	-	150	0.01950	0.01080	2
		44	A	35	0.01988	0.00263	1
			B	35	0.01988	0.00263	1
			C	35	0.01988	0.00263	1
		45	A	40	0.02272	0.00300	1
			B	40	0.02272	0.00300	1
			C	40	0.02272	0.00300	1

		46	A	45	0.02556	0.00338	1
			B	45	0.02556	0.00338	1
			C	45	0.02556	0.00338	1
		47	A	50	0.02840	0.00375	1
			B	50	0.02840	0.00375	1
			C	50	0.02840	0.00375	1
		48	A	55	0.03124	0.00413	1
			B	55	0.03124	0.00413	1
			C	55	0.03124	0.00413	1
		49	A	60	0.03408	0.00450	1
			B	60	0.03408	0.00450	1
			C	60	0.03408	0.00450	1
		50	A	65	0.03692	0.00488	1
			B	65	0.03692	0.00488	1
			C	65	0.03692	0.00488	1
		51	A	70	0.03976	0.00525	1
			B	70	0.03976	0.00525	1
			C	70	0.03976	0.00525	1
	FP1-7	52	-	125	0.01625	0.00900	2
		53	A	50	0.02840	0.00375	1
			B	50	0.02840	0.00375	1
			C	50	0.02840	0.00375	1
		54	A	55	0.03124	0.00413	1
			B	55	0.03124	0.00413	1
			C	55	0.03124	0.00413	1
		55	A	60	0.03408	0.00450	1
			B	60	0.03408	0.00450	1
			C	60	0.03408	0.00450	1
		56	A	65	0.03692	0.00488	1
			B	65	0.03692	0.00488	1
			C	65	0.03692	0.00488	1
		57	A	70	0.03976	0.00525	1
			B	70	0.03976	0.00525	1
			C	70	0.03976	0.00525	1

Appendix B

Line data for residential area LV distribution network

Transformer	Subsystem	Line Data			
		Bus	Length (m)	R _L (ohms)	X _L (ohms)
TX1	FP3-1	8	40	0.00520	0.00288
		9	130	0.01690	0.00936
		10	120	0.01560	0.00864
		11	30	0.00390	0.00216
		12	60	0.00780	0.00432
		13	150	0.01950	0.01080
	FP3-2	3	80	0.01040	0.00576
		4	20	0.00260	0.00144
		5	20	0.00260	0.00144
		6	150	0.01950	0.01080
		7	70	0.00910	0.00504
TX2	FP3-3	14	230	0.02990	0.01656
		15	30	0.00390	0.00216
		16	110	0.01430	0.00792
		17	100	0.01300	0.00720
		18	70	0.00910	0.00504
		19	40	0.00520	0.00288
	FP3-4	20	190	0.02470	0.01368
		21	40	0.00520	0.00288
		22	45	0.00585	0.00324
		23	20	0.00260	0.00144
		24	50	0.00650	0.00360

Appendix C

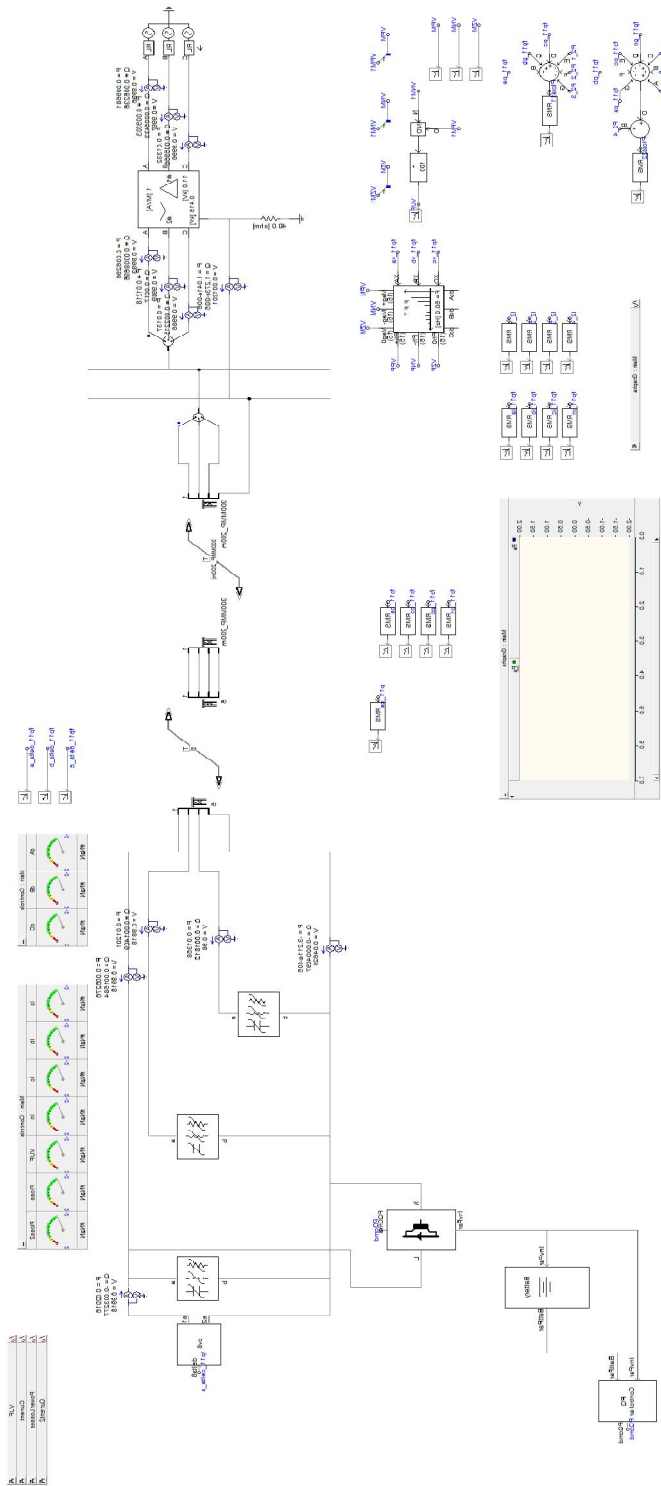
MATLAB Verification for Voltage Unbalance Factor

MATLAB Coding to verify the Voltage Unbalance Calculation:

```
V1=;           //set V1 value
V2=;           //set V2 value
V3=;           //set V3 value
a=exp(2*i*pi/3);
Va = V1;
Vb = V2*exp(i*(-2*pi/3));
Vc = V3*exp(i*(2*pi/3));
Vp = (1/3)*((Va)+(a*Vb)+((a^2)*Vc));
Vn = (1/3)*((Va)+((a^2)*Vb)+(a*Vc));
Vz = (1/3)*(Va+Vb+Vc);
vuf=abs(Vn/Vp*100)
```

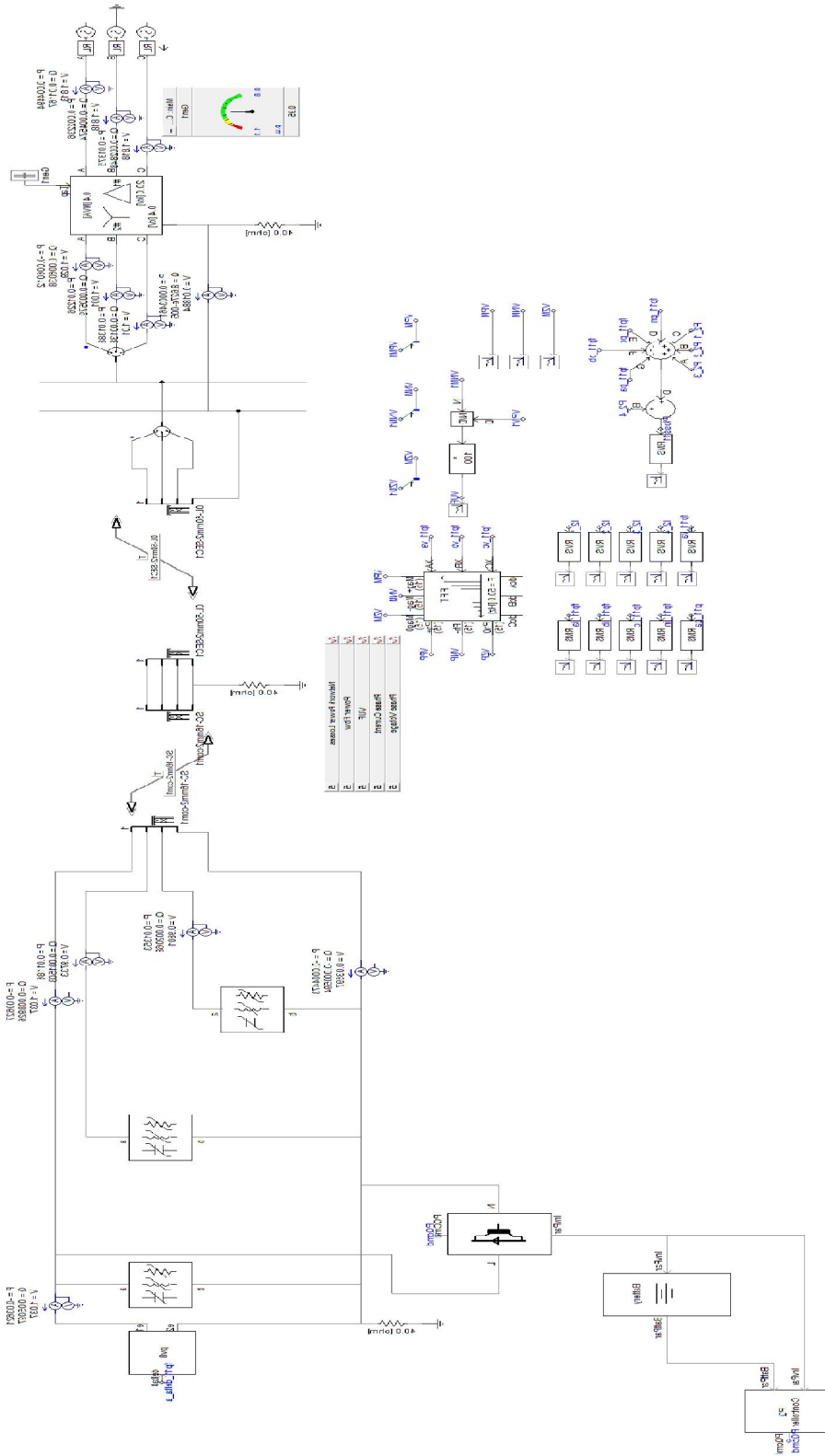
Appendix D

PSCAD Model of Network 1 with integrated ESU with four quadrant converter



Appendix E

PSCAD Model of Network 2 with integrated ESU with four quadrant converter



Appendix F

PAPER SUBMISSION

The findings from this research had been compiled and submitted to the following journals by this author:

No.	Title	Journal	Status
1.	Optimal Utilization of Small-Scale Embedded Generators In A Developing Country – A Case Study In Malaysia	Elsevier Science Direct Renewable Energy, September 2011, Volume 36, Issues 9, pp. 2562-2572	Published
2.	Mitigation of Voltage Unbalance in Low Voltage Distribution Network with High Level of Photovoltaic System	2011 IEEE International Conference on Smart Grid and Clean Energy Technologies IEEE ICSGCE 2011	Published