INVESTIGATION AND CHARACTERISATION OF VOLTAGE QUALITY ON NETWORK INTEGRATED WITH PHOTOVOLTAIC SYSTEMS

By

TANG JUN HUAT

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ABSTRACT

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Tang Jun Huat

The Malaysian government has launched various renewable energy programs to encourage the use of green technology such as Feed-in Tariff (FiT). Photovoltaic (PV) is likely to become one of the most dominant type of renewable energy source in Malaysia due to its abundant solar irradiation. However, it is extremely rare for Malaysia to have a completely clear sky due to the passing cloud. The incident solar irradiation is highly scattered and fluctuating, hence making the power output of the PV systems to be very intermittent. The intermittent power output of the PV systems causes the voltage magnitude to be fluctuating sharply and frequently.

This dissertation proposes a direct load control (DLC) for mitigating the voltage fluctuation and flicker caused by the PV systems. In this study, the power system simulation tool, namely DIgSILENT POWER FACTORY, is used to study the technical impacts of the distributed generation on low voltage (LV) distribution networks. A load control algorithm is developed using LABVIEW^{TM} as a programming platform in a computer. The proposed DLC makes use of real power to change the network voltage, as the voltage

magnitude responds predominantly to the change of real power flow in the LV distribution networks where the resistance is higher than the reactance.

Several experiments have been carried out to test the effectiveness of DLC in reducing voltage fluctuation and flicker caused by the PV power output fluctuation. However, there are a few potential problems associated with the application of DLC. One of the main problems is the social aspect of finding sufficient number of controlled loads. To investigate whether or not this problem could be a key barrier to the application of DLC, a site survey is conducted among the Malaysian community to identify their acceptance level on DLC and energy efficiency.

The experimental results show that the DLC can effectively reduce the voltage fluctuation and flicker issues caused by the PV generation system. This work proposed a solution to mitigate the voltage quality issues caused by the PV systems. This work is valuable because PV generation system has the potential to be the dominant type of RE generation in Malaysia and the proposed DLC can solve one of the most severe power quality issues caused by the penetration of PV systems in Malaysia. The potential beneficiary of the presented work is power utility and RE developer in reducing the negative impact of high penetration level of in distribution networks.

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FACULTY OF ENGINEERING AND SCIENCE

UNIVERSITI TUNKU ABDUL RAHMAN

Date: 22 November 2013

SUBMISSION OF DISSERTATION

It is hereby certifies that **TANG JUN HUAT** (ID No: 1201UEM190) has completed this dissertation entitled **"INVESTIGATION AND CHARACTERISATION OF VOLTAGE QUALITY ON NETWORK INTEGRATED WITH PHOTOVOLTAIC SYSTEMS"** under supervision of **Ir. Dr. LIM YUN SENG** (Supervisor) from the Department of Electrical and Electronic Engineering, Faculty of Engineering and Science, and **Dr. Stella Morris** (Co-Supervisor) from the Department of Electrical and Electronic Engineering, Faculty of Engineering and Science.

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

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(TANG JUN HUAT)

APPROVAL SHEET

This dissertation entitled "**INVESTIGATION AND CHARACTERISATION OF VOLTAGE QUALITY ON NETWORK INTEGRATED WITH PHOTOVOLTAIC SYSTEMS**" was prepared by TANG JUN HUAT and submitted as partial fulfilment of the requirements for the degree of Master of Engineering Science at Universiti Tunku Abdul Rahman.

Approved by:

____

(Ir. Dr. LIM YUN SENG)
Date:…………………..
Supervisor
Department of Electrical and Electronic Engineering
Faculty of Engineering and Science
Universiti Tunku Abdul Rahman

____

(Dr. STELLA MORRIS)
Date:…………………..
Co-supervisor
Department of Electrical and Electronic Engineering
Faculty of Engineering and Science
Universiti Tunku Abdul Rahman

DECLARATION

I hereby declare that the dissertation is based on my original work except for 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.

(TANG JUN HUAT)

Date: 22 November 2013

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LIST OF SYMBOLS / ABBREVIATIONS

CHP	Combined heat and power
CO_2	Carbon dioxide
DG	Distributed generation
DSM	Demand side management
EE	Energy efficiency
EHV	Extra high voltage
EM	Electromagnetic
FACTS	Flexible AC transmission system
FiT	Feed-in tariff
GBI	Green building index
GLC	Government linked company
GTFS	Green technology financing scheme
GVR	Global voltage regulation
HAWT	Horizontal-axis wind turbine
HV	High Voltage
IEC	International electro-technical commission
IGBT	Insulated-gate bipolar transistor
LV	Low voltage
MBIPV	Malaysian building integrated photovoltaic
O&M	Operation and maintenance
PV	Photovoltaic
RE	Renewable energy

RMS	Root mean square
SEDA	Sustainable energy development authority
SOC	State of charge
SREP	Small renewable energy program
SSR	Solid state relay
STATCOM	Static synchronous compensator
SVR	Static VAr compensator
TNB	Tenaga Nasional Berhad
UPS	Uninterruptible power supply
VAWT	Vertical axis wind turbine
VFI	Voltage fluctuation index
VR	Voltage regulation
VSD	Variable speed drive
VUF	Voltage unbalance factor

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CHAPTER 1

INTRODUCTION

1.1 Research Background

The consumption of fossil fuels like coal and natural gas for power generation causes adverse environmental effects. In addition, the recent trends of declining fossil fuel resources combined with the reluctance to go nuclear, forces Malaysia to actively conduct research into solar photovoltaic (PV), biomass, biogas and hydro-generation.

The Malaysian government has launched various renewable energy programs to encourage the use of green technology. The Renewable Energy Act 2011 is an Act to provide the establishment and implementation of Feed-in Tariff (FiT) to catalyse the generation of renewable energy (RE) in Malaysia under the FiT program. The utility company purchases the power generated by domestic and commercial users at competitive rates, encouraging investment in the renewable energy sector as shown in Table 1.1.

The PV systems are the most promising RE sources in the tropical countries due to the large amount of sunlight available in the regions throughout the year. As a result, the amount of PV system is expected to grow very rapidly over the next few decades. However, with a large amount of passing clouds over Malaysia, the incident solar irradiance is highly scattered and fluctuating, which makes the power output of the PV systems to be very intermittent. The highly intermittent power output of the PV systems causes the voltage at the point of connection to change frequently throughout the day. The voltage fluctuation generates a large amount of flickers onto the low voltage (LV) distribution networks.

Table 1.1: Feed-in tariff in Malaysia

Renewable Energy Generation	FiT Rates (RM per kWh) at 2013
Biogas[1]	0.3184
Biomass[2]	0.3085
Small Hydro[2]	0.2400
Solar PV[1]	1.1316

1. Up to and including 4.0 kW.
2. Up to and including 10.0 MW.

The impacts of voltage fluctuation and flicker include the nuisance due to the variation of light flux. A person who is affected by light flickering can suffer from headache, migraine, and eye discomfort. Inconsistent voltage supply can cause the motors to change their starting toque, run at varying speeds with vibration and hence reduce the operational efficiency. In addition, unstable voltage supply can cause electronic equipment to malfunction, unwanted triggering of uninterruptible power supplies (UPS) and reduction in operational efficiency. Besides, the design of the existing distribution networks does not take into account of the anticipated distributed generation (DG). Several research papers have discussed the technical issues caused by DG, including voltage imbalance, voltage rise, reverse power losses as well as cable and transformer thermal limits (Loo, 2005; Pádraig, 2009; Wong et al., 2011). However, there are limited studies on the flicker emissions and the research is not common. The flicker emissions caused by the PV power output may be unacceptable from the standpoint of power quality. Most of the previous studies are based on simulation. Additional experimental research work is required.

There are several approaches to reduce the technical impacts caused by the PV systems such as energy storage, demand side management (DSM), super-capacitor, STATCOM and Static VAr Compensator. The simulation and experimental results of the reported energy storage system have proven that it is effective to mitigate the voltage unbalance factor and power losses in LV distribution networks integrated with a large amount of PV systems (Wong, 2011). DSM is also reported to be one of the solutions to solve voltage rise issues caused by the integration of large amount of DG (Lim & Philip, 2007). The major blackout in India in July 2012, which affected more than half of India's population, is believed to be the biggest ever power failure in the world (Wikipedia, n.d.). Even before the blackout incident, DSM had been suggested as a viable approach for the power shortage issues in India (Sinha et al., 2011). In addition, Wei et al., (2007) discussed the use of super-capacitors to buffer the fluctuations caused by the PV systems due to a large amount of moving clouds. The simulation results in this paper show that a super-capacitor is capable to buffer the voltage fluctuations due to the scattered clouds and high number of irradiance fluctuations. Furthermore, STATCOM is also reported to control the injection of reactive power that is required to stabilize the voltage level (Elnady & Salama, 2007). However, STATCOM is commonly used on the transmission networks instead of LV distribution networks. Meanwhile, D-STATCOM is a fast compensating reactive power system to reduce flicker on distribution system. However, it is a very expensive device.

In this work, the impact of PV systems connected onto the existing LV distribution networks is investigated through simulation and experiments. A novel direct load control (DLC) algorithm is proposed in this work to mitigate the voltage fluctuation and flicker caused by the PV power fluctuation. The DLC makes use of real power flow to change the network voltage because the voltage magnitude responds predominantly to the change of real power in the LV distribution networks, where the resistance is much higher than reactance. The DLC is proposed because of low initial cost compared to that of STATCOM or super-capacitor. In addition, the super-capacitor has a low cell voltage. To achieve a higher voltage level, the capacitor is connected in series; which causes an internal leakage current and a higher risk of overvoltage (Wei et al., 2007). Experimental results are presented to identify the effectiveness of the proposed DLC. Finally, this dissertation reports a survey result of 990 Malaysians on energy efficiency (EE) and DLC implementation in Malaysia. It contributes to the literature by providing a better understanding of the perceptions and behaviors of Malaysians about the possible deployment of DLC. This study, to our knowledge, is the first public survey carried out in Malaysia which focuses on the DLC.

1.2 Research Objectives

The main objectives of this research are:-

i To use DIgSILENT PowerFactory to model commercial and residential LV distribution networks.

ii To investigate the technical impacts of PV systems connected onto the LV distribution networks.

iii To design and develop an experimental LV network emulator integrated with renewable sources in order to study the intermittent PV power output.

iv To mitigate the voltage fluctuation and flicker caused by PV systems.

v To conduct surveys in order to study the public acceptance level of direct load control.

1.3 Research Methodology

The research objectives are achieved using three approaches.

Approach I (Simulation): At the initial stage, a simulation model is developed to study the technical impacts of connecting PV systems onto the existing LV distribution networks.

STEP 1: A literature review is carried out to study the design and characterization of the LV distribution network emulator, the technical impacts of connecting PV systems onto existing LV distribution networks, and existing methods to mitigate the voltage quality issues.

STEP 2: DIgSILENTPowerFactory is used to model the commercial and residential LV networks from Aman Jaya, Selangor, Malaysia.

STEP 3: These models are used to investigate the impacts of high penetration of PV power injected into the LV distribution networks.

Approach II (Experiment): The second stage of the research uses an experimental approach to investigate the effectiveness of the proposed solution to mitigate the voltage fluctuation and flicker emission caused by PV systems.

STEP 1: An experimental LV network emulator is setup to investigate the power quality issues caused by PV systems.

STEP 2: To develop the direct load control (DLC) algorithm in LabVIEW to mitigate the voltage fluctuation and flicker caused by PV power fluctuation.

STEP 3: To setup the experiments to identify the effectiveness of using DLC in mitigating the voltage fluctuation and flickers caused by the variable power output from PV systems. The DLC is tested in the off-grid systems with and without the battery storage and also on-grid systems.

Approach III (Survey): In order to identify the social and psychological aspects of controlling customer's appliances such as water heaters, site surveys are conducted to investigate the public acceptance level of DLC. A survey is conducted with the Malaysian electricity users in the final stage of the work. This is to investigate the acceptance level of the proposed solution to be integrated to the existing network.

1.4 Scope of Dissertation

The structure of this dissertation is outlined in the following manner:-

The second chapter summarizes the findings from the literature review on the characteristics and design model of the Malaysian LV distribution networks, the possible technical impacts caused by PV systems, the existing methods used to mitigate power quality issues and demand side management.

Chapter Three presents the details of the modelling approach for commercial and residential LV distribution networks in DIgSILENT PowerFactory. This chapter also discusses the technical impacts of an anticipated amount of centrally planned and non-centrally planned PV systems connected onto the LV distribution network.

Chapter Four describes the design and experimental setup of the UTAR LV distribution network emulator integrated with renewable energy. This chapter also includes the details of the proposed DLC to mitigate the voltage fluctuation and flicker caused by the PV systems. The voltage supply quality is accessible through the voltage fluctuation index, the global voltage regulation, short-term flicker and long-term flicker.

Chapter Five presents the severity of the PV power output fluctuation in Malaysia. In addition, the effectiveness of DLC in reducing the voltage fluctuation and flicker caused by the intermittent power output of the PV systems is evaluated. The test results of the proposed DLC in the off-grid system with and without the battery storage and on-grid system are also presented in this chapter.

Chapter Six presents the survey questionnaire and the results from 990 respondents. The survey has accessed the behavioral aspects of Malaysians on energy efficiency (EE) initiative and DLC acceptance level.

Finally, the key findings of the research are presented in Chapter Seven. In this chapter, the research conclusion, publications and future works are also presented.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Malaysia is well endowed with primary energy resources such as oil and gas as well as RE sources like solar energy, biomass from oil palm, biogas, and hydroelectric. However, coal is one of the major fuels for power generation in Malaysia next to natural gas. In Peninsular Malaysia, fossil fuel dominates (94%) the total energy mix in 2011 (Koh et al., 2011; Che Khalib, 2012). Figure 2.1 shows the electric generation mix in year 2011. Malaysia imports coal from Indonesia, Australia and South Africa. Reliance on fuel that must be imported for power generation makes Malaysia exposed to potential energy security issues.

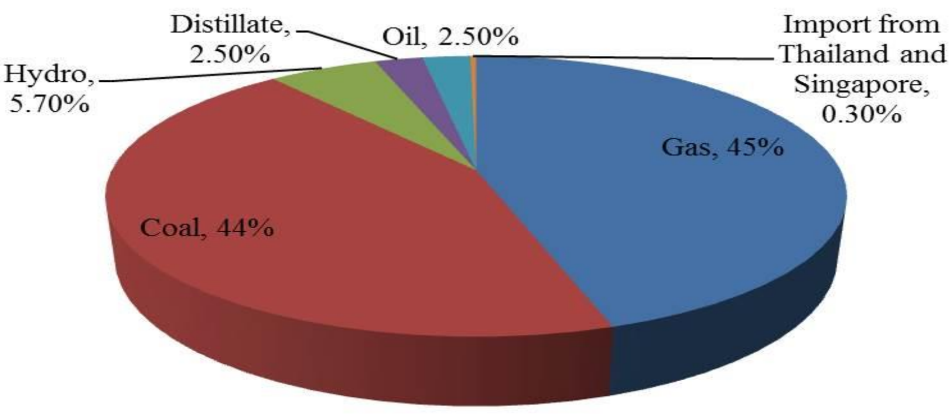


Figure 2.1: Peninsular Malaysia energy mix in 2011

Recently, the Malaysian Government has launched various renewable energy programs to encourage the use of green technology in order to minimize the dependence on fossil fuels (Wong, 2011). In addition, the government has committed to the reduction of the greenhouse gas (GHG) emissions by 40% in 2020 at the Copenhagen meeting on climate change in 2009. This has led to a high investment in the RE by the government, government linked companies (GLC) and private sectors. To promote the growth of green technology activities, the Malaysian Government has allocated more than RM1.5 billion as a soft loan to consumers and manufacturers, through the Green Technology Financing Scheme (GTFS) in the announcement of Budget 2010 (Nazariah, 2011). In addition, building owners who get the Green Building Index (GBI) certification during the period between 24th October 2009 and 2014 will be granted the income tax exemption, which is equalled to the additional capital expenditure incurred to obtain the certificate.

PV systems are the most promising renewable energy sources in tropical countries due to the large amount of solar irradiation availability throughout the year. Hence, PV power generation will be the major RE generation on the LV distribution networks in the near future. As mentioned earlier, PV systems when connected to the existing LV distribution networks will impose several technical issues such as voltage fluctuation and flicker, because of the high frequency of passing clouds. Besides, the high penetration of PV output power on the LV distribution network also causes voltage rise, voltage imbalance and power losses because the existing LV network is designed for uni-directional power flow and does not cater to the anticipated amount of the PV systems.

This chapter presents the literature reviews of some related research works done by other researchers. Initially, the design of the conventional LV distribution networks and existing distributed generation (DG) technology are studied. This is followed by an investigation of the existing PV development in Malaysia, together with the pros and cons of the connecting PV systems on an existing LV network. The power quality issues arise because of the DG penetrations which are briefly reviewed. The existing methods to mitigate voltage quality issues are also described in this chapter. This includes the implementation of super-capacitors, injection or absorption of reactive power STATOM and DSM. Furthermore, the benefits and challenges of integrating DSM and DG in the future LV distribution networks are studied.

2.1.1 Conventional Power System in Malaysia

The Malaysian electricity utility company namely Tenaga Nasional Berhad (TNB), supplies electricity to the Peninsular Malaysia, while the Sarawak Electricity Supply Corporation (SESCO) and Sabah Electricity Sdn. Bhd. (SESB) take care of the electric supplies for Sarawak and Sabah.

The voltage levels of Malaysia’s main transmission networks are 500kV, 275kV, and 132kV whilst that of the distribution networks with voltage rating of 33kV, 11kV and 415/240 volts. In certain parts of Johor and

Perak, the distribution voltage levels are 22kV and 6.6KV. The supply frequency is 50Hz $\pm 1\%$. The high voltage (HV) and extra high voltage (EHV) systems use the 3 phase configuration where the system is solidly grounded or grounded through an impedance. The EHV and HV systems use underground and overhead lines for electricity transmission. The LV systems are of 3-phase 4-wire configurations. The neutral point is solidly earthed at the secondary side of transformers.

At present, there are 46 major power stations distributed nationwide, mostly sized between 100MW to 2 GW; feed three-phase AC power into the national grid of HV transmission lines which interconnect generators to distribution lines, substations and customers. The national grid is designed in such a way that it provides reliability and redundancy of service, so that if any of the overhead lines, underground cables, transformer or generators fails, power can be delivered from other sources via a different route through the electrical grid. This has resulted in a huge vertically integrated power system. For example, Malaysia's national transmission grid handles approximately 104 TWh of energy per year, through more than 11,000 km of transmission infrastructure (Energy Commission, 2010).

Electricity on the transmission networks is then transmitted to the distribution networks through step down transformers in the substations. The distribution networks in Malaysia are typically interconnected or spot network. The interconnected networks allow the licensee to operate flexible configurations. When a fault occurs, a small area of the networks can be isolated while the healthy part of the network operates to minimize the power outage.

In the distribution substation, voltages are stepped down to 415/240 volts via Delta-Wye transformers. This configuration enables the T-T earthing system on LV side, where both transformer neutral and the frame are earthed (Tenaga Nasional Berhad, 2011). The system configuration is shown in Figure 2.2. Distribution feeder delivers the electricity from distribution substations to consumers through overhead line, underground cables or aerial cable. Normally, substations are located nearby the load centre to minimize the development cost and power losses. These LV networks have a radial topology and low X/R ratio, where its impedances are primarily resistive (Wong et al., 2011).

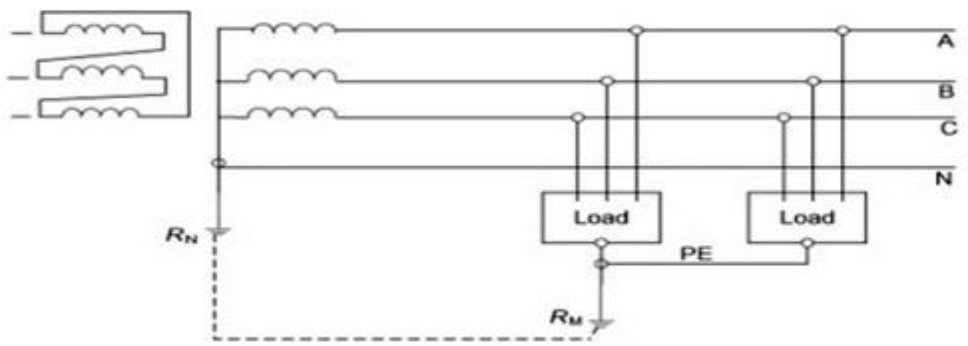


Figure 2.2: T-T earthing system configuration (Sallam & Malik, 2011)

In a nutshell, the conventional power system in Malaysia is designed in such a way that it allows electricity to be transmitted from generators through transmission and distribution systems to the load centre. To cope with an increase in maximum demand, a drop of reserve margin, the generation capacity has to be increased (Energy Commission, 2010). Increasing the generation capacity while minimizing environmental pollution, renewable energy base power generation will be a viable option (Koh & Lim, 2010).

2.2 Distributed Generation (DG) Technology

Generally, DG refers to any electric power generation technology that is integrated within the distribution systems which are close to the points of load demand. DG is normally connected to the medium voltage or LV networks. Normally, they are not centrally planned and have a smaller capacity, less than 30MW (Arthur, 1999). The concept of DG is different from the conventional centralized power generation, where small or micro generators are connected near to the load centre along the distribution networks. The DG systems have drawn a strong interest because of its potential to offer environmental friendly, efficient, flexible and reliable on-site power generation alternative. DG systems complement central power generation by providing a relatively low capital cost response to increasing power demand, strengthening energy security and avoiding transmission and distribution congestion (Konstantinos, 2004).

The DG systems encompass a wide range of technologies including solar power, wind turbine, fuel cell, combined heat and power (CHP), micro turbine, battery storage system, and reciprocating engine (Ipinnimo et al., 2012). Diesel and gasoline fuelled reciprocating engines are the most common

DG technologies in use today in Malaysia, especially for standby power and rural area applications (Abdul Muhaimin, 2010). However, as these technologies are non-renewable, they create pollutants. Solar energy, wind turbine, fuel cell and CHP are the common renewable DG systems installed around the world (Pádraig, 2009).

2.2.1 Photovoltaic System

PV systems use solar modules to convert Sun's light energy into electricity. Power electronic based inverters is required to convert the direct current (DC) generated from the solar modules to alternating current (AC) before exporting the power to the national grid. Figure 2.3 shows the single phase PV configuration. PV systems are expensive options, at present, about RM10.00 per watt (Choong, 2012). However, PV systems have the advantages of zero fuel cost and minimum operating and maintenance (O&M) costs. In addition, PV systems have a service life of 20 years and do not produce any GHG. Nevertheless, the PV power generation relies upon the variable and unpredictable solar irradiation. Currently, PV systems are the most promising renewable energy sources in Malaysia due to the large amount of solar irradiation availability throughout the year.

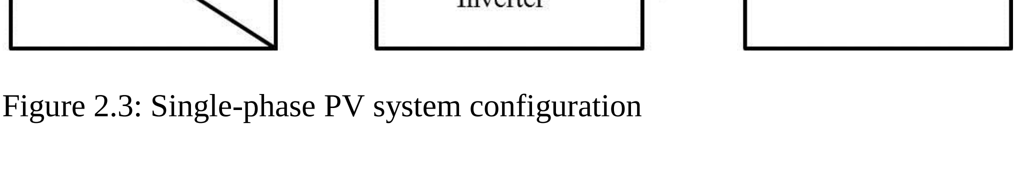


Figure 2.3: Single-phase PV system configuration

Most of the solar module technologies are currently using silicon PV cells. There are typically two categories of PV cells, mono-crystalline and poly-crystalline. The third generation solar cells are thin film cells. Mono-crystalline silicon PV cells are made from silicon wafers that are cut from cylindrical single crystal silicon ingots. These solar cells show predictable and uniform behavior, but it is expensive. Poly- crystalline cells are made from cast square ingots and are less expensive and less efficient. Thin film PV cells are constructed by depositing a thin layer of photovoltaic semiconductor material onto a backing material such as glass. The thin film material that is commercially used is amorphous silicon (Energypedia, 2012).

2.2.2 Wind Turbine

Wind turbine is used to convert the kinetic energy from wind into a useful form of energy, electrical power. A power electronic based converter is required to convert the 3-phases AC output from the wind turbine to a stable DC output and also control the rotational speed of the wind turbine. Then, the wind inverter is used to convert the direct current to single phase 240V AC at 50Hz. Figure 2.4 shows the wind power generation configuration. Wind power generation has the advantage of zero fuel costs, low O&M costs and longer service life (Konstantinos, 2004).

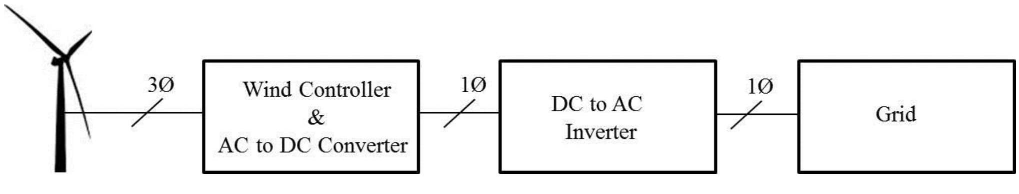


Figure 2.4: Block diagram of wind turbine power generation

There are different types of wind turbines and they can be divided into two major technologies, the horizontal and vertical axis wind turbines (Sandra et al., 2008). The rotational axis of horizontal axis wind turbines (HAWT) must be oriented parallel to the wind direction in order to produce power. Whilst, the rotational axis of vertical axis wind turbine (VAWT) is perpendicular to the wind direction (Castillo, 2011). Although HAWT are considered more efficient in operation than VAWT and are commonly used in large wind farms, the VAWT has the advantages of better safety and minimum wind speed requirement from any direction, and being noiseless (Hannes, 2003). Furthermore, the wind turbine generation relies on the wind speed, and wind volume that are variable and unpredictable. Availability of wind energy in Malaysia is still under study due to the low wind speed throughout the year, which is less than 3 m/s. The highest mean daily wind speed recorded at Mersing, Johor is 3.8 m/s (Malaysia Meteorological Department, 2010).

2.2.3 Small Hydro

Hydroelectric generation is the generation of electric power from the flow of water. Normally, a small hydro project is defined as hydro projects with a generation capacity of up to 10MW. Typically, the stored river water is fed from a reservoir through a channel into the turbine. The flow of water on the turbine blades causes the shaft to rotate. The rotating shaft is connected to an electric generator which converts the mechanical energy into electrical energy. Figure 2.5 shows the hydroelectric power generation configuration. Hydroelectric can provide continuous power through the day with zero emission and low operation cost. However, the argument against hydroelectric arises because of the environmental degradation caused by the reservoir dam. Malaysia has a large number of rivers that are suitable for building large or small hydro dams for electricity generation, especially in the state of Sarawak and Sabah. Total hydropower generation capacity in Malaysia is about 29 GW with 70% in Sarawak. Small hydro power generation is one of the most feasible rural electrification methods in Malaysia (Benjamin & Scott, 2011) because Malaysia is the tenth highest rainfall receiving country in the world, with a volume of about 289 cubic centimetre of water per square centimetre of land area (Sasi Group, 2006).

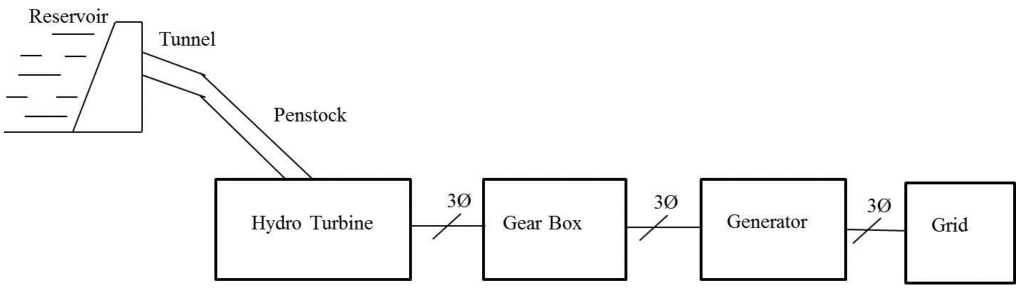


Figure 2.5: Hydroelectric generation configuration

2.2.4 Other Technologies

Combined Heat and Power (CHP) also called Cogeneration is the use of the small heat engine which provides the power for building, heating, and ventilation. CHP utilizes the waste heat produced as a by-product and hence increase the energy efficiency. However, the CHP implementation in Malaysia is not common, because Malaysia is a warm country and cooling is preferred than heating. Fuel cells generate electricity by combining hydrogen and oxygen electrochemically like a battery. The basic fuel cells have two electrodes, cathode and anode, separated by an electrolyte. The by-product of the electrochemical reaction is water and heat with low emission level (Fuel Cells 2000's, 2013). The advantages of fuel cells are low to zero emissions, high efficiency, and are noiseless. Currently, fuel cells are still a new technology for Malaysia, therefore it is not a popular DG options at this moment.

2.3 Development of Photovoltaic Systems in Malaysia

Malaysia is one of the tropical countries in Southeast Asia that receives abundant sunshine and thus solar radiation. Malaysia is a maritime country near equator, surrounded by the South China Sea and Malacca Straits as shown in Figure 2.6 (Koh & Lim, 2010). The constant evaporation of the sea water results in an enormous amount of clouds passing through the country.

Figure 2.6: Malaysia map

As mentioned in the previous section, solar PV will be the major RE source on the distribution networks in the near future. Hence, this research is focused only on PV systems as the main distributed generators connected to the LV distribution networks. Therefore, a brief introduction of the development of solar PV in Malaysia, and the power quality issues that arise in PV systems will be discussed in this section.

The Malaysian government announced the Five Fuel Diversification Policy in the year 2000 making renewable energies such as solar PV, biomass, and mini hydro, as the fifth source of energy (Lim et al., 2008). This policy is introduced to replace the Four Fuel Diversification Policy of 1981 that is dependent on conventional sources of energy such as oil, natural gas, hydroelectric, and coal. This new policy induces a wide range of the installation of renewable power generators, especially solar PVs.

Another RE initiative program was launched in 2001, namely Small Renewable Energy Power Program (SREP). The launch of this program is one of the steps being taken by the Malaysian Government to encourage the use of RE power generation. Under this SREP program, the owners of renewable power plants can apply for a license to sell their electricity to the utility company for a period of 21 years, which will be effective from the date of commissioning of the plant (Ministry of Energy, Green Technology and Water, 2009).

The Malaysia Building Integrated Photovoltaic (MBIPV) program is introduced in the year 2005 under the 9th Malaysia plan (Hussin et al., 2011). The objective of this program is to reduce the GHG emission by introducing grid connected PV systems and to enhance the development of the PV industry in the country. This project is administered by the Ministry of Energy, Green Technology and Water Malaysia and is partially funded by the United Nations Development Program and Global Environment Facility. The total capacity of the grid tied PV systems installed and commissioned under MBIPV project is approximately 1.5 MWp by the end of 2010.

Another project introduced by the Malaysian Government, namely 'SURIA 1000' was officially launched on June 2007. This program provides direct opportunities for residential and commercial customers to be involved in renewable energy initiatives and greener environment. SURIA 1000 targets to install a total of 1000 roof top and grid connected PV systems with a capacity of 790 KWp (Wong, 2011).

The Malaysia Feed in Tariff (FiT) system launched in December 2011 results in a new era in Malaysia moving towards to achieve green environment and pollution free power generation. The FiT system obliges the utility company such as TNB and SESC to buy from Feed-in Approval Holders the electricity produced by RE and sets the FiT rate shown in Table 1.1. By guaranteeing access to the grid and setting a favorable price per unit of RE electricity, the FiT mechanism would ensure that RE becomes a viable and long term investment for individuals and the industrial sector. The RE sources included in the program is solar PV, small hydro, biomass, and biogas. The solar PV and small hydro renewable electricity generated could be sold to the utility company and paid with the FiT rate for 21 years, whilst it is 16 years for biomass and biogas resources (SEDA Malaysia, 2013).

2.4 Power Quality in with Photovoltaic Systems

With all the fiscal incentives and programs introduced by the Malaysian Government and other parties to promote renewable energy, especially PV, it is projected that the amount of PVs connected to the existing LV networks will be increased. Hence, it is important to mitigate the technical issues caused by the PV systems in order to maintain the stability, reliability and security of future LV networks.

The general technical issues caused by the distributed generation have been studied (Farid et al., 2006; Basso, 2008; M.J. Ortega, 2013). Technical issues that might arise by the high penetration of PV systems are voltage fluctuation, flicker, voltage rise and regulation, and voltage imbalance. The major issues caused by the PV systems are the voltage quality and current harmonic. Guidelines and recommendations for connecting various DGs in the Malaysian distribution networks are discussed (Loo & Abdul Aziz, 2007). In addition, technical issues such as capacity adequacy, network losses, voltage regulation and control, fault level and protection are also discussed.

2.4.1 Voltage fluctuation and flicker

Table 2.1 shows the average amount of cloud and frequency of completely clear sky occurrence in several regions. As tabulated in Table 2.1, the average amount of clouds in Malaysia is about 77% which is one of the highest in the world. Figure 2.7 and Figure 2.8 show the total cloud cover and frequency of completely clear sky occurrences at various regions around the world, respectively (Stephen & Carole, 2010).

Table 2.1: Average amount of cloud and frequency of completely clear sky occurrence in several regions

Regions	**Europe**	**US**	**South Africa near equator**	**South America near equator**	**Malaysia**
Average Amount of Cloud (%)	53.29	56.44	60.44	62.81	76.86
Frequency of Clear Sky Occurrence (%)	22.95	16.87	11.37	13.10	0.71

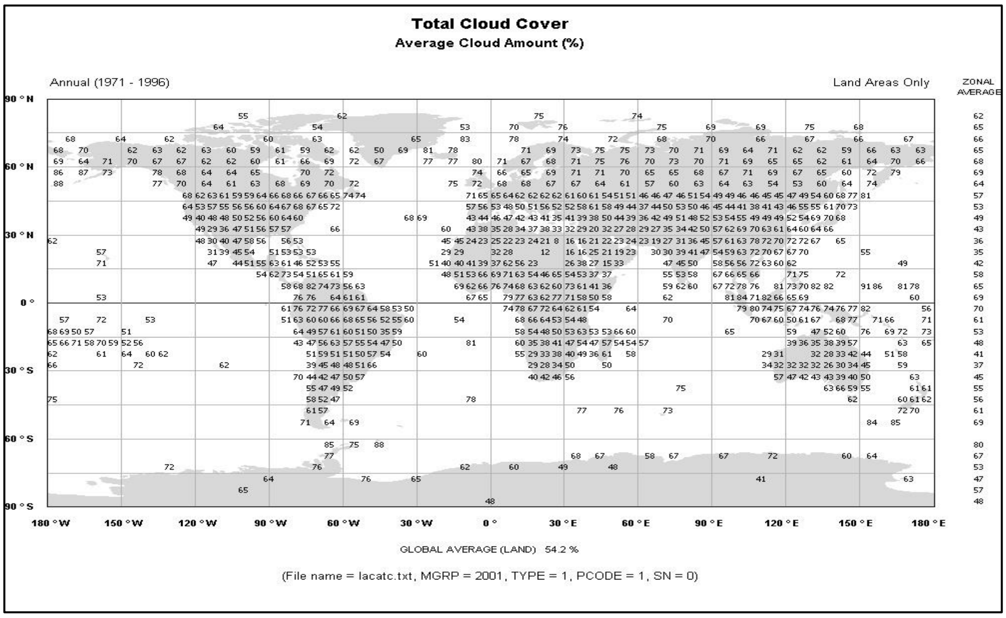


Figure 2.7: World map showing the average cloud amount (%)

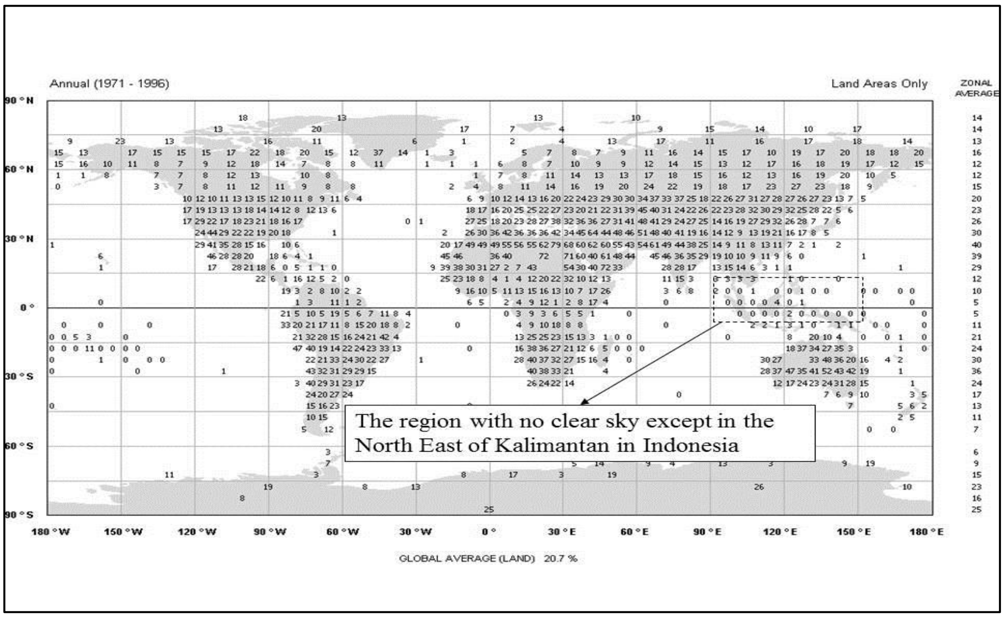


Figure 2.8: World map showing the frequency of complete clear sky occurrence (%)

With a large amount of clouds passing over Malaysia, the incident solar irradiance is highly scattered and fluctuating, hence making the power output of the PV systems to be very intermittent. The highly intermittent power output of PV systems causes the voltage at the point of connection to be fluctuating sharply and frequently; hence generating a large amount of voltage fluctuation and flickers to the low voltage distribution networks (Albarrac ń & Hortensia, n.d.; McDermott, 2010; Guinane et al., 2012; Ammar, 2012). These papers have presented that the flicker caused by the wind and solar can result in the capacitor and tap changer switches continually hunting as they attempt to improve the power quality, which increase the number of switching surges.

Albarrac ń & Hortensia simulation studies have proved that irregular solar irradiation caused by a passing cloud introduces voltage fluctuation and flicker from PV power fluctuation. This paper has presented the model of flickermeter according to the IEC 61000-4-15. In the study, different weather scenarios were simulated depending on the time, day and passing clouds. The PV block has defined the characteristics of solar PV based on maximum power point tracking method. Then the converter block is used to convert the DC power to AC power. After this, the flickermeter block is used to measure the short term and long term flickers. The whole simulation of the flicker assessment model is shown in Figure 2.9: Flicker assessment model

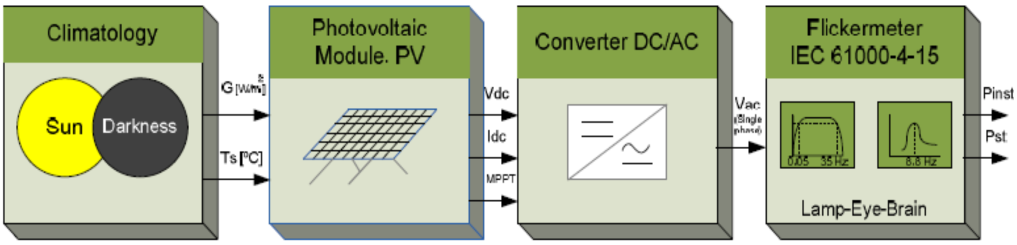


Figure 2.9: Flicker assessment model

McDermott (2010) has identified the voltage control and voltage fluctuations in distributed resource interconnection. This paper has revealed that a large penetration level of wind and solar could lead to light flicker, temporary over-voltages and other power quality impacts. Both wind and PV energy sources produce variable power output, and hence complicate the voltage control on the distribution feeder. Mitigation methods such as changing the regulator setting and dispatching the reactive power are proposed in this paper. However, these mitigation options may be expensive. The conventional tap changer is not suitable to control the voltage fluctuation and flicker caused by the intermittent PV power. This is because changing the tap position too frequently is unacceptable and may also degrade the power quality due to the switching voltage transients.

At present, little attention is placed on the flicker emissions by the PV systems because the majority of the countries have clear sky most of the time. Flickers introduced by wind turbine have been studied (Hu et al., 2009; Nambiar et al., 2010; Ammar, 2012). These papers provide a review of the technical issues related to voltage flickers introduced by the continuous operation of distributed wind generators.

2.4.2 Voltage Rise and Voltage Regulation

In the past research, substantial studies have been carried out to investigate the impact of integrating PV systems on the distribution network voltage. The problem of voltage rise in the grid is caused by the high penetration of grid-connected PV systems are discussed (Masters, 2002; Singh & Goswami, 2010; Wong et al., 2011; Chidi et al., 2012). These papers have concluded that the voltage rise caused by the DG is because of the active power injection. Singh & Goswami (2010) also described the suitable location for DG to minimize the power losses. The paper also stated that the traditional passive networks distributed the power from higher voltage down to lower voltage level and generally not designed for the connection of DG. Therefore, there are many technical issues that must be considered when connecting a DG to the distribution network so that the power quality, network reliability and safety can be maintained.

Pádraig (2009) and Wong (2011) have identified voltage rise to be one of the issues when there is an anticipated amount of DGs connected to the existing LV distribution networks. They have presented an implementation of distributed energy storage control to mitigate the voltage rise and improve voltage regulation. The load controls and demand side management are also effective means for reducing the voltage rise problem caused by the DGs (Lim & Philip, 2007). A technique based on STATCOM or reactive power control of the DG to investigate the voltage rise issues is discussed (Carvalho et al., 2008; Sulligoi & Chiandone, 2012). This technique is capable of controlling the flow of reactive power at the point of connection and reducing the voltage rise. According to (Loo, 2005), there is only 645.8MW of on-grid DG systems in Malaysia, which contributes to less than 6% of the total maximum demand.

2.4.3 Voltage Imbalance

Theoretically, a three phase power system is designed to operate in a balanced condition. However, the LV distribution networks normally operate in an unbalance condition due to the inconsistent loading and single phase DGs connected to the LV distribution networks. Voltage imbalance is defined as the ratio of the negative sequence voltage component to the positive sequence voltage component based on the IEC standard (Von Jouanne & Banerjee, 2001).

Wong et al. (2011) and Chua et al. (2011) have investigated the voltage unbalance in Malaysian LV networks with a high penetration of small scale embedded generations. Wong et al. (2011) have discussed the allowable PV volume on the existing LV distribution networks without violating the voltage unbalance factor of 1%. The majority of the PV systems are single phase; therefore the voltage imbalance on the distribution networks is likely to happen in the future. The simulation results using PSCAD have proven the effectiveness of energy storage systems in reducing the voltage imbalance caused by the DGs. Experimental studies on the voltage imbalance cause by the DGs in UK LV networks had been carried out (Pádraig, 2009). The author believes that the voltage imbalance would be a serious problem when anticipated amount of small scale distributed generators are connected to the LV distribution networks.

2.4.4 Reverse Power Flow

The existing LV distribution networks are designed in such a way to allow unidirectional power flow. With the anticipated amount of DGs integrated into the LV distribution networks, power tends to flow reversely whenever the generation exceeds the demand. (Cipcigan & Taylor, 2007; Qian et al., 2011; Maurizio et al., 2013). These papers investigate the ability of the existing power transformers, cable and protection equipments to cater to the reverse power flow, resulting from the DGs. The active load controller operating within the energy zone is proposed to control the DG power output, and also balance out the generation and consumption in order to minimize the reverse power flow.

2.5 Existing Methods for Voltage Quality Improvement

The power generation from RE sources is proven to be financially attractive ensuring better fuel security with minimum GHG emission in Malaysia (Koh & Lim, 2010). However, conventional radial LV distribution networks operate with single sources feeding the downstream load without any other DG. Consequently, the LV distribution networks with a high penetration of DG may cause numerous technical issues affecting the stability of the power system. Currently, there are a few methods to improve the power quality in the distribution networks integrated with DGs. It can be categorized as follows:-

- Super-capacitor
    - Buffers the voltage fluctuation with very high cycle frequency.
- STATCOM
    - Voltage source converter used of shunt capacitor to change the reactive power capacity to compensate the voltage drop and flickers.
- Static VAr Compensators
    - Generate a constant reactive power to regulate the voltage fluctuation and flickers and establishing the system.
- Distributed Energy Storage
    - Charges or discharges the stored power to the distribution networks based on the network condition.
- Demand side management
    - Load management on the customer side to maintain the demand and supply balanced.

2.5.1 Super-Capacitor

Super - capacitors can be used for power quality improvement in electrical distribution networks (Degobert et al., 2006; Palizban et al., 2011). These papers have proposed the use of capacitor banks in parallel with DG sources in order to reduce the bus voltage variation. During normal operations, the capacitor bank is used to improve the networks and power factor by supplying reactive power to the inductive load. On the occurrence of voltage drop, the capacitor discharges to support the network voltage. A novel control scheme is proposed with a series connected super-capacitor in the PV generation systems (Li et al., 2008). The proposed charging controls the duty cycle of the IGBT in the Boost-Buck converter to shorten the charging time and improve the usage of the intermittent power output from the PV systems.

The power output fluctuations introduced by the PV systems are undesirable. The voltage controllers are needed to react to these fluctuations and buffer the voltage ripple. A double layer capacitor or so-called super-capacitor is proposed (Woyte et al., 2003). The authors have described that the super-capacitor is a complement to the batteries and fuel cells because of its rapid response or high cycle frequency. In addition, the voltage quality improvement could contribute to the increase in the lifetime of battery storage systems. This paper also determines the size of the applied super-capacitor by means of localized spectral analysis in order to mitigate the power fluctuations from PV systems.

A control algorithm based on super-capacitor for a hybrid energy system with PV systems and fuel cell is introduced. (Payman et al., 2008; Thounthong et al., 2011). The super-capacitor can respond faster to compensate the PV power output fluctuation. The super-capacitor functions by supplying energy to regulate the voltage. In the proposed hybrid systems, fuel cells are used to supply energy to the super - capacitor in order to keep it charged. The simulation and experimental verification results prove that adding a super-capacitor to the distributed power system improves power quality such as voltage rise and efficiency.

The main drawback of using super-capacitor is that the capacitor has low cell voltage. Multiple capacitors are required to achieve a higher voltage level. Due to the capacitance difference, there will be a leakage current between different capacitors and may have the risk of overvoltage (Wei et al., 2007).

2.5.2 STATCOM

The Static Synchronous Compensator (STATCOM) is a shunt device which control the real and reactive power flows by injecting the current with a controllable angle (Wong, 2011). The use of STATCOM technology based on voltage source converters to reduce the voltage flicker is discussed in Joorabian et al., (2009). It is proved that 12-pulse STATCOM together with an RLC filter can be used to mitigate the voltage flickers. The STATCOM is a power electronic based voltage source inverter with variable voltage amplitude. In an over-excited mode, the voltage amplitude is higher than the grid voltage; reactive power will be injected to the grid. During an under-excited mode, it absorbs reactive power from the grid. Even though, STATCOM can effectively reduce voltage flicker and fluctuation, it is normally used in the transmission systems rather than LV networks. In addition, using STATCOM is always an expensive option for reactive power control (Aziz et al., 2013).

2.5.3 Static VAr Compensator

Static VAr Compensator (SVC) is typically used to supply the reactive power to compensate the voltage deviations. In addition, SVC can control the supply of unbalanced reactive power to reduce the voltage fluctuation and flickers to keep the voltage within the permissible limits (Prinz et al., 2005). SVC used the capacitor bank to inject or absorb reactive power to stabilize the network voltage. SVC has economical solutions, higher capacity and is faster compared to STATCOM (Padiyar, 1999). However, SVC is applied to the transmission system only.

2.5.4 Distributed Energy Storage

There are numerous types of storage technologies such as Lead-acid/ Nickel-cadmium/Lithium-ion batteries, flywheel, Hydrogen fuel cell and Superconducting Magnetic Energy. However, a Lead-Acid battery is the most appropriate storage option because of its low cost and efficiency (Baxter, 2005; Pádraig, 2009). The distributed energy storage systems are proven to be one of the solutions to mitigate power quality issues on LV networks with PV systems (Chua et al., 2012). This paper proposes to use energy storage in an intelligent active management system for mitigating voltage unbalance and improving the efficiency. The PSCAD simulation results show that the voltage unbalance and network losses on LV networks integrated with PV systems could be effectively reduced.

Mohod et al. (2011) has proposed to use energy storage to control the flow of real and reactive power in the grid and to maintain the power quality. This paper has also presented the MATLAB simulation results. The inverters control the injection or the absorption of reactive power and hence enable the real power to flow to the load. Wang et al. (2012) has presented the simulation and laboratory results to demonstrate that energy storage can be used to mitigate voltage rise problems. These two papers have revealed that the inverter integrated with energy storage system is capable of providing rapid response to support the grid power quality.

2.5.5 Demand Side Management

The demand side management (DSM) or demand response refers to changing the electricity consumption patterns of the end user to improve energy efficiency and power quality (Han & Piette, 2008; Strbac, 2008; Sinha et al., 2011). The voltage rise issues in the distribution networks integrated with a large amount of DGs are discussed (Lim & Philip, 2007). This paper has proposed a load control method to mitigate the voltage rise issue. The results show that the proposed method can reduce the voltage rise effectively. Tande (2000) showed that the load management is an effective method to balance the supply from wind power generation and demand.

2.6 Integration of DSM and DG in the future distribution networks

The trend in the electrical sector is transforming from passive to active networks. In the future, both renewable and non-renewable DGs at the LV networks would enable consumers to contribute electricity to the system. The electrical sector would no longer be centralized but distributed. DSM will play a major role in the future smart grid to ensure the security, reliability and efficiency of the power systems (Javed et al., 2012). Currently, major DSM techniques that have been put into practice (W.Gellings, 2009; Zhong et al., 2010; Sinha et al., 2011) are briefly reviewed as follows:-

- Direct load control
  - Apply to the appliances that can be turned off or switch on such as water heater, thermal storage, water pumps and so on.
- Time of use pricing
  - Electricity tariff is higher during peak periods and lower during off peak periods.
- Night time cooling/ heating with load switching
  - Reduce the operation of peak load power plant during daytime. More balanced use of electricity generated from base load power plants throughout the day.
- Load limiters
  - Limit the power that can be taken by individual consumers.

2.6.1 Benefits of DSM

DSM is an effective way to improve the power quality issues caused by the DG. In addition, DSM helps to reduce the generation margin and reduce the reserve margin (Hamidi, 2007; Nair et al., 2008). Currently, without DSM, the total installed generation capacity is much larger than the maximum demand to ensure the security of supply. DSM is able to improve the transmission and distribution networks operation efficiency (Strbac, 2008). This approach could be used for deferring the new network investment, relieving congestion in a power substation, increasing the amount of DG and achieving carbon reduction.

2.6.2 Challenges of DSM

Lack of understanding of the benefits of DSM will be the major challenge of DSM implementation. One of the main problems associated with the DSM is the difficulty of finding sufficient load to control. This involves the cooperation between the licensee and consumer (Lim & Philip, 2007). The author has recommended a site survey needed to be carried out in order to identify the social and psychological aspects of the implementation of DSM. The lack of incentives to encourage and promote DSM technology is also a key barrier for integrating DSM in the future LV distribution networks. Gajjar& Tajularas (1998) have studied the feasibility of residential level DSM in Malaysia. This paper indicates the need for customer education and incentives for the acceptance of DSM.

2.7 Conclusion

The PV systems will be the major RE sources on the LV distribution networks in the near future resulting from the various renewable energy programs and fiscal incentives. However, technical issues caused by the PV systems need to ensure the security of the power system. Most of the existing methods to mitigate the voltage quality issues are provided by the simulation studies. Simulations are run under ideal conditions. However, the real world is not perfect and ideal. Experimental results from the actual system are more accurate and practical. The existing method on mitigating voltage fluctuation and flicker might not be economically attractive for the RE developer as the super-capacitor, STATCOM and SVC are too expensive. STATCOM and SVC are commonly used in transmission system rather than LV distribution networks. DLC is economically viable and suitable for LV distribution network application. Nevertheless, DSM and DLC seem to give a positive result for the mitigation of power quality issues in LV distribution networks, including voltage fluctuation and flicker, voltage rise, reduced peak demand and reduction in power losses. Besides that, DLC would be one of the important functions in the future smart grids, which is more active rather than a passive operation.

CHAPTER 3

SIMULATION STUDY ON LV DISTRIBUTION NETWORKS INTEGRATED WITH PV SYSTEMS

3.1 Introduction

This chapter presents the simulation study results on the impact of DG on the existing LV distribution networks.

The growth of the PV systems connected to the existing LV distribution networks has the potential to cause several technical issues that will reduce the power quality and operational efficiency. Simulations are required to investigate the potential technical issues that may arise when a large number of PV systems is connected to the LV distribution networks. The assessment is based on the commercial and residential LV distribution network in Aman Jaya, an urban area of Selangor, Malaysia. The network configurations, system design and parameter data are obtained from the local utility company, Tenaga Nasional Berhad.

DIgSILENTPowerFactory, a power system analysis tool is used to model commercial and residential LV distribution networks. This tool is used because it can analyse the unbalanced condition of the 3-phase networks. PSCAD can only model small networks due to the limited capacity of the subscription. Besides, DIgSILENT can model big network and run 3-phase load flow. This simulation tool caters for all standard power system analysis including distributed generation. The modelling of LV networks, methodology and simulation results are discussed in this chapter.

3.2 Modelling of Commercial LV Distribution Networks

The network is integrated with a PV system connected to the grid, with an increment of 1.0 kW/step up to 10.0 kW. The commercial network is radial in nature, and connected to a 1 MVA, 11/0.415 kW 3-phase transformer equipped with off load tap changer on the high voltage side. With Delta-Grounded Wye connection, the transformer adeptly handles single-phase loads in any of the three phases. TT type earthing arrangement is used where the potential earth (PE) of the customer is separated from the electricity supplier at the transformer side. The length of LV feeder that connects the substation to the customer varies from 35m to 80m. All the customers are connected at the remote end of the LV feeder. Figure 3.1 and Figure 3.2 show the single line diagram and DIgSILENT model of the commercial network respectively.

The commercial LV networks consist of 3 double circuit feeders using 300sqmm 4C XLPE AL cables laid from the local substation transformer to the distribution feeder pillar. The commercial customer's service entrances are connected to the distribution feeder pillar using 70sqmm 4C XLPE AL underground cable. The parameters of underground cable and transformer are given in Table 3.1. The majority of the commercial customers are served by 3-phase supply. The maximum demand of each customer is approximately 13.0 kW and it occurs between 12pm and 5pm. The maximum total demand recorded is approximately 530.0 kW.

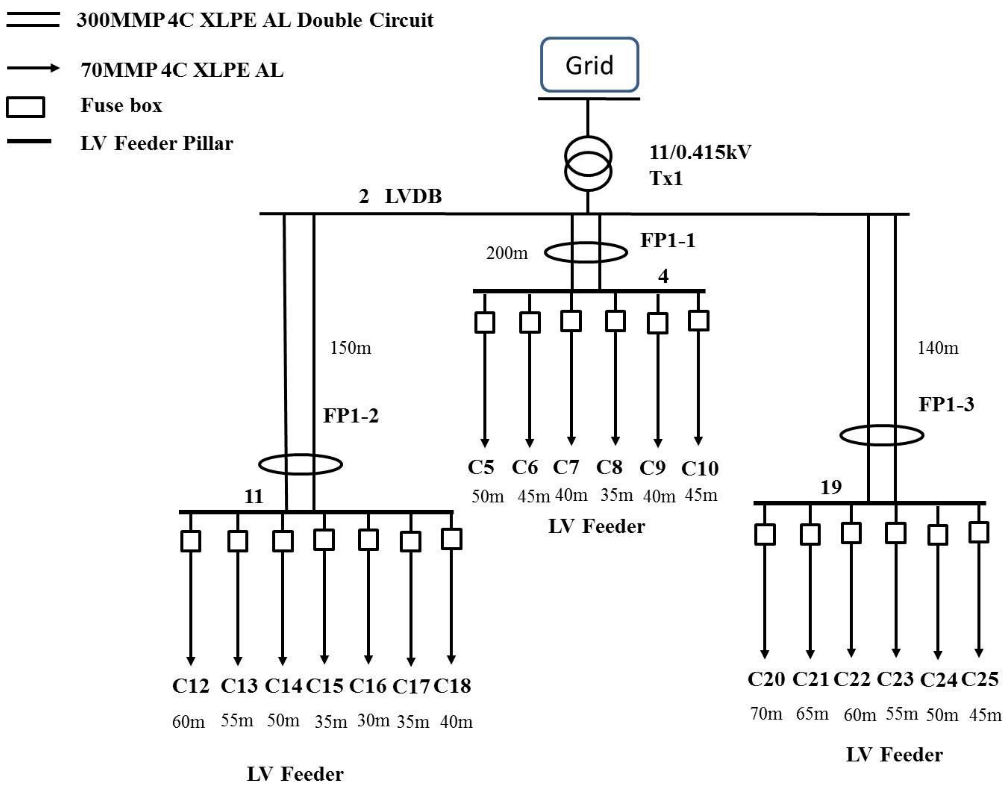


Figure 3.1: The layout of Aman Jaya commercial LV distribution networks

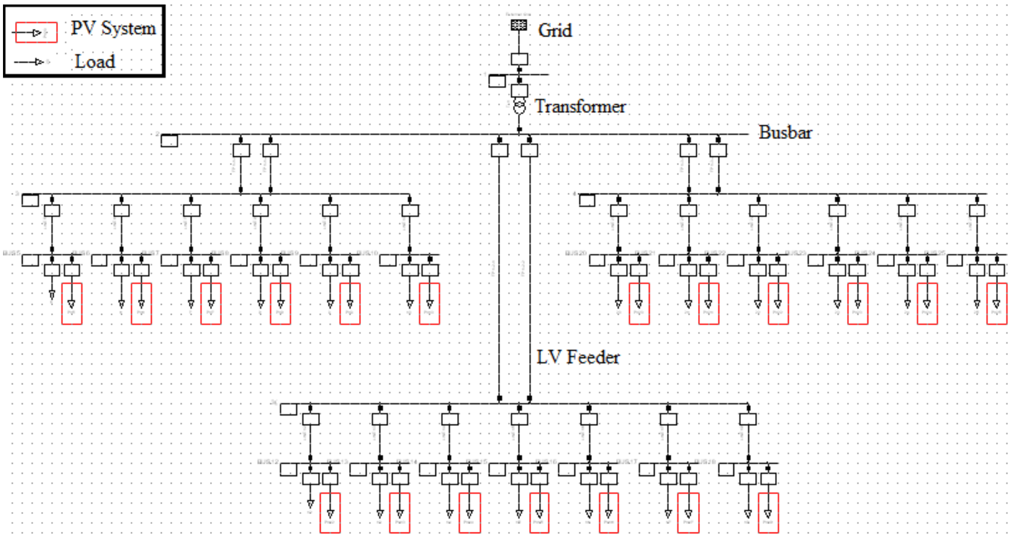


Figure 3.2: DIgSILENT model of Aman Jaya commercial LV distribution network

Table 3.1: The parameters of LV equipment

Equipment	Resistance (at 50Hz at 20 °C)	Reactance
300 sqmm 4C XLPE AL	0.13 ohms/km	0.072 ohms/km
70 sqmm 4C XLPE AL	0.568 ohms/km	0.075 ohms/km
1MVA Transformer	0.00385 ohms	0.00807 ohms

3.3 Modelling of Residential LV Distribution Networks

The residential network is integrated with a PV system connected to the grid with an increment of 1.0 kW per step up to 10.0 kW. The residential network is radial where a single source feeds the downstream loads that are connected to the remote end of each feeder. The length of LV feeders that connect the substation to the customer varies from 40m to 110m. Figure 3.3

and Figure 3.4 show the single line diagram and DIgSILENT model of the residential network, respectively.

The residential LV networks consist of 2 double-circuit feeder using 300sqmm 4C XLPE AL cables laid from the local substation transformer to the distribution feeder pillar. The residential customer's service entrances are connected to the distribution feeder pillar using 70sqmm 4C XLPE AL underground cable. The parameters of underground cable and transformer are given in Table 3.1. The majority of the residential customers is served by a single-phase supply and the maximum demand of each customer is approximately 5.0 kW. The maximum demand occurs between 6pm and 8am. The minimum total demand recorded is approximately 18.9 kW.

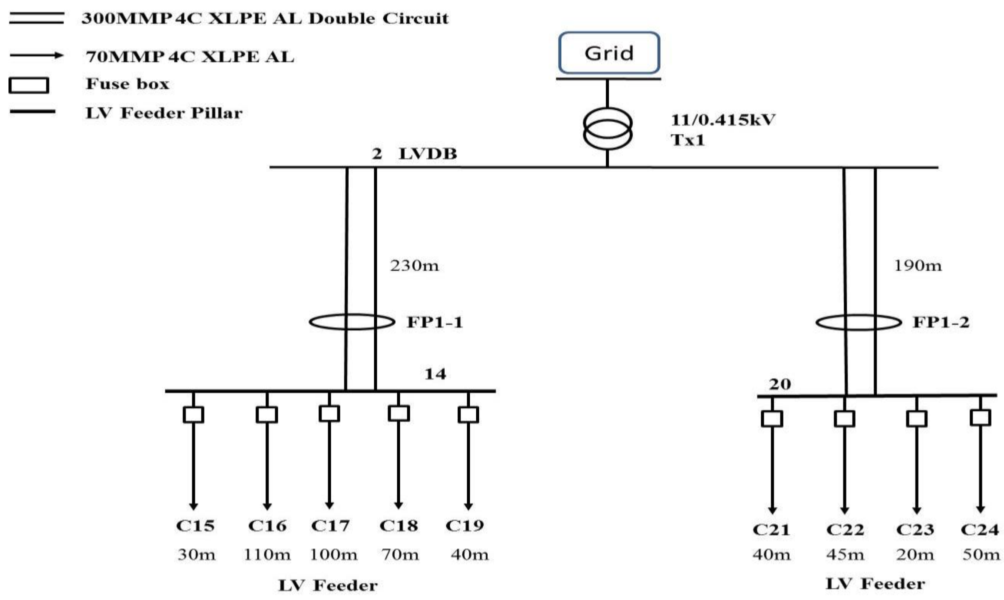


Figure 3.3: The layout of Aman Jaya residential LV distribution networks

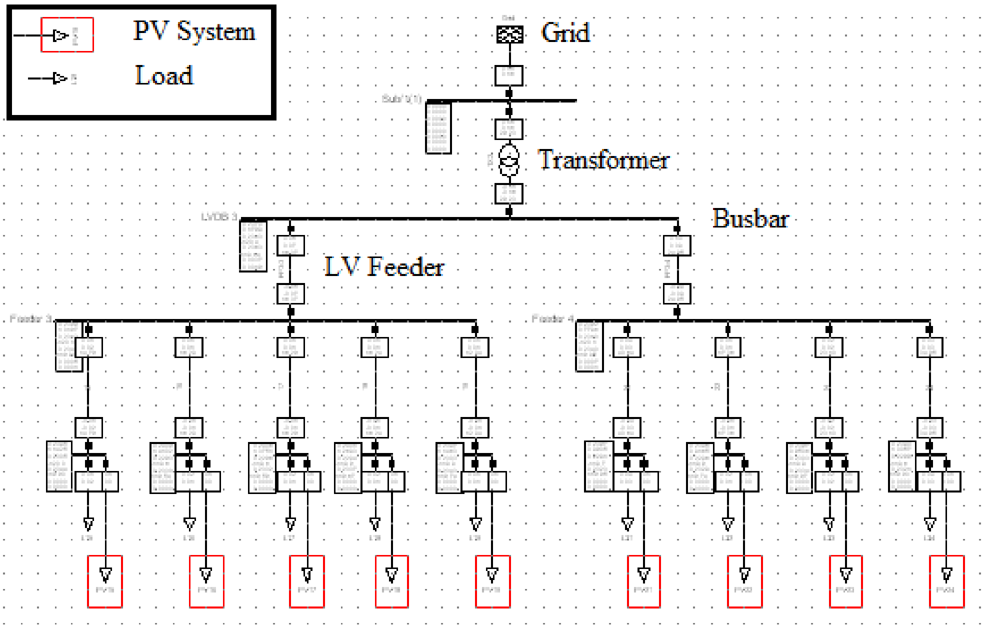


Figure 3.4: DIgSILENT model of Aman Jaya residential LV distribution networks

3.4 Description of Methodology

The commercial and residential LV distribution networks are modelled with DIgSILENT PowerFactory to study the impacts of aggregated PV systems connected to the existing network. The simulation studies focus on voltage rise, voltage unbalance and power losses in the LV distribution networks with two extreme scenarios:-

1) Centrally planned PV system;
2) Non-centrally planned PV system.

Centrally planned PV systems may be implemented by the utility companies or government regulatory bodies so that PV systems can be evenly distributed across the distribution networks. The worst case scenario of non-centrally planned PV systems is used in this simulation where all the PV systems are connected at the same phase, which is phase B. Besides that, the simulation work is extended to investigate the impacts of different feeder cable lengths and power factor at the point of connection where PV systems are connected. Negative loads are used to represent the PV power generation that injects power into the LV distribution network.

At present, most customers have installed single phase PV systems. The two extreme scenarios i) centrally planned PV systems and ii) non-centrally planned PV system of PV distribution may not happen in the real world situation. However, it is necessary to study these two scenarios in order to foresee the possible problems caused by the PV systems. This simulation study simulates the operation of the LV networks during peak power output of the PV systems, from 12pm to 2pm. During this period, commercial networks consume the highest power whilst residential customers consume the lowest power. Therefore, a maximum demand is used in the simulation of commercial networks and a minimum demand for the residential networks.

3.5 Simulation Results for Commercial LV Distribution Networks

For each network, the simulation study is based on two scenarios of PV distribution; i) centrally planned where PV systems are evenly distributed across the three phase networks and ii) Non centrally planned where PV systems are installed only on Phase B of the networks. The voltage rise, voltage unbalance factor (VUF) and network power losses are studied. The power factor (PF) and cable length which affect the VUF and losses are also considered.

According to the Malaysian standards of LV distribution networks, the allowable voltage tolerance is +10% and -6% of the rated nominal voltage of 230V (Tenaga Nasional Berhad, 2011). Figure 3.5 illustrates the inconsistent voltage variations observed across the three phases. It can be seen from the figure that the large quantity of PV generation on Phase B of the LV network results in violations of the voltage statutory limits. The voltage magnitude at Phase A slightly increases while the voltage drops at Phase C. This is because of the neutral voltage displacement and the changes in the voltages at the terminals of the secondary distribution transformer during unbalanced conditions (Pádraig, 2009). Additionally, the behavior of the generator is complicated by mutual impedances between the windings (Jones, 1967). Voltages are induced in the Phase A and Phase C windings of the synchronous machine due to the current flow in Phase B. At the PV capacity of 3.0 kW, the voltage magnitude at Phase B rises up to 252V which is the upper voltage limits of the tolerance. As a result, the PV developer is not recommended to install PV systems more than 3.0 kW per customer under non-centrally planned PV distribution. However, the Malaysian standard has implied that the maximum allowable DG injected onto the LV distribution networks is 10.0 kW. Therefore, the simulation of the PV capacity is increased up to 10.0 kW (SEDA, 2011).

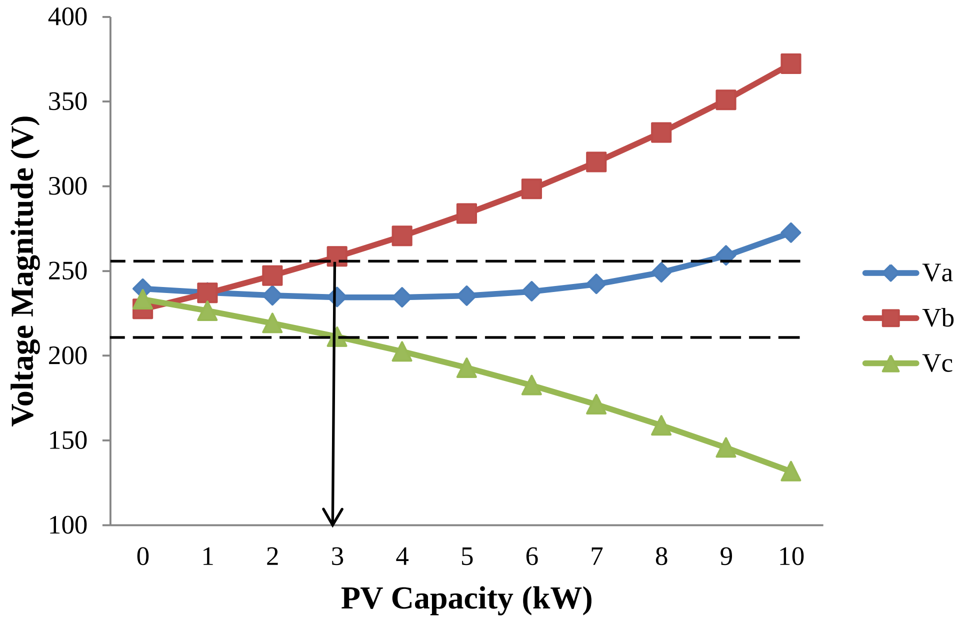


Figure 3.5: Voltage magnitude at feeder C6 with the increase in PV capacity in the commercial networks under non-centrally planned scenario

Figure 3.6 shows the comparison of voltage variation under centrally and non-centrally planned PV systems. The result shows that if the PV systems are randomly distributed, then the allowable PV capacity connected to the LV networks without exceeding the voltage rise limit is about 3.0 kW. In this case, all PV systems are assumed to be connected to the same phase, which is Phase B. If the PV systems are distributed evenly, the allowable PV volumes to be accommodated on the networks are more than 10.0 kW without violating the voltage rise's statutory limit.

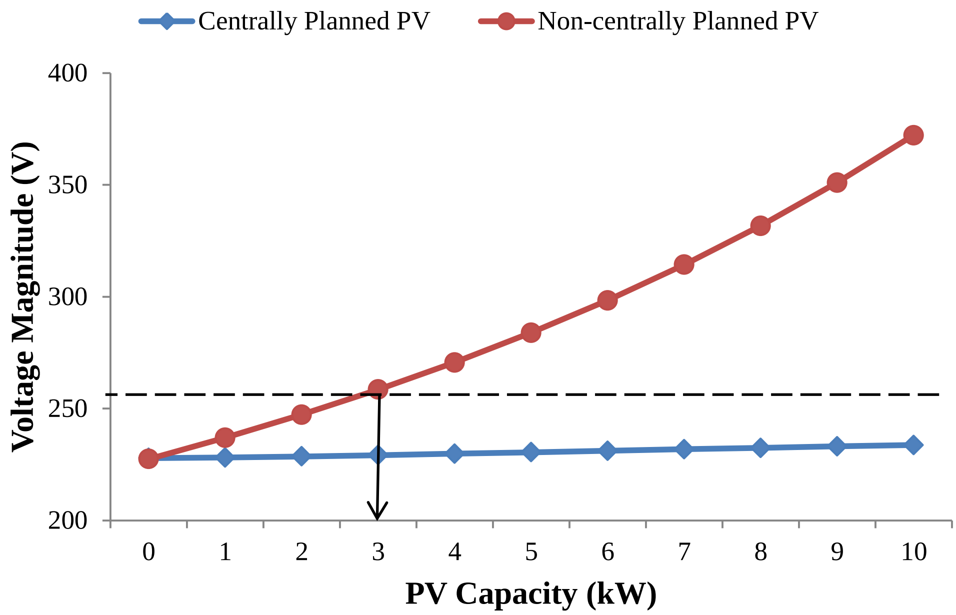


Figure 3.6: Voltage magnitude with the increase in PV capacity in commercial networks under centrally and non-centrally planned scenario

At present, single phase PV systems are likely to be connected onto the LV distribution networks. Furthermore, the installation is consumer driven and not centrally planned. Therefore, it is likely to cause voltage unbalance at the remote end of the LV distribution networks. Voltage unbalance is a condition in which the three phase voltages differ in amplitude and displaced from their normal 120 ° phase relationship. Figure 3.7 shows the behavior of voltage unbalance factor as the PV capacity increases on the commercial LV distribution networks under non-centrally planned condition. The voltage unbalance increases dramatically as the PV capacity increases. At about 5.0 kW of PV capacity, the voltage unbalance factors of the feeders are about 1.0 which is the upper limit of the allowable limits in Malaysia. This means that the allowable volume of PV to be accommodated by the commercial networks without violating the statutory limit is less than 5.0 kW per customer.

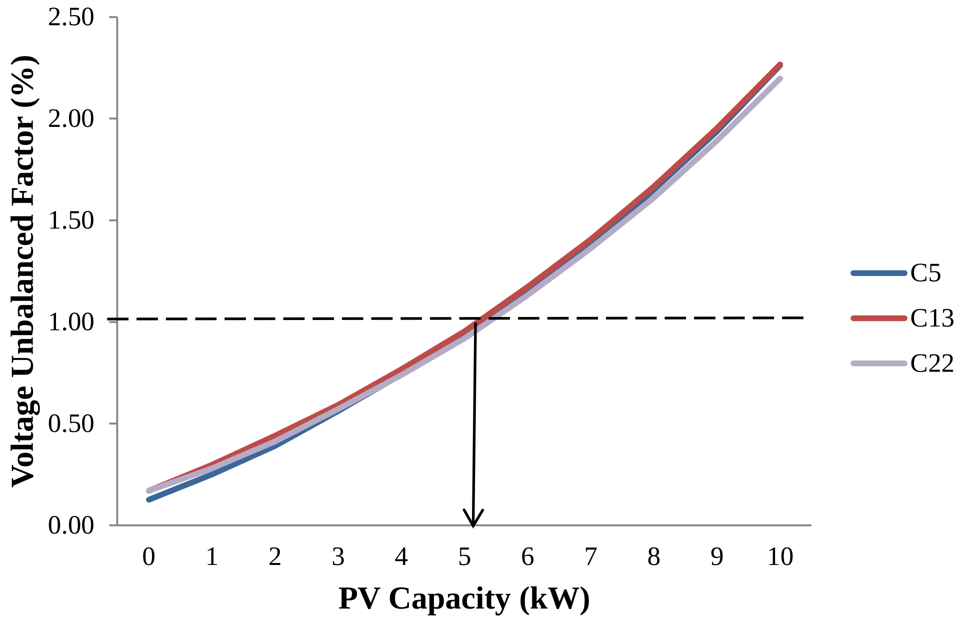


Figure 3.7: VUF at commercial networks in non-centrally planned scenario

Figure 3.8 shows the comparison of voltage unbalance factor under centrally and non-centrally planned PV distributions. It is shown that non-centrally planned PV creates greater voltage imbalance as compared to that of the centrally planned PV systems. Centrally planned distribution of PV systems allows for a higher capacity without violating the statutory limit of voltage unbalance factor. The capacity of 5.5 kW of PV penetration can cause the voltage unbalanced factor to be 1.0%, which is the limit.

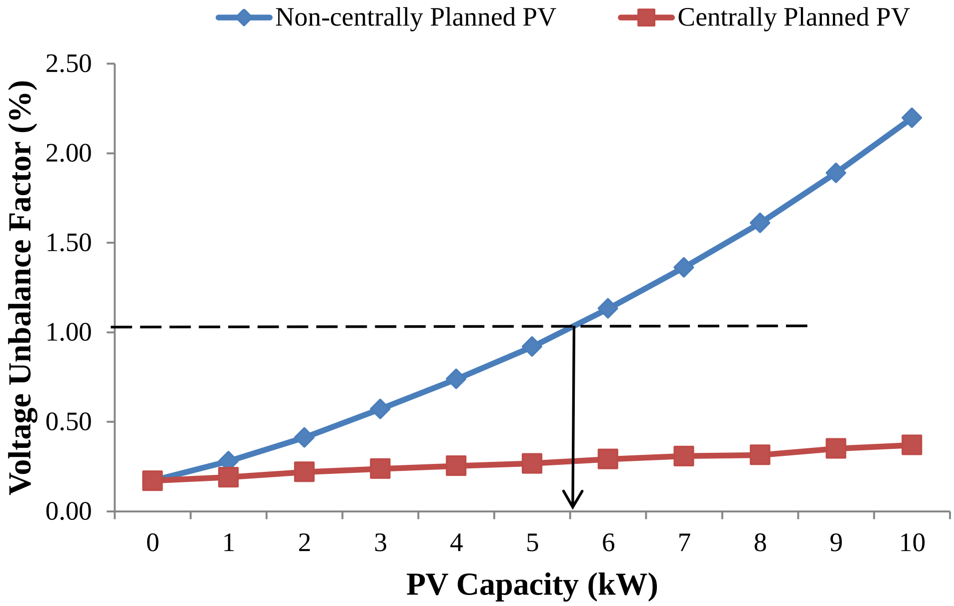


Figure 3.8: Comparison of the VUF between centrally and non-centrally planned PV distributions in commercial networks

Figure 3.9 shows the total network losses under centrally and non-centrally planned distribution of PVs for commercial networks. The figure shows a change in the total power loss as the PV capacity increases from 0 to 12.0 kW on commercial networks. The network power losses are contributed by the impedance of the conductors. In the case of non-centrally planned PV systems, the power losses decrease as the PV capacity increases from 0 kW to 4.0 kW. However, the power losses begin to rise as the PV capacity is more than 4.0 kW. As for the centrally planned PV distribution, the total power losses decreased when the PV capacity increases from 0 kW to 8.0 kW. Further increase in the PV volume increases the power losses in the commercial networks.

The simulation results show that both the PV distribution scenarios have the same trend. If the generated power of PV is less than the demand, the network power losses have a decreasing trend, whereby the customers are supplied by the PV power instead of being supplied by the utility. Therefore the network power loss is minimized. But, when the PV generation is more than the demand, the network power losses increase dramatically due to the reverse power losses. Furthermore, it can be seen that the commercial network is capable to cater more PVs with the minimum power losses under centrally planned PV systems. The centrally planned PV system in the distribution networks is able to cater for 8.0 kW of PV with minimum losses while non-centrally planned PV system is able to cater only for 4.0 kW PV with minimum losses.

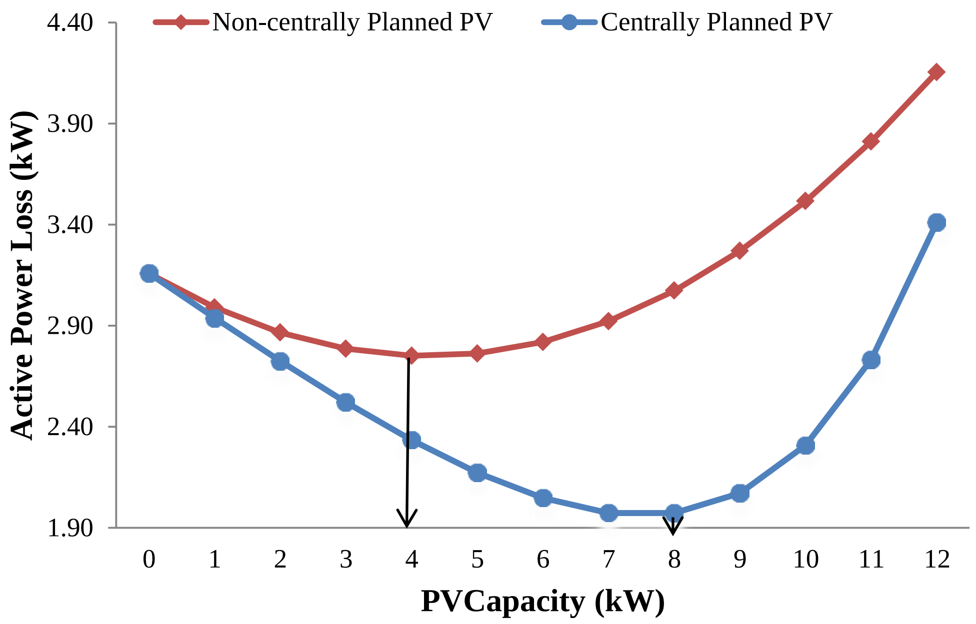


Figure 3.9: Total network power losses in the commercial networks

Figure 3.10 shows the variation of voltage unbalance factor with respect to the cable length in the commercial LV distribution networks. It is seen from the figure that the voltage unbalance increases as the cable length increases in the distribution networks under both the PV distribution scenarios. This is because of the interrelation between the cable impedance and network power losses. The network power losses increase as the cable length increases, likewise the voltage drops. The voltage drop in the phase where the PV system is connected is more significant due to an excess current flow from the PV and contributes to the voltage imbalance. It is noticed that the non-centrally planned distribution of PVs across the commercial network has a higher voltage unbalance factor compared with that of the centrally planned PV distribution.

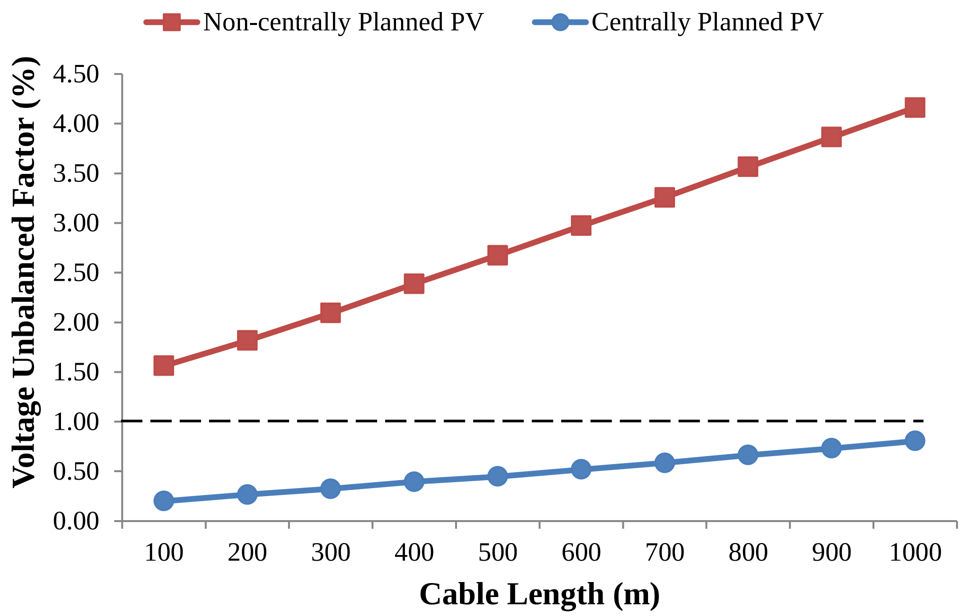


Figure 3.10: VUF with the increase in feeder cable length in the commercial networks

A unity power factor is always desired by the utility company to minimize the power loss as well as energy wastage. Figure 3.11 shows the variation of the voltage unbalance factor with respect to the power factor in the commercial network under the non-centrally planned distribution of PV systems. It is noticed that the voltage imbalance is minimum when the power factor is unity or slightly capacitive. This is because the networks with unity power factor have no reactive power that affect the network voltage magnitude and hence voltage unbalance. In addition, a low power factor increases the current and I^2R losses which is turn, induces the voltage drop.

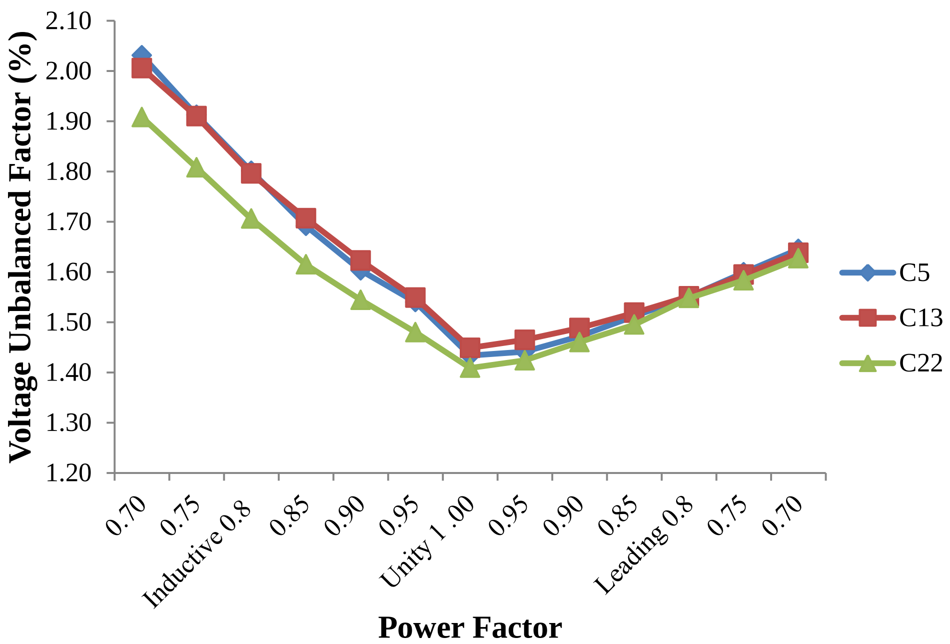


Figure 3.11: VUF with different power factor at point of connection in the commercial network under non-centrally planned distribution of PV

3.6 Simulation Results for Residential LV Distribution Networks

The introduction of FiT creates an opportunity and economically viability for residential customers to install PV systems on their rooftop. The technical impacts caused by the PVs on residential networks are determined. The characteristic differences between commercial and residential LV distribution networks have been discussed in the previous Chapter 2.

Figure 3.12 shows an increase in the voltage magnitude at a residential network when the capacity of PV is increased. It was observed that the voltage rise occurs in phase B, where the PV system is connected. A high penetration of PV generation during low power demand causes the voltage rise issues at residential area of LV distribution networks.

Figure 3.13 shows that the non-centrally planned PV systems have a higher voltage rise as compared to the centrally planned PV systems distribution. It can be seen from the figure that the allowable PV capacity connected to LV networks under the non-centrally planned PV distribution is only 1.0 kW. Whilst for centrally planned PV systems, the allowable PV capacity without violating the limits increased to 7.0 kW.

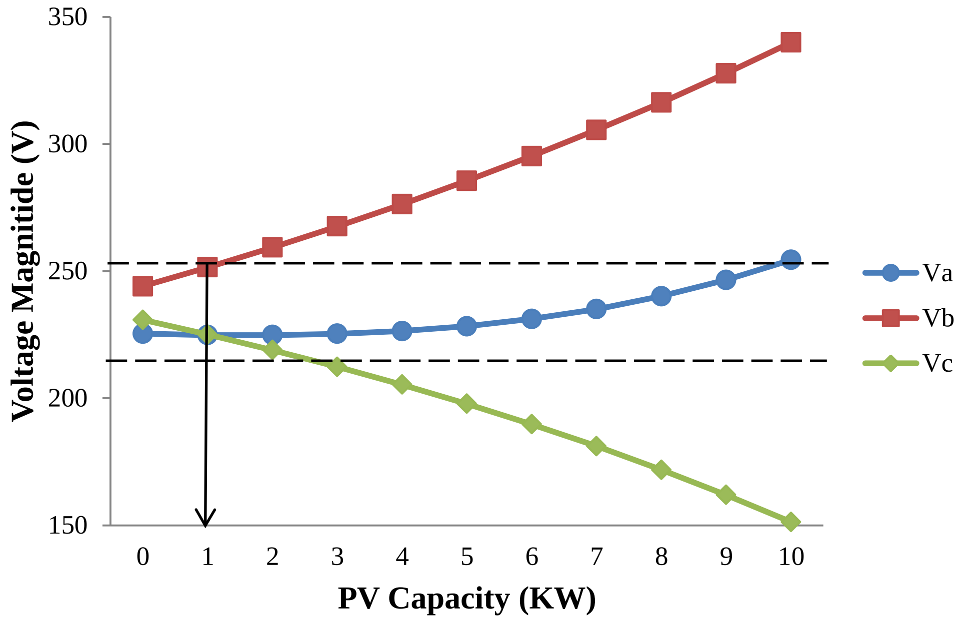


Figure 3.12: Voltage magnitude at feeder C16 with the increase in PV capacity in the residential networks under non-centrally planned scenario

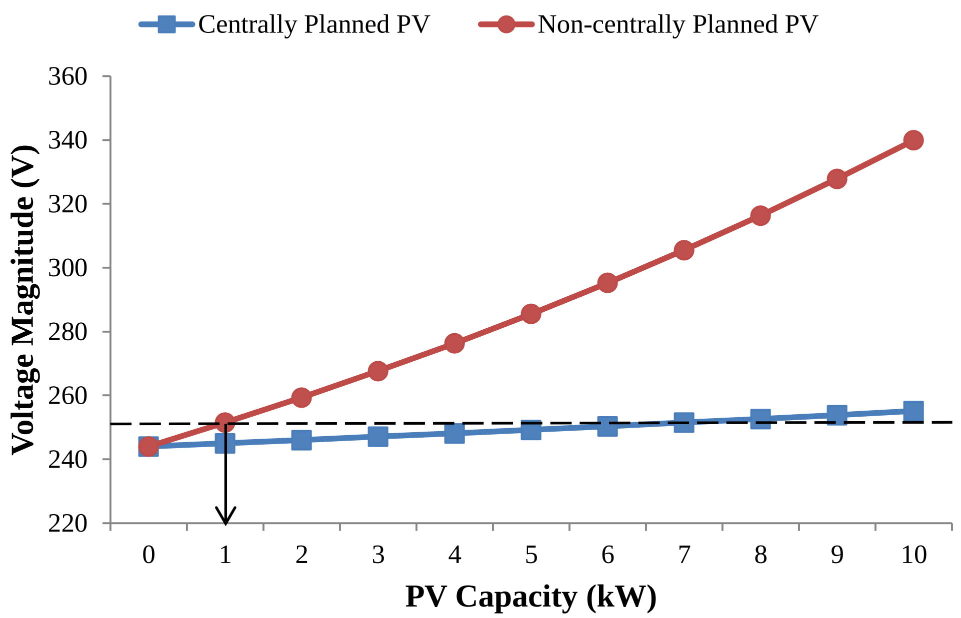


Figure 3.13: Voltage magnitude with the increase in PV capacity in residential networks

Figure 3.14 shows the voltage unbalance factor of the residential LV distribution networks under non-centrally planned PV distribution. The allowable PV capacity that can be distributed randomly before violating the statutory limit of 1% is about 6.0 kW. As the PV capacity increases, the %VUF tends to increase. This is because the injection of real power into the network causes the voltage magnitude to increase, hence increasing the voltage variation between the three phases.

Figure 3.15 shows the VUF between centrally and non-centrally planned of the residential network, it is observed that the allowable PV capacity under centrally planned distribution is higher than that of the non-centrally planned distribution. The coordination of PV installation is important to minimize the voltage variation range, so to reduce the voltage imbalance on the distribution networks. High VUF contributes to the network power losses as additional current flows in the neutral line.

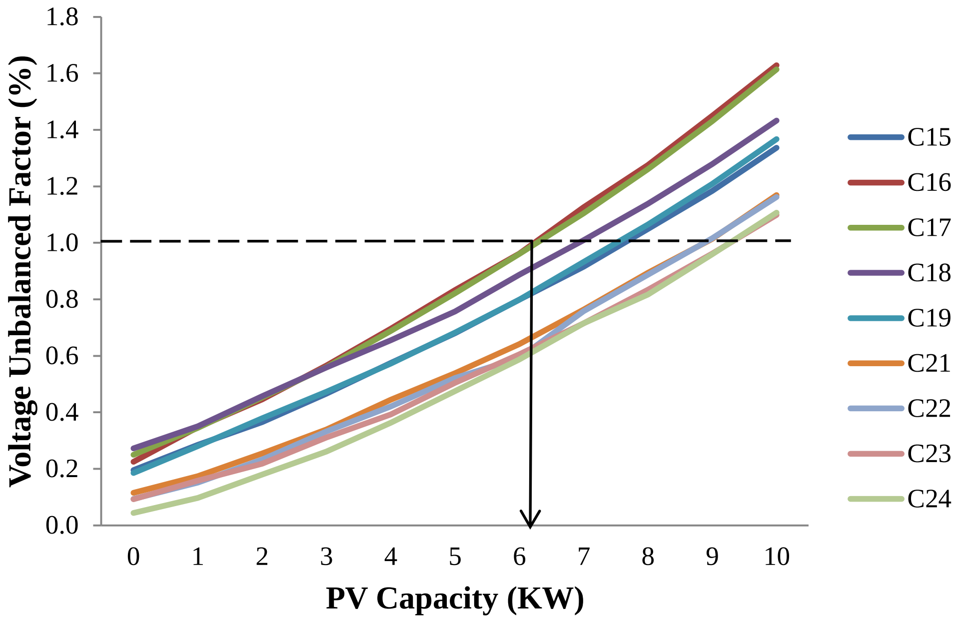


Figure 3.14: VUF at residential networks under non-centrally planned scenario

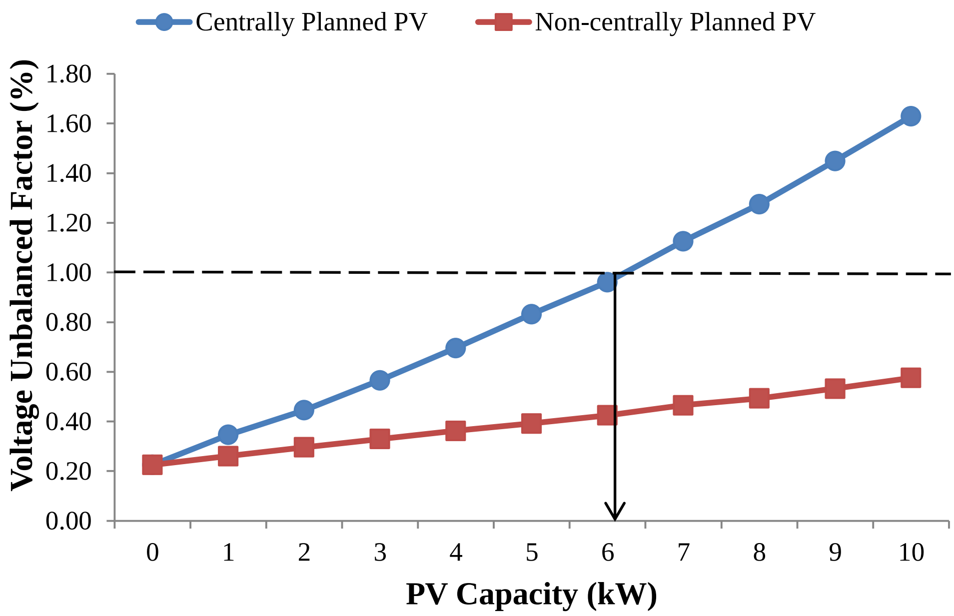


Figure 3.15: Comparison of the VUF for centrally and non-centrally planned PV distributions in residential networks

Power losses reduce the power system efficiency. Figure 3.16 shows the total network power losses in the residential LV networks under centrally and non-centrally planned PV system distributions. A minimum total network power loss happens at 5.0 kW for non-centrally planned PV and 7.0 kW for centrally planned PV systems. This result shows that the centrally planned PV distribution is able to minimize the network power losses.

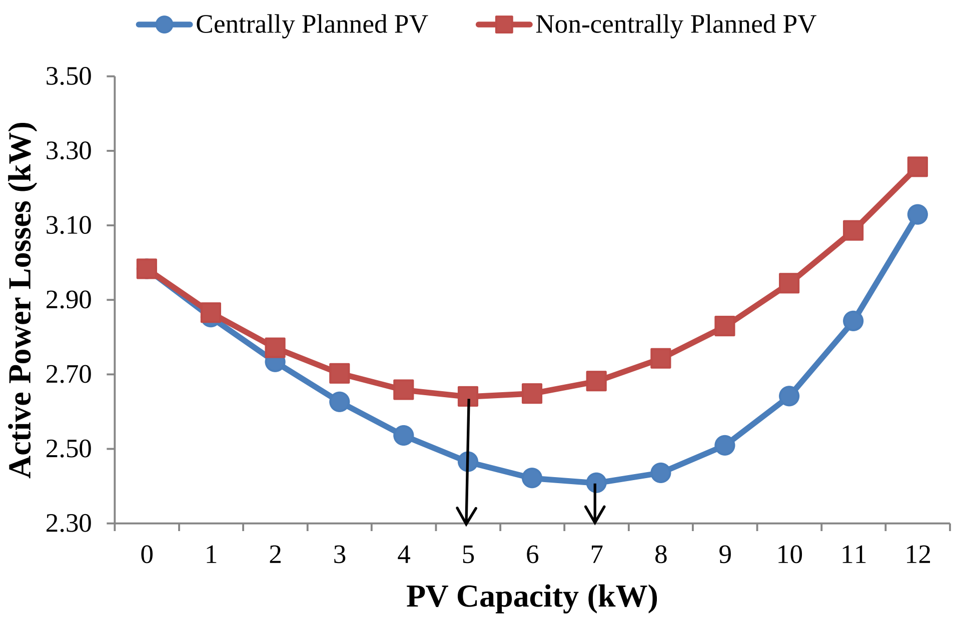


Figure 3.16: Total network power losses in the residential networks

Figure 3.18 shows the %VUF with various feeder cable lengths under centrally and non-centrally planned PV distributions. The figure shows that voltage unbalance increases as the cable length increases. Besides that, the results show that the losses can be reduced if the PV distribution is properly planned and evenly distributed across the three phase networks. A variation of %VUF with respect to the power factor at the point of connection in residential networks is shown in Figure 3.18. The result proves that the minimum VUF occurs when the PV systems are connected to the bus with unity power factor.

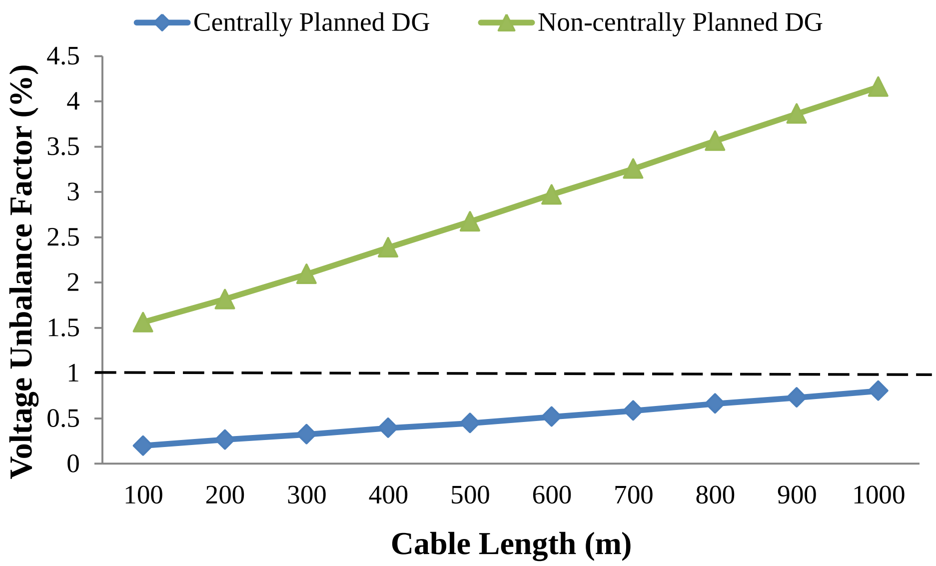


Figure 3.17: VUF with respect to different cable lengths in the residential networks

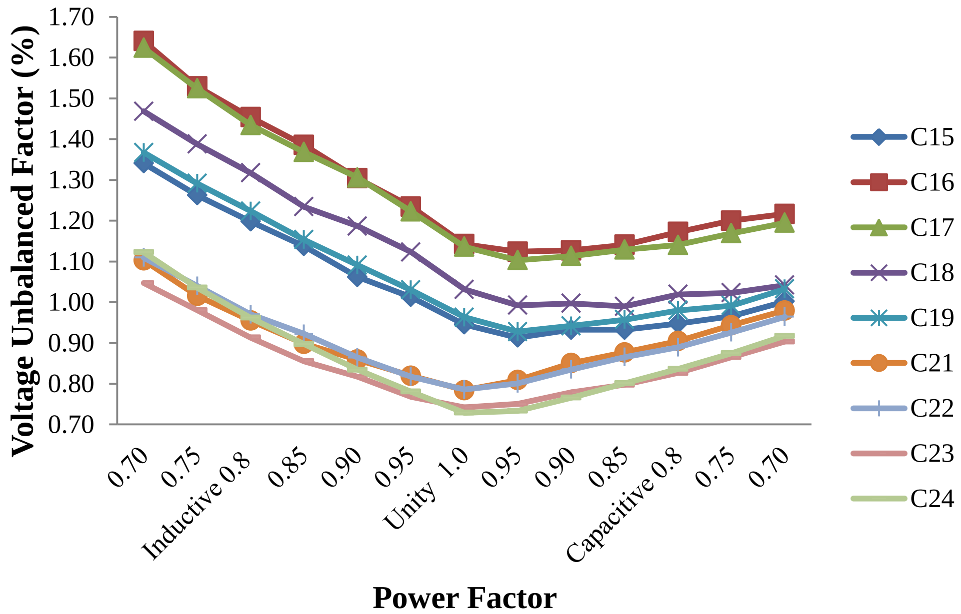


Figure 3.18: VUF with respect to various power factors at point of connection in the residential network

3.7 Conclusion

The deployment of large number of PV systems on LV distribution networks has the possibility to impose several technical issues including voltage rise, voltage unbalance, and power losses as identified in both commercial and residential LV distribution networks. These technical issues must be overcome in order to satisfy the power quality requirement. A simulation study is carried out by using DIgSILENT PowerFactory. The impacts of the PV system on the LV distribution networks are studied under two scenarios: i) centrally planned PV which means the PV system installation is planned properly or evenly distributed across the three phases and ii) non-centrally planned PV based on " plug and inform" policy.

Table 3.2 show the summary of the simulation results. The allowable PV capacity that can be installed in commercial networks under centrally and non-centrally planned PV without violating any of the technical issues were found to be 8.0 kW and 3.0 kW, respectively. In the residential networks, the allowable PV capacity without violating any technical issues is 1.0 kW for non –centrally planned PV systems and 7.0 kW for centrally planned PV systems distribution.

Throughout the simulation result, we can conclude that non-centrally planned PV distribution can cause serious technical problems as compared to that of centrally planned PV system installation. It can also be noticed that the voltage supply quality can be degraded by the growth of PV systems without proper coordination before installation. To allow for more grid connected PV systems, pre-installation study should be performed and planned.

Table 3.2: Summary of the simulation results

	Commercial Networks		Residential Networks	
	Centrally Planned PV	Non-Centrally Planned PV	Centrally Planned PV	Non-Centrally Planned PV
PV Capacity before voltage rise limit	>10 kW	3.0 kW	>10 kW	1.0 kW
PV capacity before VUF violation	>10 kW	5.5 kW	>10 kW	6.0 kW
PV capacity before power loss increase	8.0 kW	4.0 kW	7.0 kW	5.0 kW

CHAPTER 4

DESIGN AND DEVELOPMENT OF LV DISTRIBUTION NETWORKS EMULATOR WITH DIRECT LOAD CONTROLLER

4.1 Introduction

As discussed in Chapter 2, Malaysia might be one of the cloudiest countries in the world. The voltage fluctuation and flickers caused by the intermittent power output of the PV systems have been identified as the major challenges to the PV systems' installation. In addition, the degradation of voltage supply quality has been identified in the simulation study, as discussed in Chapter 3. The newly launched FiT, by the government, has encouraged the installation of grid connected DGs, especially PV systems. In the near future, small scale PV systems are likely to be found scattered across the LV distribution networks. With this scenario, the voltage quality issue is likely to increase as the PV generation is greater than the load consumption. From the study it is understood that, it is always the best solution to maintain the voltage level at the point of common connection for PV systems in order to avoid unsatisfactory voltage level at the LV distribution network.

Furthermore, in order to allow a higher capacity of the PV systems to be connected to the existing LV distribution grid with minimum power quality issues, a direct load controller (DLC) method is proposed. The DLC is installed at the appropriate point of the LV distribution network in order to manage the supply and demand balance depending on the networks and weather conditions.

In this chapter, an experimental LV network emulator integrated with DLC is discussed. The experimental network is used to study the interaction between the DLC and PV systems. This chapter also provides a preview of the distributed generation, load bank design and data acquisition system. This is followed by the description of the DLC control algorithm developed by using LABVIEW. Eventually, a method to quantify the voltage fluctuation and flicker is discussed.

4.2 Design of Experimental LV Network Emulator

The experimental LV distribution network is designed to investigate the impacts of high penetration of PV systems. The proposed DLC method is integrated into the experimental LV distribution network in order to evaluate the performance and effectiveness to mitigate the voltage quality issues. The experimental setup includes a 15 kVA network emulator, 1.8 kWp PV system, 3.0 kW load bank, 480 Ah energy storage system and a data acquisition system. The energy storage is used to study the stand-alone power systems supported by the energy storage instead of the grid or generator.

4.2.1 Network Emulator

The network emulator consists of a 15 kVA synchronous machine coupled with an induction motor driven by a variable frequency drive as shown in Figure 4.1. This is designed in such a way to isolate the experimental network emulator from the utility grid. With this design, it is possible to prevent the fault during the testing and experiment stages from spreading to the grid and affecting the utility grid's operation. The variable frequency drive typically drives the induction motor at 1500rpm, so as to regulate the network frequency at 50Hz at all time.

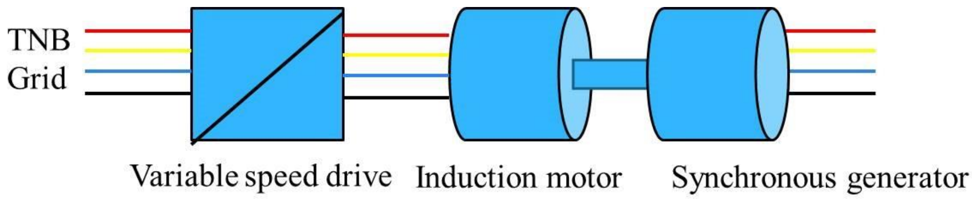


Figure 4.1: Network emulator

The proposed experimental LV network has a tapered, radial topology and its impedances are primarily resistive, in accordance with LV networks as described in Chapter 2, where X/R ratios are low. This network emulator is of three-phase four-wire topology with a T-T earthing system which is common in Malaysian LV distribution networks.

4.2.2 PV system

The PV system is built with 32 panels of poly-crystalline PV modules manufactured by Panasonic. Each of the modules contributes a maximum power of 230W. These panels are divided to 4 strings with 8 panels in a string. Each string has the capacity of 1.84 kWp and is detachable from the solar inverter such that the capacity of the PV system can be fixed at 1.84, 3.68, 5.52 and 7.36 kWp. The total capacity of the PV system is 7.36 kWp. Figure 4.2 shows the single line diagram of 2 string PV module connected to a 3.0 kWp PV inverter namely Zigor Sunzet SP3. This PV system is integrated with the proposed experimental LV network emulator.

The PV module is oriented to face north, with a 5 °tilt angle from the horizontal plane. This enables the PV systems to receive sunlight throughout the day and the dust on the PV module could be cleaned by the rain water.

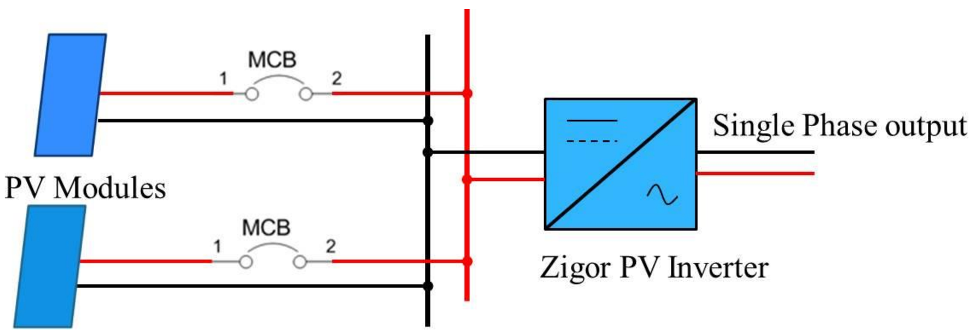


Figure 4.2: PV system

4.2.3 Energy Storage System

The energy storage system consists of a SMA Sunny Island 5048 bi-directional inverter integrated with 4 x 120 Ah lead acid batteries as illustrated in Figure 4.3. The proposed energy storage system is used as one of the supply sources or DGs in the experiment.

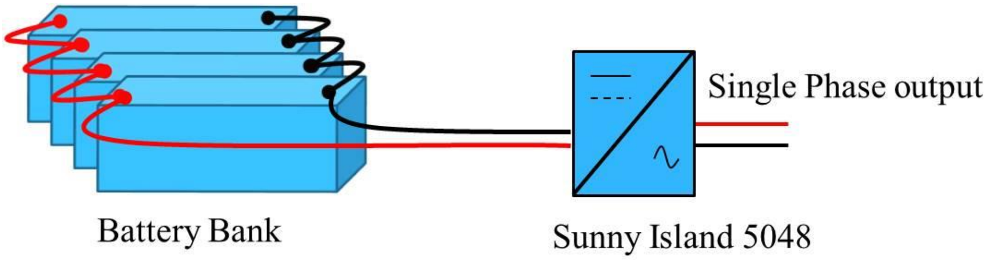


Figure 4.3: Energy storage system

The Sunny Island interfaces with a computer to enable the control to inject or absorb the power from the battery bank. The Sunny Island is capable of forming a grid, keeping the voltage and frequency of the grid at a constant level. The nominal voltage of the lead acid battery is 12V which results in an energy capacity of 5.76 kWh. The lead acid battery is reported to have a higher operational efficiency, a longer lifetime and cost efficiency.

4.2.4 Load Bank

The load bank is designed to emulate the operation of the real load. This load bank enables a flexible, organized and fully controllable load as compared to the real load on the power system. The proposed three-phase load bank consists of 15 units of the power resistors, with a rating of 200W/each. Each resistor is controllable via LabVIEW control system by triggering the solid state relay connected to the power resistor. The three-phase controllable load bank is capable to vary its rating from 200 W, up to 1000 W, with a 200 W increment in each step. The limitation of the proposed controllable load bank is that it is purely resistive. Therefore, the load bank is only suitable to emulate the unity power factor load. Figure 4.4 shows the configuration of the proposed controllable load bank.

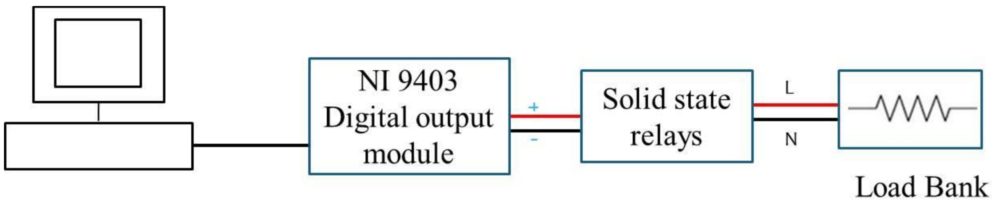


Figure 4.4: Controllable load bank

The digital input or output module, NI 9403 is used as an interface between the supervisory computer and the controllable load. The NI 9403 has a 37 pin connector that provides connections for the 32 digital input or output channels shown in Figure 4.5. The 32 channels are internally referred to the common, COM so any of the four COM lines can be used as a reference for the external signal. Each channel has a 5 V digital output pin which is used to connect to the solid state relay (SSR) as shown in Figure 4.6. The SSR used is silicon controlled rectifier output suitable for heavy industrial loads. It has the feature of zero crossing for resistive loads. The D2425 SSR that has the control voltage in between 3-32V and rated at 25A is used in the controllable load bank. Fifteen units of pure resistive, 200 W, power resistors shown in Figure 4.7 are used as dump load to consume the energy.

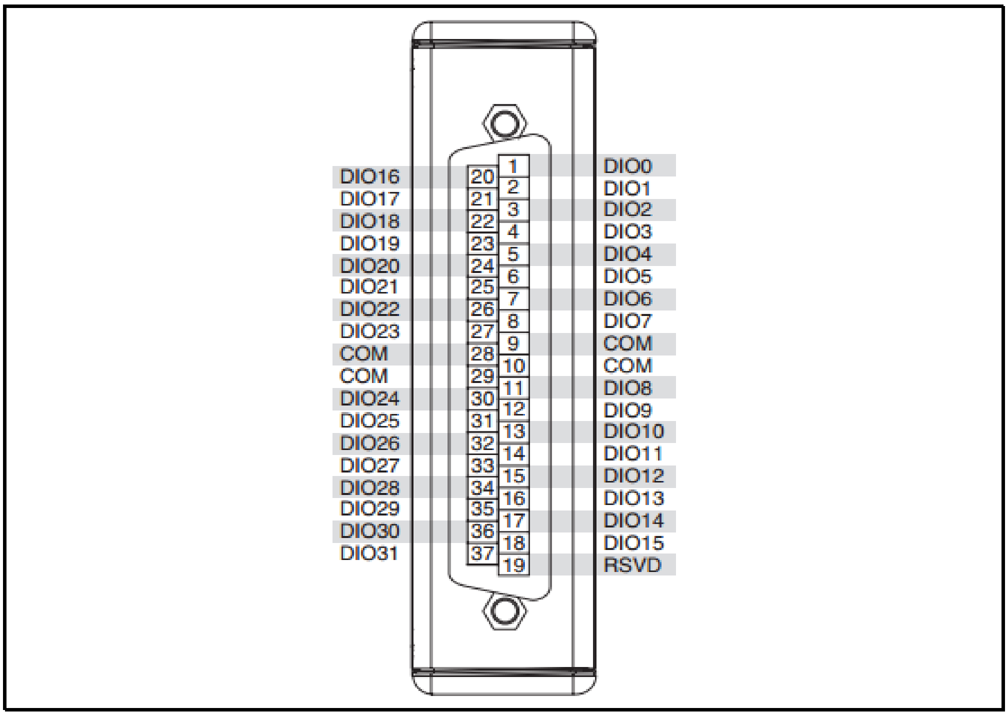


Figure 4.5: NI 9403 37-pin assignments

Figure 4.6: Solid State Relay D2425

Figure 4.7: Custom made 200W power resistor at 288 Ω

4.2.5 Data Acquisition System

A data acquisition and control is required to measure the impacts of voltage fluctuation and flicker caused by PV systems on the LV networks. It determines whether the measured voltage is within its acceptable tolerance, so as to activate the controller to send command to the solid state relay. The three-phase voltage and current at the point of connection around the LV distribution networks are monitored by using national instrument's (NI) voltage and current modules. The data acquisition device consists of a c-DAQ 9174 Data Acquisition Chassis, NI 9225 voltage module and NI 9227 current module. The chassis is connected to a supervisory PC in order to monitor the RMS voltage and RMS current with LabVIEW. These measurements are used as a feedback to activate the direct load controller. The output command is sent to the solid state relays that control the power resistor via NI- 9403 Digital I/O module. Figure 4.8 shows the flow chart for the data acquisition process.

Figure 4.9 shows the flexible LV monitoring panel. DG and the load can be connected at any point of the LV network through the 5-pin plug at the main bus bar. The power can be injected to either phase via the yellow phase selector switches. The STAR power meters are used to monitor the LV network condition during the experiment. The main circuit breaker, MCB is used to protect the connected load bank from overcurrent. The change-over switch allows the connection to the utility grid, or generator or Sunny Island as the supply source to the LV network. The overcurrent protection and residual current circuit breaker are also included in this panel to protect the equipment and safeguard the operating personnel.

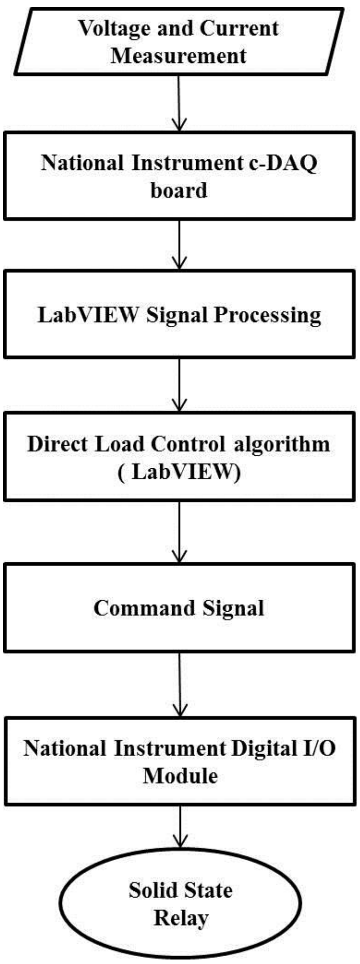


Figure 4.8: Data acquisition system flow chart

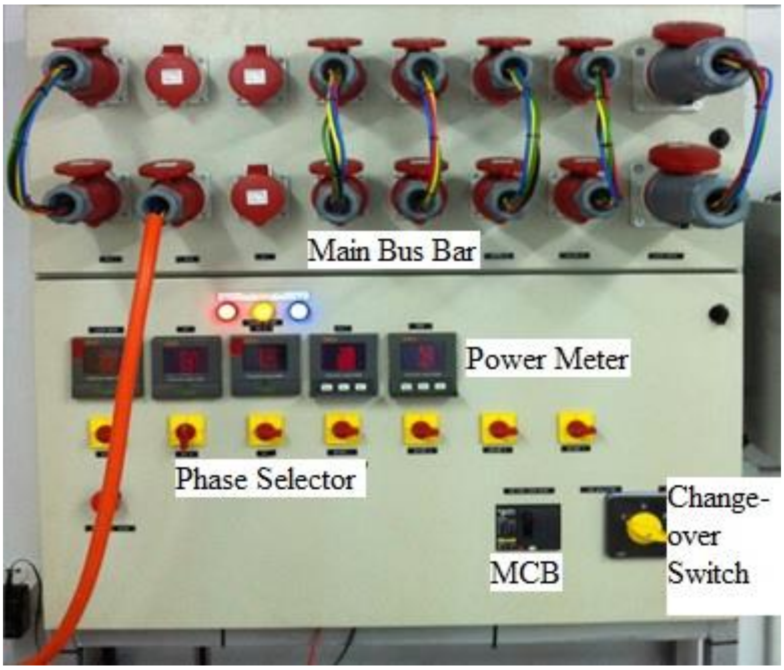


Figure 4.9: Flexible LV panel

4.3 Design of DLC Algorithm

The direct load control is one of the DSM methods. DLC is usually used to control the level of power consumption on the electrical grid. This method is used to reduce the peak demand to avoid any large power interruption on the national grid and to maintain the frequency of the stand-alone power systems due to the limited capacity of the power generation.

The proposed load control algorithm is used to control the load bank, where the load controller makes use of the real power to change the network voltage. This is because the resistance is greater than the reactance in the low voltage distribution networks, and hence the voltage magnitude responds predominantly to the real power changes. A previous study by Hingorani, (1991) showed that the Flexible AC Transmission System devices and VAR compensator are already widely used for the voltage correction, by reactive power compensation, in a transmission network. However, these devices have limited effect on LV distribution networks where the X/R ratio is low. Wong, (2011) has proved the concept of energy storage unit integrated with four quadrant converter capable of controlling the flow of real and reactive power to correct the network voltage magnitude. Nevertheless, the energy storage device and the converter will be the expensive devices that would increase the total investment cost for a RE developer. A super capacitor is also proposed as a viable solution to reduce the voltage quality issues (Degobert et al., 2006; Palizban et al., 2011). However, the capacitor has low cell voltage. In order to use in high voltage application, several capacitors have to connect in series. This will introduce the current leakage. In addition, the super capacitor is also more expansive than the proposed DLC which uses resistor.

A voltage change in the LV distribution networks with DG can be described below.

$$\Delta V = \frac{(P_G - P_L)R + (Q_G - Q_L)X}{|V|} \quad (1)$$

Where

$P_{G,}$ Q_G = Real and reactive power of generator, respectively

$P_{L,}$ Q_L = Real and reactive power of load, respectively

R, X = Cable resistance and reactance, respectively

ΔV = Voltage change

V = Line voltage

Since the X/R ratio is low in the LV distribution networks, the resistance, R is much higher than reactance, X. This means that the reactive power has less influence on the distribution network voltage compared to that of the real power. Hence, we propose to use the real power to correct the voltage fluctuation and flicker.

To understand exactly how ΔP is related to ΔV, the correlation between ΔP and ΔV has to be determined. It is known that the change in voltage magnitude (ΔV) and current (ΔI) is related as follows:-

$$\Delta V = Z \times \Delta I \quad (2)$$

Where Z is the impedance of the line where the PV system is connected to.

The change in PV power output (ΔP) is related to ΔI by the following equation.

$$\Delta P = (V + \Delta V) \times \Delta I \quad (3)$$

Then ΔI is related to ΔV by the following equation.

$$\Delta I = \frac{\Delta V}{Z} \quad (4)$$

By substituting Equation (3) into Equation (2) gives the following

$$\Delta P = (V + \Delta V) \times \frac{\Delta V}{Z} \tag{5}$$

V is the nominal voltage and is much greater than ΔV. Therefore,

$$\Delta V \approx \left(\frac{Z}{V} \right) \times \Delta P \tag{6}$$

From the derived equation, it can be seen that the change in the voltage magnitude depends on two factors. It depends on the change of the PV power output and the impedance, Z of the cable where the PV system is connected to.

The load controller is proposed to mitigate voltage fluctuation and flicker because its components are cheap. Also, it is an effective means for reducing flicker by switching the resistors on and off very rapidly in order to compensate for the impacts of the sudden increase and decrease in the PV power output. The power dissipated in the load controller can be used to heat up water for multipurpose applications.

Figure 4.10 shows the block diagram of the proposed DLC. It consists of a load bank with 5 units of 200 W power resistors per phase that adjust the real power consumption in the LV distribution networks. A measurement unit measures the voltage magnitude at the point of connection and sends signal to the controller that decides whether to turn on or off the power resistor. Real time voltage magnitude will be compared to the pre-set reference to determine the number of power resistor needed to turn on/off. The controller responds immediately when it detects the voltage rise or voltage drop to compensate for the voltage fluctuation and flicker.

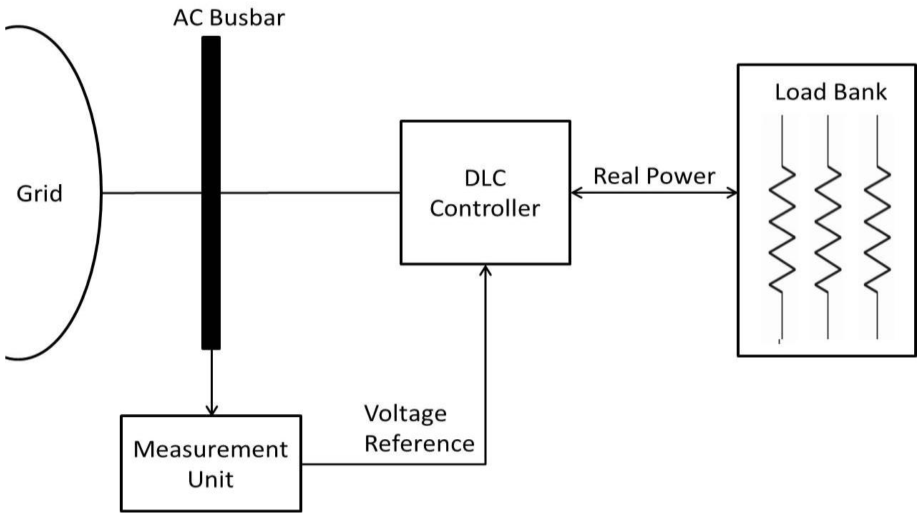


Figure 4.10: The block diagram of the DLC controller

Figure 4.11 shows the flow chart of the control algorithm. It consists of a load bank with 5 units of 200W power resistors with solid state relays to switch on and off the power resistors. A simple control algorithm is developed using LabVIEW as a programming platform shown in Figure 4.12. The front panel of the power quality monitoring is shown in Figure 4.13. From the front panel, network operators can easily monitor the real time power quality of the LV distribution networks.

The system begins with measuring the voltage magnitude at the point of connection. It is then followed by comparing the Vinst to the Vsp. The controller will not activate until the Vinst is out of the tolerance limit or dead band shows in Figure 4.17. A dead band is an area of a signal range where no action is taken by the controller. The dead band prevents repeated activation and deactivation of the DLC controller. The controller will activate one 200W resistor once at a time until the Vinst exceeds the dead band. Similarly, if the Vinst is lower than the Vsp, the controller will deactivate one of the 200W resistors one at a time in order to mitigate the voltage back to its acceptable limit. The load bank control is shown in Figure 4.18. The proposed control algorithm is simple; therefore it can effectively activate and deactivate the resistor dynamically with minimum delay.

Figure 4.14 shows the LabVIEW coding for voltage measurement. Instantaneous voltage is converted to RMS voltage. Then the dynamic data are converted to array data type. In addition to voltage, the frequency is also measured as shown in Figure 4.15. The current measurement is shown in Figure 4.16. Due to the NI 9227 the maximum current module allowable current is 5 A. Ring type current transformers are used to step down the measured current. The Class 3 current transformer used has a ratio of 250/5A. Hence, the measured current value has to be multiplied by fifty to get the actual current value in the LabVIEW program.

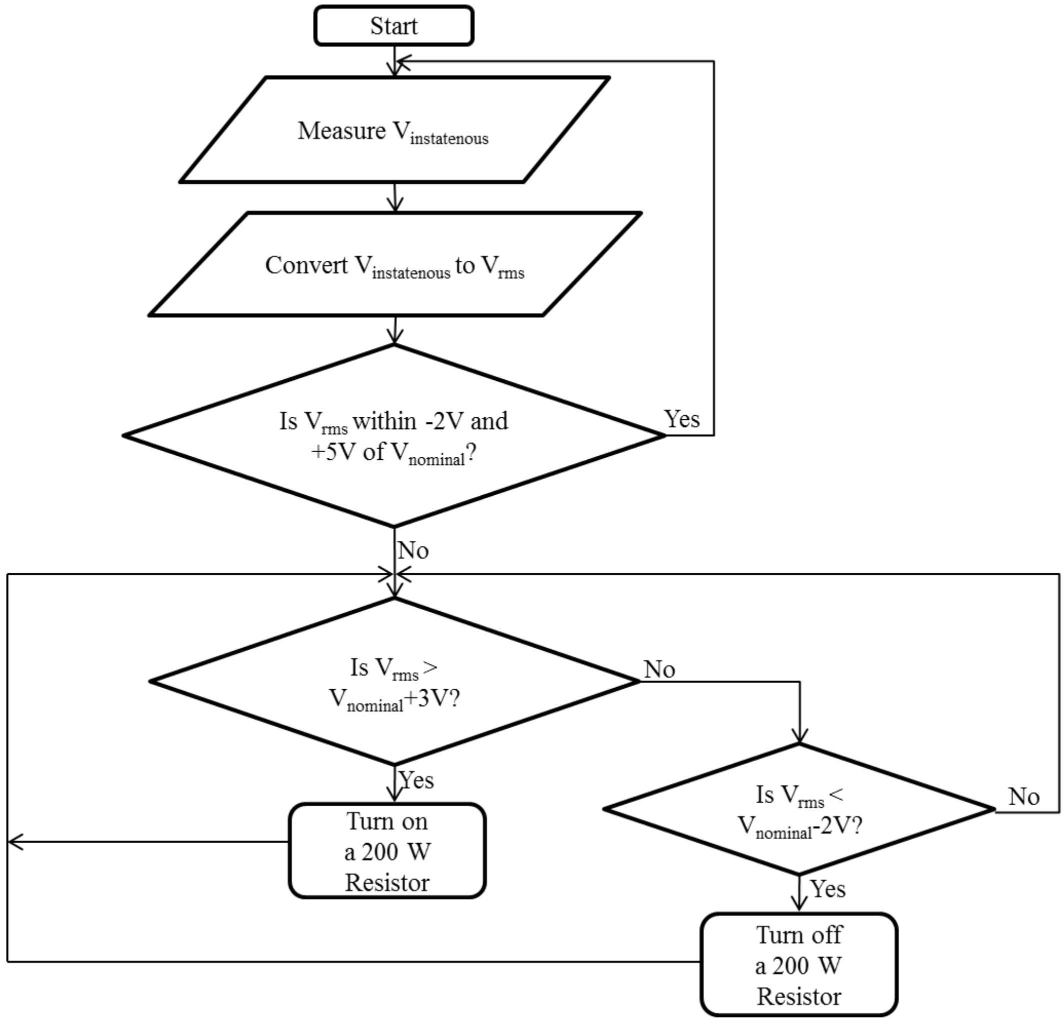


Figure 4.11: Flow chart of the control algorithm

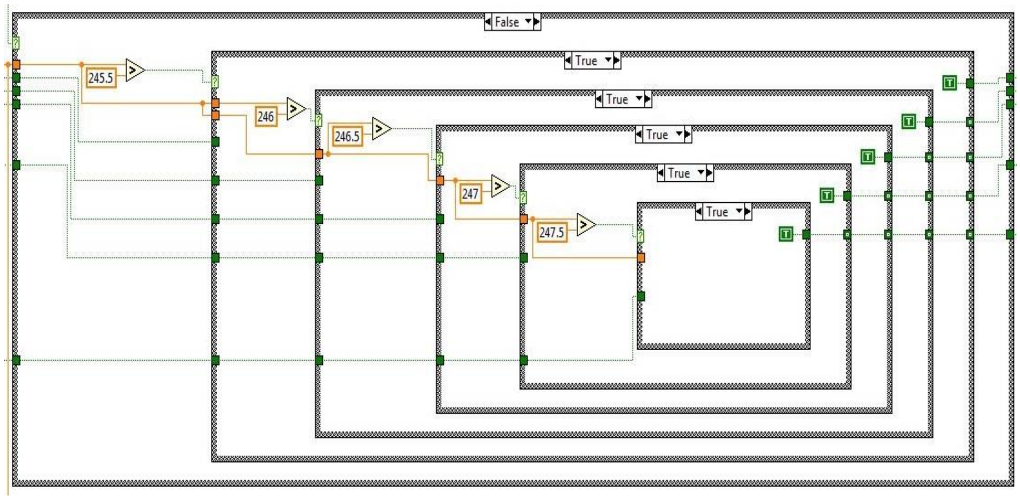


Figure 4.12: LabVIEW programming coding for DLC

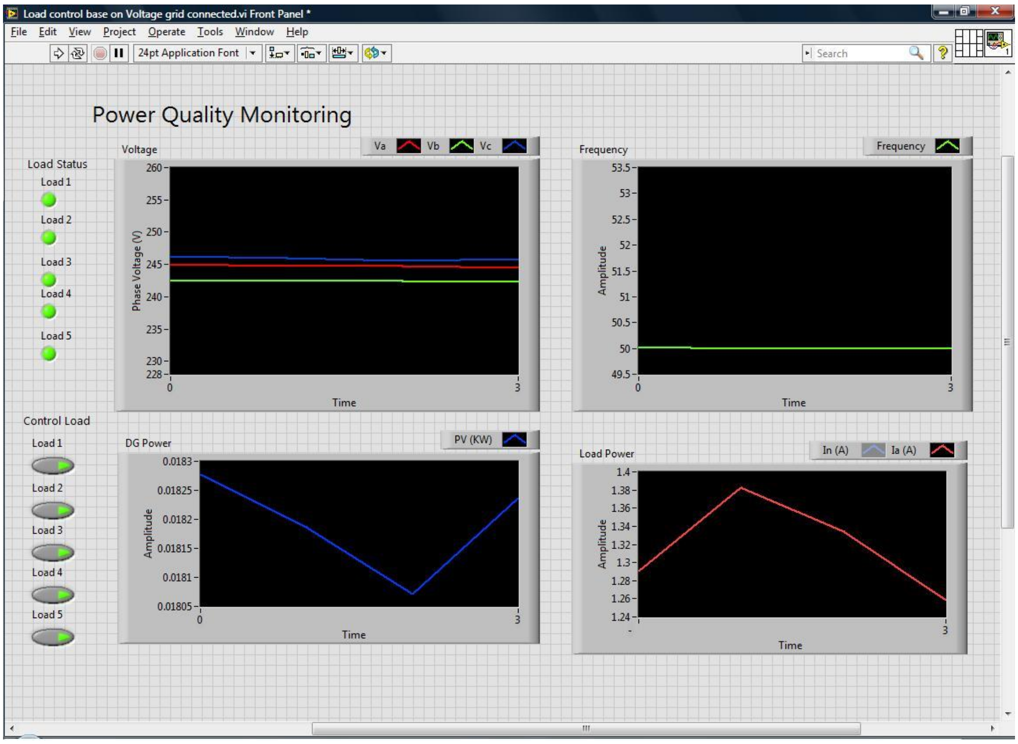


Figure 4.13: Front panel for power quality monitoring in LabVIEW

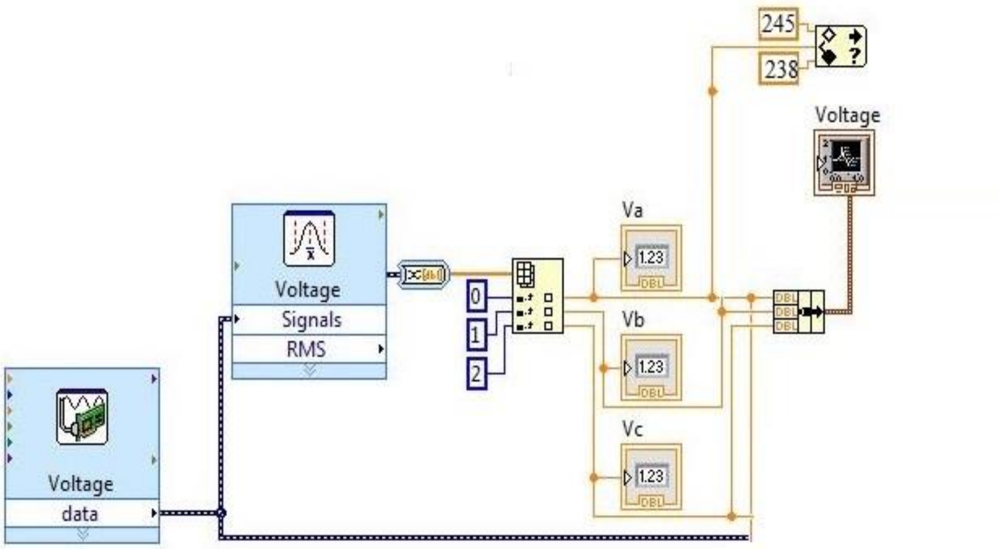


Figure 4.14: LabVIEW model for Voltage measurement

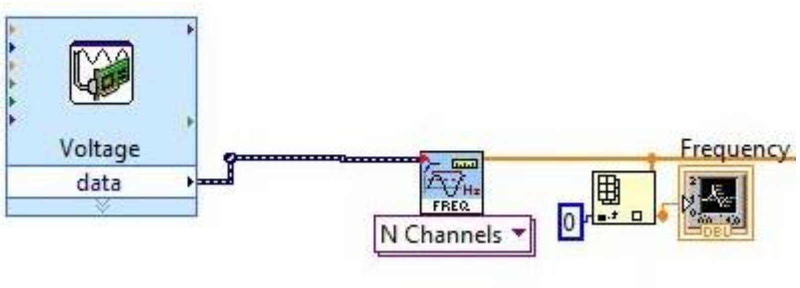


Figure 4.15: LabVIEW model of frequency measurement

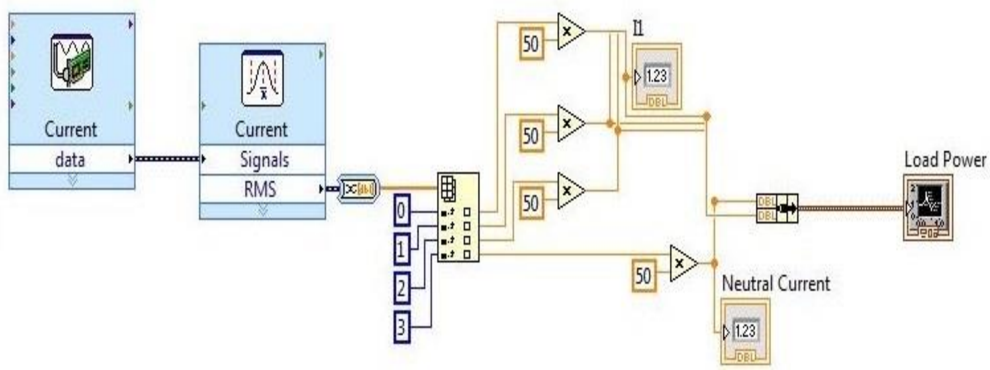


Figure 4.16: LabVIEW model for current measurement

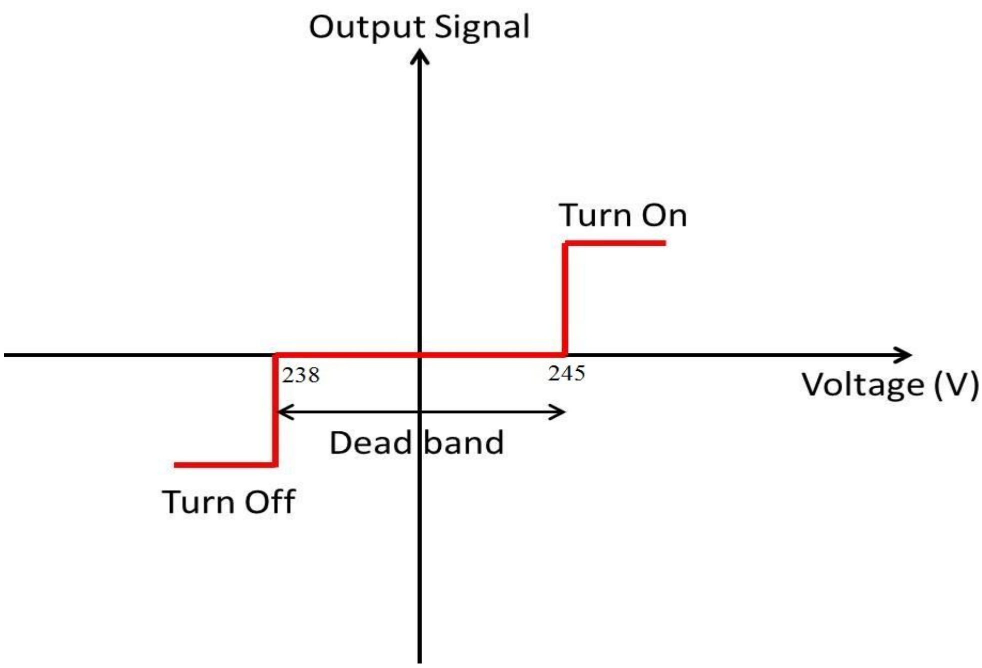


Figure 4.17: Dead band between 238 to 245V

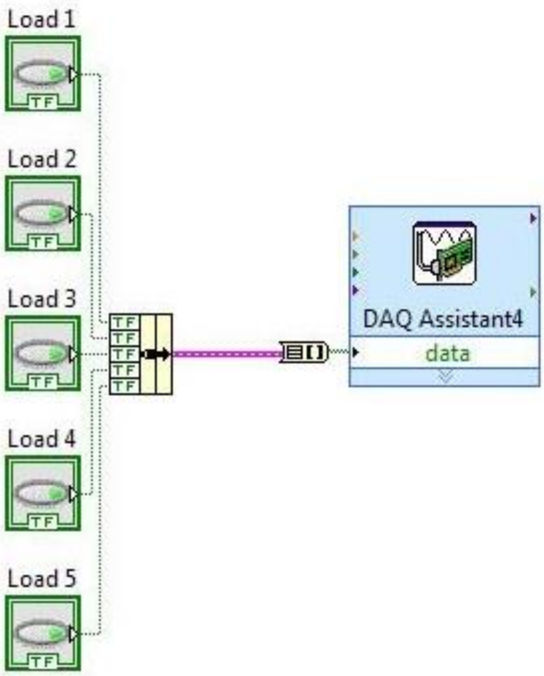


Figure 4.18: Load bank control

4.4 Set up of the experimental low voltage distribution network

An experimental three-phase low voltage distribution network is set up in the power laboratory to study the characteristics of the PV power output and voltage magnitude at the point of the PV connection as shown in Figure 4.19. A PV system and a controllable load bank are connected to the experimental distribution network. The generation of the experimental distribution network can be chosen through a changeover switch between the utility grid, 15KVA generator and a bi-directional inverter coupled with a battery bank.

Three scenarios are studied based on the experimental LV distribution network, as follows:

Case Study 1: The 15KVA generator is used to study the voltage fluctuation purely generated by the PV system in the conventional off-grid system.

Case Study 2: The utility grid is used to study the impact of PV systems connected to the existing LV distribution networks.

Case Study 3: The bi-directional inverter coupled with the battery bank is used to study the modern off-grid system which includes the distributed generation, both renewable and non-renewable.

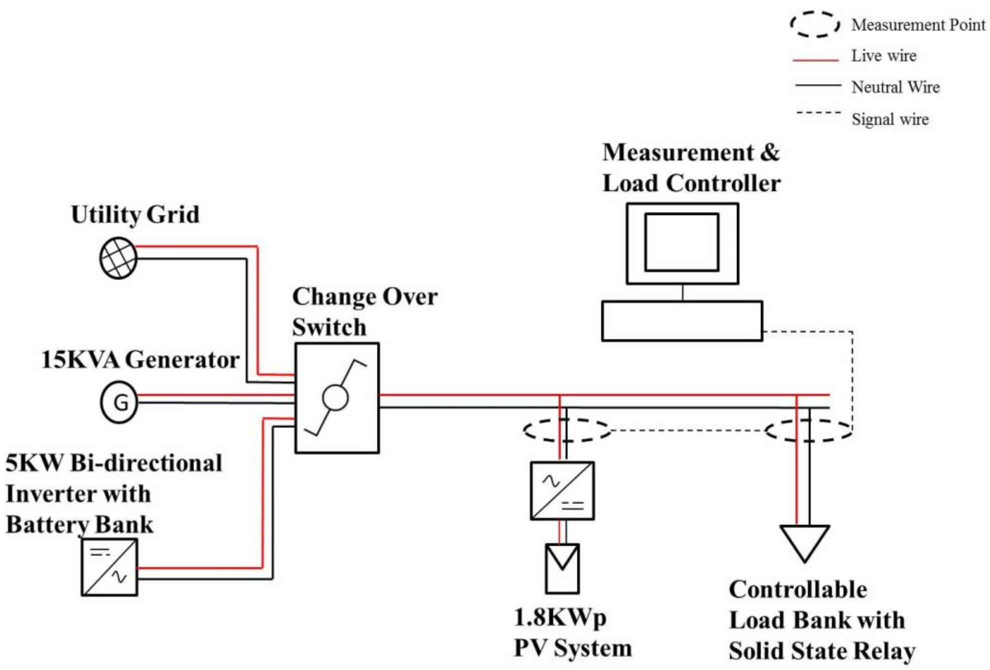


Figure 4.19: Experimental setup

4.5 Quantification of Voltage Fluctuation and Flicker

To quantify the voltage fluctuation and flickers produced by the photovoltaic system, a number of standard formulae are adopted (Deokar & Waghmare, 2010; Nambiar et al., 2010; Ortega et al., 2013). In this section, the voltage sensitivity, the voltage fluctuation index, the global voltage regulation, and the flicker will be discussed briefly.

4.5.1 Voltage Sensitivity Gradient

The voltage sensitivity curve is used to determine the sensitivity of the change in the PV power output with respect to the change of network voltage magnitude. A two axis graph is plotted with the Y-axis representing the change in the PV power output and the X-axis representing the change in the voltage as shown in Figure 4.20. It is assumed that the change of the PV power is linearly proportional to the change of the voltage. The gradient is then calculated.

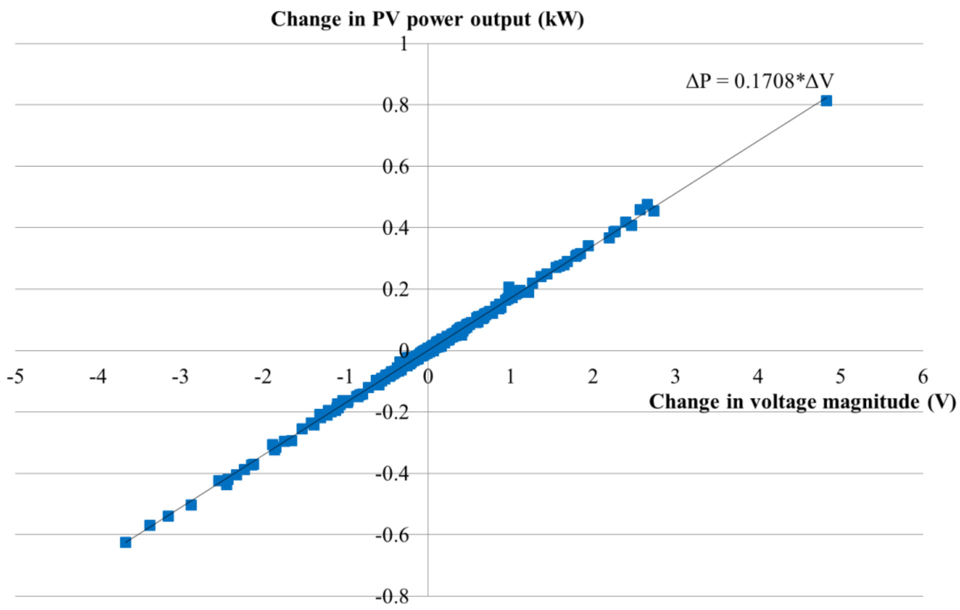


Figure 4.20: Correlation between ΔP and ΔV

4.5.2 Voltage Fluctuation Index

The voltage fluctuation can be quantified by the voltage fluctuation index (V_{FI}). V_{FI} quantifies the average change in the RMS voltage magnitude during each excursion over the entire period considered. In this work, the period of time is defined from 9am to 5pm, which is 8 hours, when the sunlight is available. The formula for calculating V_{FI} is given as follows:-

$$V_{FI} = \frac{\sum_{i=2}^{N} \left| V_i - V_{i-1} \right|}{N-1} \qquad (7)$$

Where V is the voltage magnitude; i refers to the instant time and N is the number of samples.

4.5.3 Global Voltage Regulation

The Global Voltage Regulation (GVR) is used to quantify the voltage fluctuations in the network with DG. To calculate the global voltage regulation, the difference between the maximum and minimum RMS voltage magnitudes in the same time interval is measured. The time interval of this calculation is set to 10mins. The GVR equation is defined as:-

$$GVR = \sqrt{\frac{\sum_{i=1}^{N} (Vi_{MAX} - Vi_{MIN})^2}{N}} \tag{8}$$

Where Vi_{MAX} is maximum voltage; Vi_{MIN} is the minimum voltage; N is the number of samples.

4.5.4 Short Time Flicker

The standard IEC 61000-3-3 provides and explains the voltage flicker emission limits of the equipment connected to the LV distribution networks. The IEC 61000-4-15 presents the flicker measurement and assessment. A simplified short time flicker (P_{ST}) assessment method is proposed in this work. It is also known as the unity flicker severity curve approach. This method makes use of the fact that the flicker severity is a linear parameter to the magnitude of the voltage changes that caused it. This method is chosen and incorporated into the control algorithm of the DLC because it is a quick and simple assessment approach which creates a very little delay in the execution of the DLC. This method is listed as follows:

i) Determine the magnitude of every voltage changes over the specific minute using the following equation.

$$d = \frac{V_{\max} - V_{\min}}{V_{nom}} \times 100\% \qquad (9)$$

Where V_{max} is the maximum voltage, V_{min} refer to minimum voltage and V_{nom} is the nominal voltage, which is 230V in Malaysia.

ii) Determine the number of voltage changes within the specified minute, r.

iii) Calculate the average value, *d* of the all the voltage change ΔV happening within the specified minute.

iv) Substituting, r, expressed as the number of voltage changes per minute, into the severity curve as shown in Figure 4.21 to find the corresponding relative voltage change, d_0, that produces $P_{ST0} = 1.0$.

v) The short time flicker can therefore be calculated using the following correlation:-

$$P_{ST} = P_{ST0} \times \frac{d_0}{d} \qquad (10)$$

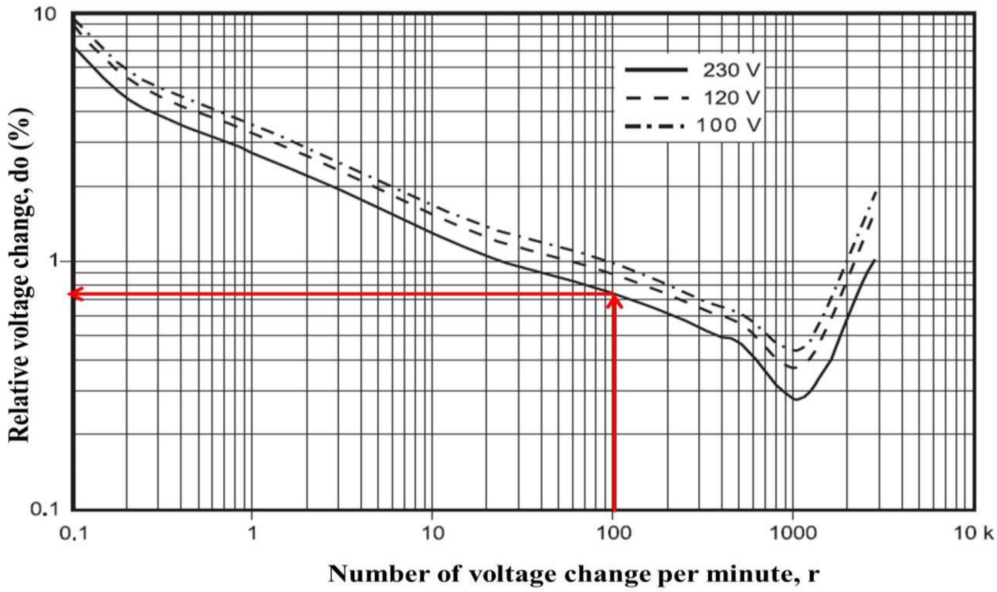


Figure 4.21: Unity flicker curve at $P_{ST0} = 1$

4.5.5 Long Time Flicker

Short-time flicker is used to evaluate the long-time flicker (P_{LT}) for a longer period. In this work, the period is defined as 2 hours by using the cubic law as follows:

$$P_{LT} = \sqrt[3]{\frac{\sum_{i=1}^{N} \left(P_{STi}\right)^3}{N}} \tag{11}$$

4.6 Conclusion

This chapter described the details of the experimental LV distribution network. It is designed in such a way to comply with the Malaysian LV distribution network topology. The proposed experimental LV distribution network is a three-phase four-wire network with radial design. The LV network is earthed in a T-T configuration where the customer is responsible to ground the exposed metallic path to earth. This experimental LV distribution network is designed to study the effectiveness of the DLC in an on-grid and off-grid set-ups. The generation source of the experimental network can be chosen between the utility grid, generator or battery storage. The proposed DLC algorithm is developed using LabVIEW which operates by using a supervisory PC. The control flow and the three scenarios are described in this chapter. These scenarios are designed to study the effectiveness of the proposed DLC in mitigating voltage fluctuation, and voltage flickers.

CHAPTER 5

VOLTAGE FLUCTUATION AND FLICKER IN LV DISTRIBUTION NETWORKS WITH PV SYSTEMS AND THE CORRECTIVE METHOD OF LOAD CONTROLLER

5.1 Introduction

The previous chapter described the design and development of the experimental LV distribution network integrated with DLC algorithm. In this chapter, the characterization of the PV power fluctuation is discussed. This is followed by a study of the voltage fluctuation and flicker issues that may arise due to the intermittent PV power output. Three case studies are presented to show the effectiveness of DLC in mitigating the voltage fluctuation and flicker on the LV distribution networks.

5.2 Characterization of the PV Power Output

A case study is carried out to characterize the power output of a 3.0 kW PV system in the experimental network. The PV is connected to Phase A of the experimental LV distribution network. National Instrument (NI) data acquisition devices are used to log the terminal voltage and the current output of the PV system. The data acquisition system consists of a data acquisition chassis, NI-cDAQ and two measurement modules, NI 9225 voltage card and NI 9227 current card. LabVIEW is used as a programming platform to monitor and log the data into excel file format. The PV system is monitored over a period of 9 months. Figure 5.1 shows the relationship between the voltage magnitude and PV power output on 29th December 2013. The PV power output fluctuates very rapidly, causing the voltage magnitude to change frequently throughout the day. Three unique characteristics of the PV power outputs can be observed from the result as listed below:-

1. Few high PV power outputs happen within a short duration.
2. Some of the high PV power outputs drop down suddenly instead of gradually. For example, the high PV power output of 2.7 kW that happens between 12.00 and 12.22 pm drops immediately to 1.2 kW after 12.22 pm.
3. The magnitude of reduction in the PV power output is significant, about 63 % of reduction in the PV power output.

A high PV power output happens within a short durations because of the high frequency of the passing clouds over the PV panel. The sudden reduction in the PV power outputs are caused by the thick clouds that reduce the total solar irradiation arriving at the solar panels. Some of the thick clouds can reduce the solar irradiation substantially, hence making a significant reduction in the PV power output.

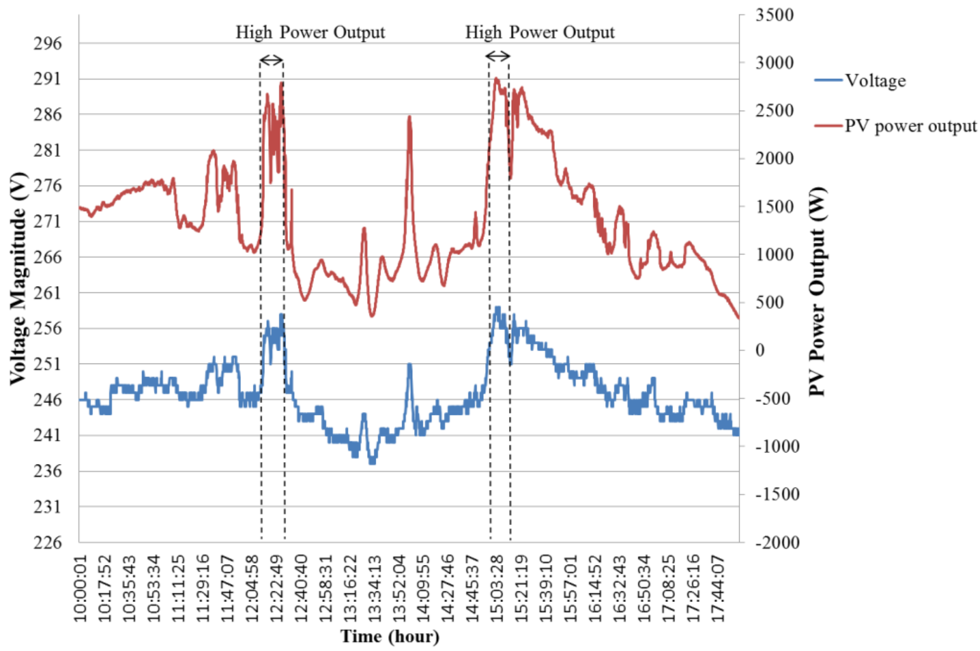


Figure 5.1: Fluctuation in PV output and voltage magnitude

5.3 Voltage Fluctuation and Flicker Caused by PV system

A preliminary case study is carried out to investigate the severity of voltage fluctuation and flickers introduced by PV systems. A 1.84 kW PV system is connected to phase A of the experimental LV distribution network. A 15 KVA synchronous generator is used to be the supply source to the network because it does not generate any severe voltage fluctuation and flickers to the network. As a result, any flickers experienced at the point of connection are generated from the PV system.

The voltage magnitude at the point of the common coupling is measured and recorded on a regular basis. Figure 5.2 shows the variation in voltage magnitude caused by the fluctuation in the power output of the 1.84

kW PV system. These voltage are used to calculate the voltage fluctuation index (V_{FI}), the short-time flickers (P_{ST}) and the long-time flickers (P_{LT}). There are 47 short-time flicker indices that can be calculated by equation (10) from the measured data as shown in Figure 5.3. The short-time flicker is then used to calculate the long-time flicker for a period of 2 hours. It is noticed that the maximum value of short time flicker exceeds the statutory limit. This result shows that the flickers produced by the PV systems can exceed the allowed limits.

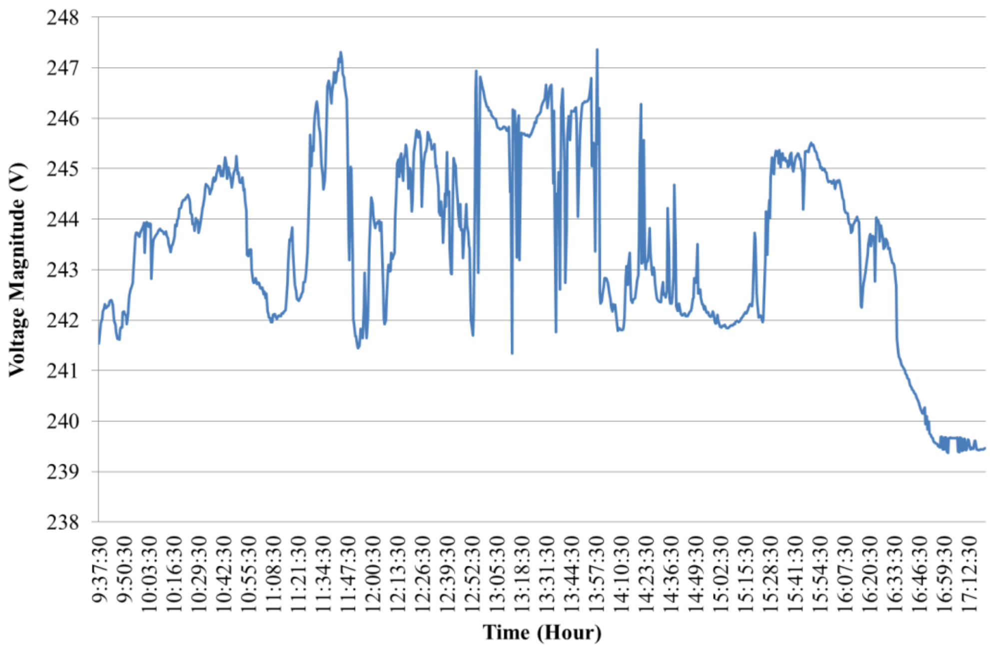


Figure 5.2: Variation in voltage magnitude caused by the fluctuation in the power output of the 1.84 kW photovoltaic system

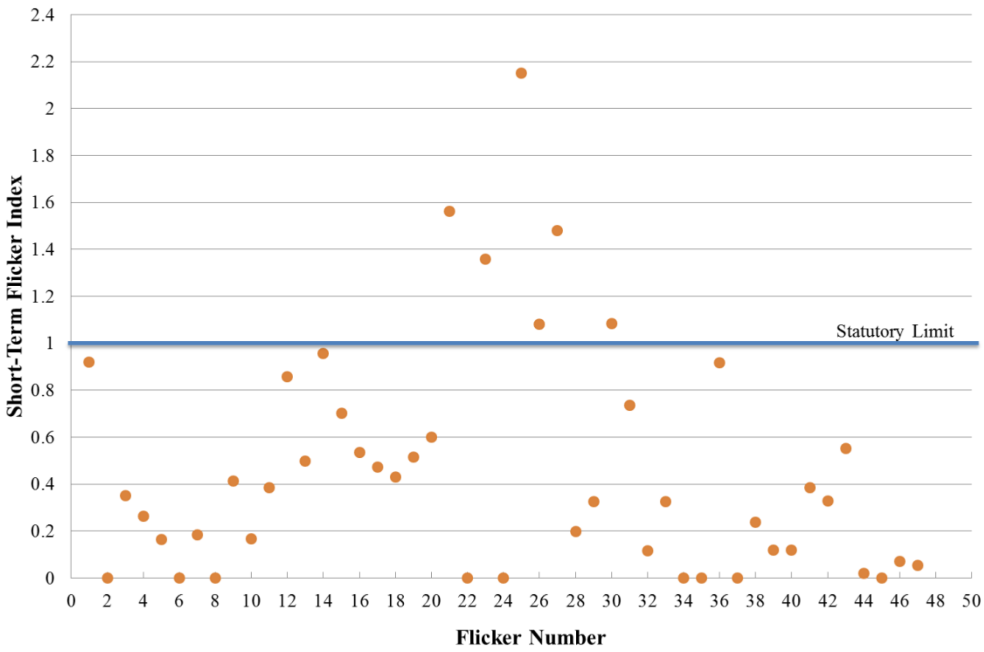


Figure 5.3: A number of short-time flickers being calculated from the collected voltage magnitude

5.4 Solar Density Chart

The solar density chart is introduced to study the PV system performance in Malaysia. The solar density chart is useful to give a quantitative impression of the PV system's performance. The chart shows the frequency of various PV power outputs within a certain range and the corresponding duration. The solar density chart will be categorized into sunny, cloudy, and rainy days in Malaysia. In addition, the average data from Thailand, Hong Kong, China, and UK are also presented in this section. In the chart, all the PV output magnitude ranges are of equal size. However, the duration is in different size because there are more PV power with short duration and high magnitude in the duration and magnitude plane. Therefore, the resolution chosen is higher for the shorter duration PV output.

5.4.1 Nine Month Average

The PV power output obtained from the 9 month monitoring in Malaysia is shown in Figure 5.4. The maximum power output of the PV system is 3.6kWp. From this figure, we can observe that the majority of the PV output in Malaysia happens within a short duration, less than 5 minutes. There are a few number of low PV output with a longer duration, in between 5 to 10 minutes. This result proves that Malaysia has high solar irradiation throughout the year. However, the PV system performance is degraded by the passing clouds. The passing cloud causes the PV power output to be very intermittent and fluctuating.

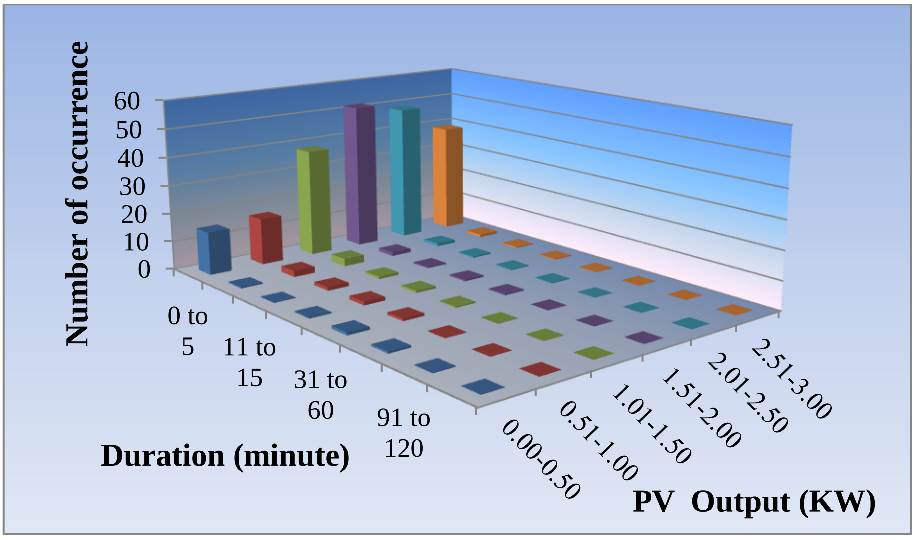


Figure 5.4: A 9 months solar density chart in Malaysia

5.4.2 Sunny

Sunny day is defined as a day with sunlight from 8 am to 6 pm and PV panels are exposed to the direct rays of the sun. Figure 5.5 shows the PV power output on 10/9/2012. The majority of the PV output has a magnitude range greater than 1.0 kW but less than 2.5 kW. There is also a significant number of high PV power output, ranging from 2.5 kW to 3.0 kW, happening within 30 minutes or less. The solar density chart as shown in Figure 5.5 has a similar trend to the Malaysian solar density chart as shown in Figure 5.4. Therefore, the solar density chart shows that Malaysia has a sunny day most of the time.

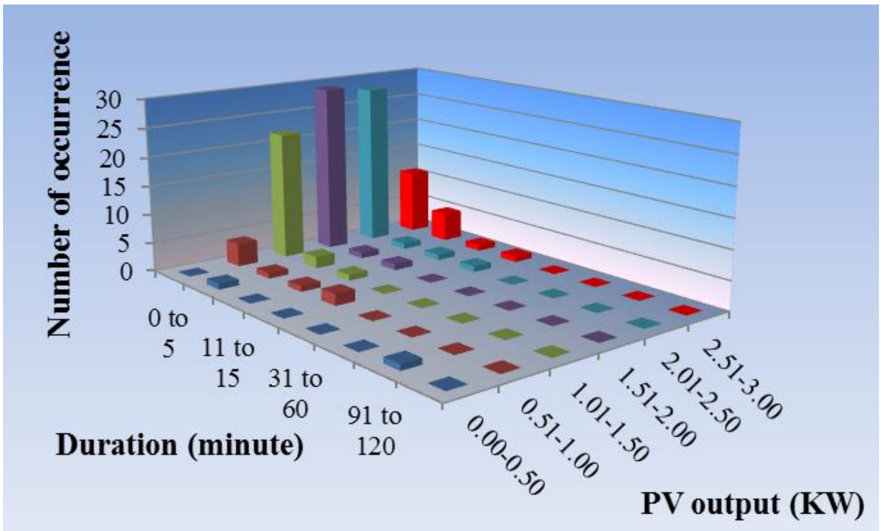


Figure 5.5: Malaysia's Solar Density Chart under Sunny condition

5.4.3 Cloudy

Throughout the monitoring period, 14/9/2012 was a cloudy day. Figure 5.6 shows the PV power output on that particular day. The chart shows a highly fluctuating PV power output. Cloudy day is defined as a day with soft and diluted sunlight throughout the day. The majority of the PV output has a magnitude between 1.0 kW to 1.5 kW with a duration less than 5 minutes. There are many low PV power outputs, less than 1.5 kW, happening for a longer period. Some of the PVs with a magnitude less than 0.5 kW can last for an hour. The occurrence of high PV output is very rare. This is because the sky is covered with the big white cloud, reducing the total solar irradiation substantially, hence making the PV power output to be very intermittent.

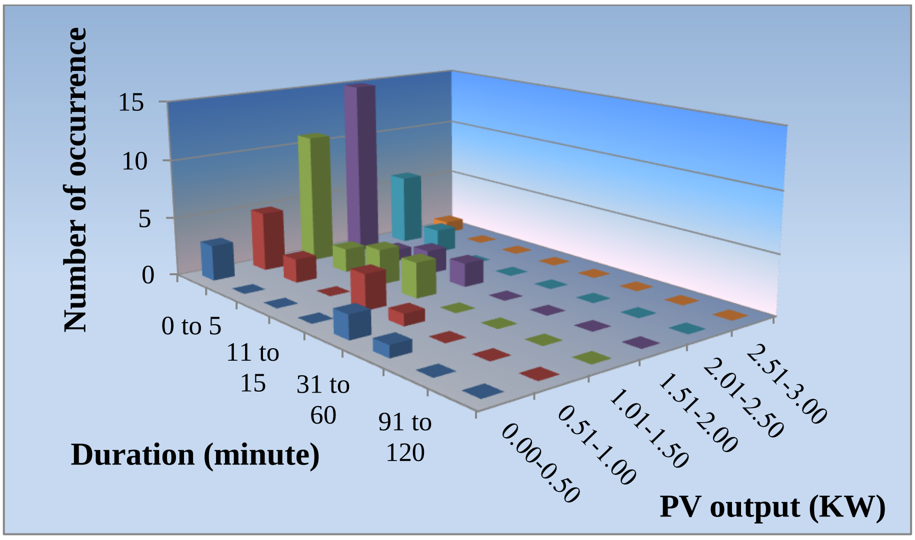


Figure 5.6: Solar Density Chart for cloudy day in Malaysia

5.4.4 Rainy

Figure 5.7 shows the solar density chart during a rainy day. The solar density chart shows that the majority of the PV output has a magnitude less than 1.5 kW with a duration of 30 minutes. There are a significant number of low PV outputs, less than 0.5 kW, happening for more than 2 hours. During rainy days, none of the recorded power output falls between the ranges from 1.5 kW to 3 kW. The solar density chart shows the characteristic of low PV power output for a longer period during rainy days.

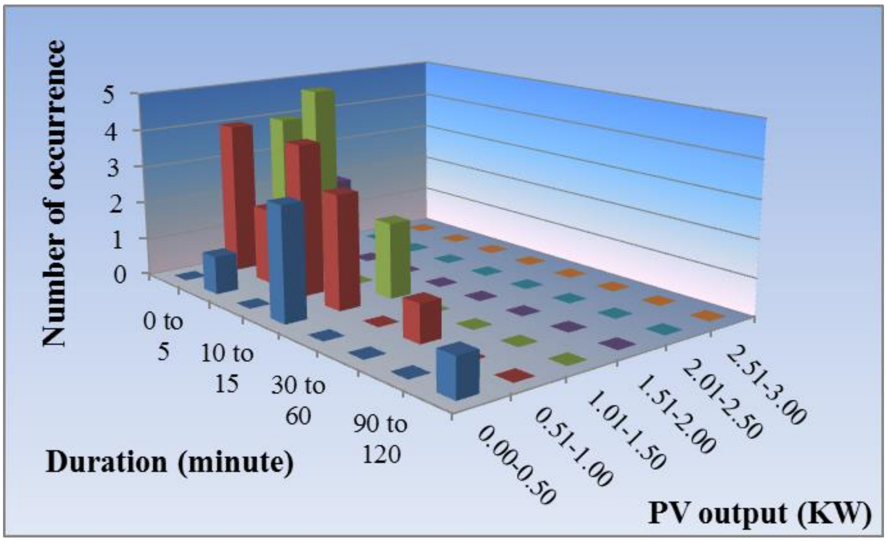


Figure 5.7: Solar Density Chart for Rainy day in Malaysia

5.4.5 International

To compare the PV output characteristics of other countries, a comprehensive PV monitoring data from Thailand, China, Hong Kong and the UK are collected from the sources of Li et al., (2005); Chokmaviroj et al., (2006); Zou et al., (2012); Scott, (2012). Figure 5.8 shows the characteristics of PV power output in Thailand, China, Hong Kong and the UK. It is shown that the majority of the PV power output in China, Hong Kong and the UK happened for more than 30 minutes which is much longer than that in Malaysia. Furthermore, the PV power output reduces gradually. Therefore, the magnitudes of voltage fluctuation and flickers produced by the photovoltaic systems are significantly less than that in Malaysia. It is noticed that the life span of some high PV power output in Thailand is short, less than 5 minutes. This is because Thailand is close to Malaysia, making this region to be vulnerable to much passing clouds.

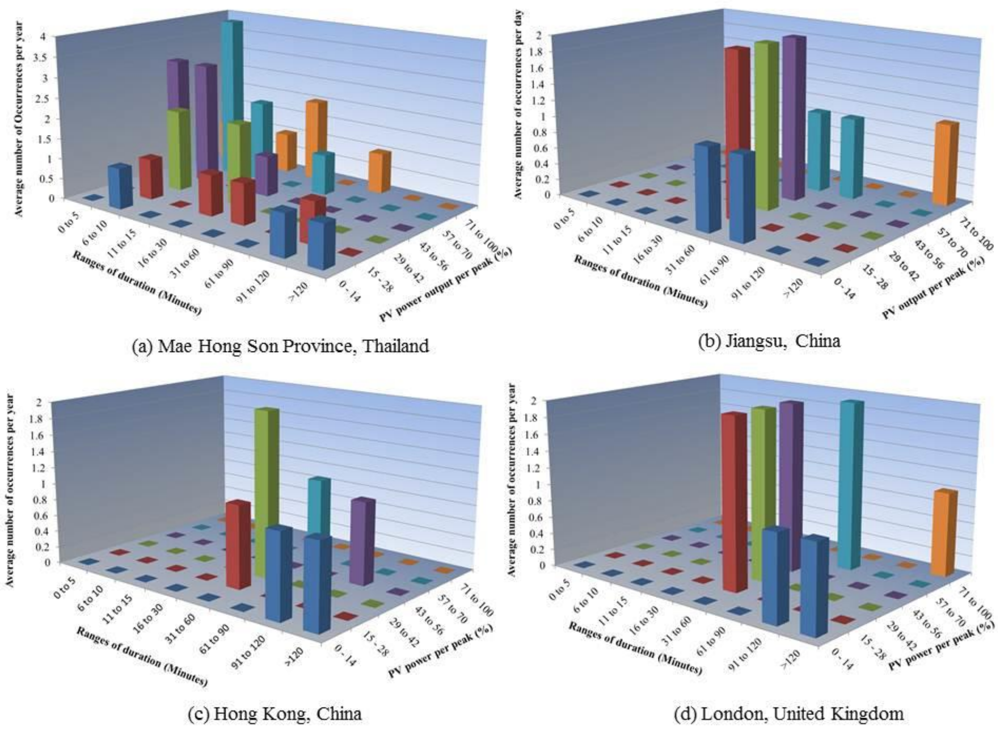


Figure 5.8: International's Solar Density Chart

5.5 Case Study 1: Off-grid System with a 15 kVA generator

5.5.1 Description

In this case study, a 1.84 kW PV system is connected to Phase A of the distribution network. A 15 kVA synchronous generator is used to be the supply source to the network. This is a conventional off-grid network configuration without battery storage. The system configuration is shown in Figure 5.9. This case study is to investigate the voltage fluctuation and flicker if the PV system is connected to the existing off-grid system. The experiment is run throughout a sunny day and data are recorded on a regular basis.

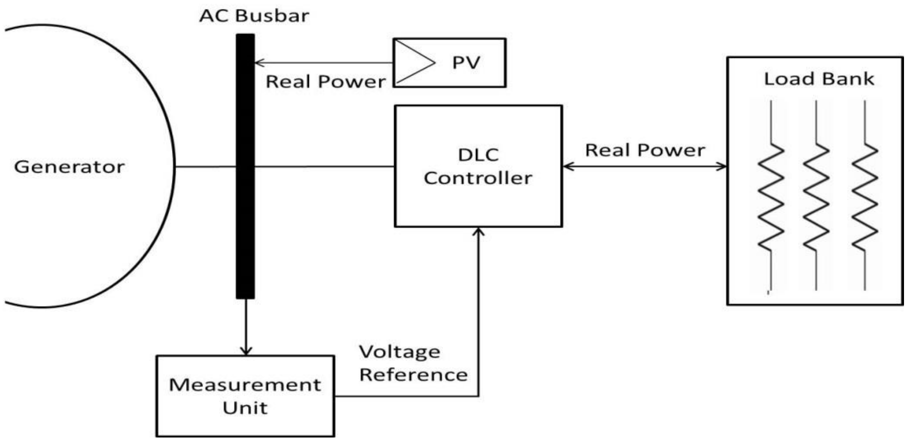
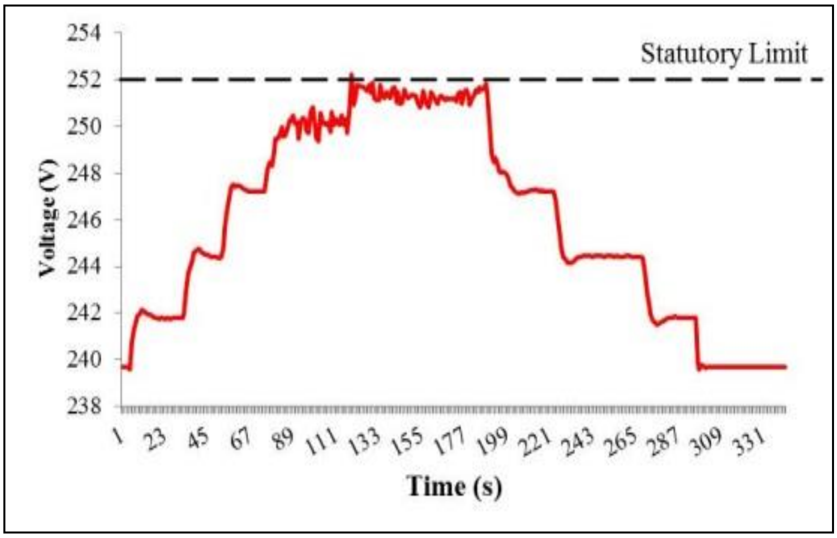


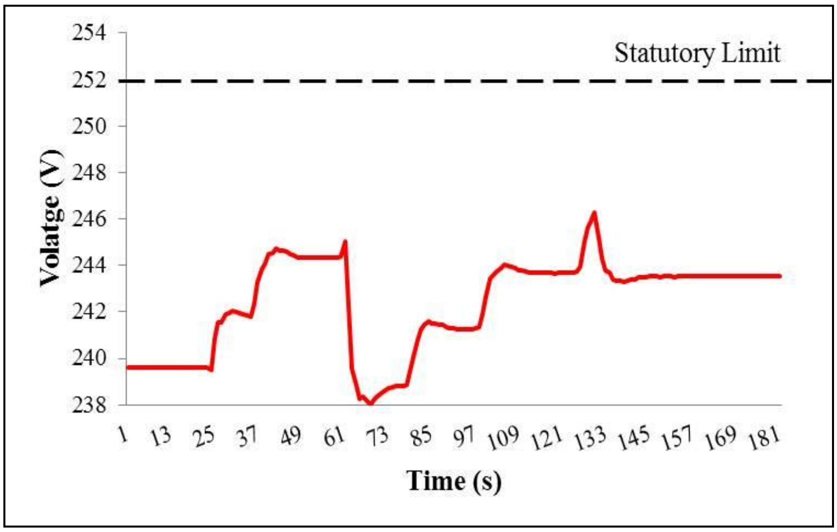
Figure 5.9: Off-grid system configuration

5.5.2 Experiment Results

The experimental results show the effectiveness of the proposed DLC to reduce the voltage rise of the distribution networks with a high penetration of PV system. Figure 5.10 shows the voltage at Phase A before and after the implementation of DLC. The statutory tolerance for voltage excursion on the LV distribution networks is +5% to -10% with reference to the nominal voltage of 240V. Before implementing the DLC, the voltage rises up to 252V which is equivalent to 5.1% above its nominal voltage. The implementation of DLC manages to reduce the voltage level from 252V to 246 V. The DLC manages to reduce the voltage rise by 2.5%.



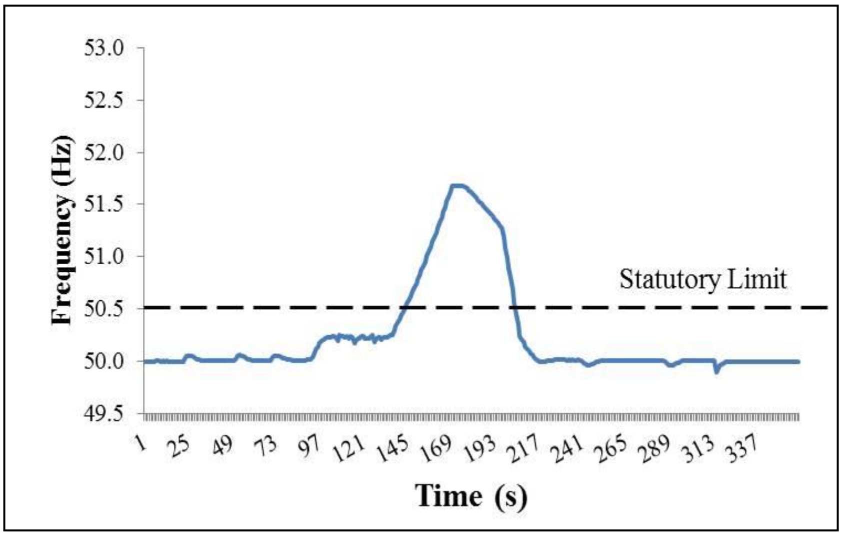
(a)



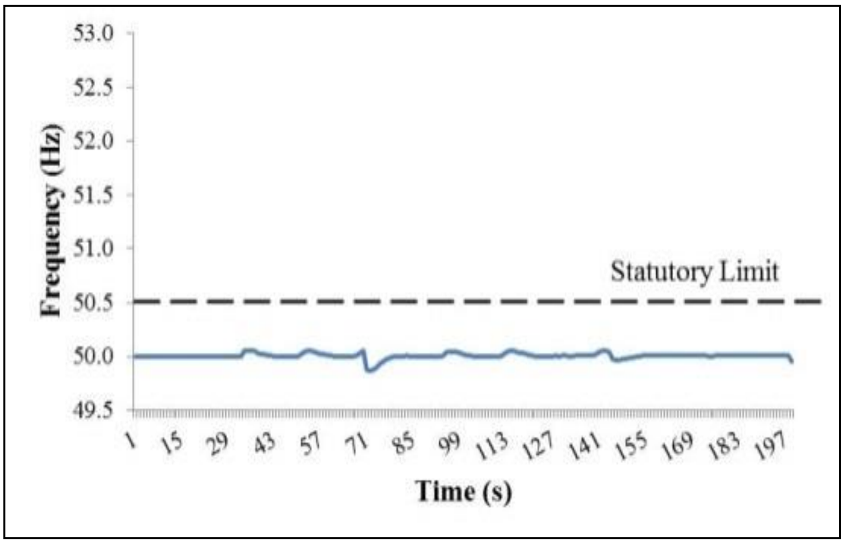
(b)

Figure 5.10: Network voltage magnitude due to the connection of PV on phase A (a) before and (b) after the implementation of the DLC

The network frequency in the LV network with a high penetration of PV systems is shown in Figure 5.11. This figure shows that the surplus energy in the distribution networks can cause the network frequency to rise above 51.7 Hz without any control. The Malaysian standard network frequency should be maintained at 50Hz ±1%. In this case, the PV system's owner can opt to curtail the excess renewable energies or increase the network consumption in order to reduce the network frequency back to 50Hz. It is recommended to fully utilize the available renewable energy rather than curtail it. The proposed DLC is capable of increasing the load consumption automatically when there is a surplus renewable energy in the networks. After the DLC, the network frequency level has been reduced. The maximum frequency after DLC is 50.05Hz.



(a)



(b)

Figure 5.11: Frequency regulation before (a) and after (b) the implementation of DLC in the LV network with a PV system

Figure 5.12 shows the short-tern flicker indices with and without the DLC. It is shown that all the short-time flicker indices are reduced when the load controller is implemented. The maximum flicker index is reduced to a lower value which fulfils the statutory limit. From the case study, the proposed DLC has proven its effectiveness to mitigate the voltage fluctuation and flickers.

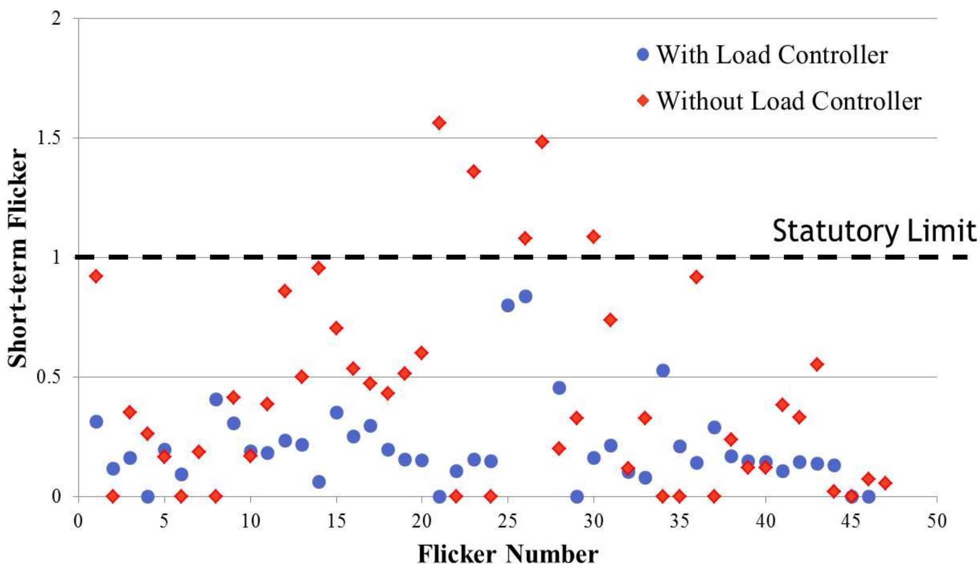


Figure 5.12: Value of short time flickers produced by 1.84 kW PV system on the laboratory network

The voltage fluctuation index is further quantified by using the standard equations (7) as discussed in the previous chapter. Table 5.1 shows the voltage fluctuation and flicker index of the LV distribution networks integrated with PV systems before and after the implementation of the proposed DLC. It is shown that the voltage sensitivity gradient reduces significantly from 5.75 to 2.66 when the DLC is used to mitigate the voltage fluctuation of the affected phase caused by the PV system. It is seen that the voltage fluctuation index reduces from 0.25 V to 0.15 V and the global voltage regulation decreases from 2.35 V to 1.50 V with the DLC. A short-time flicker of 1.56 calculated without DLC has been reduced to 0.84 with the DLC. Similarly, a long-time flicker of 0.72 without DLC is further reduced to 0.34 with the DLC. Theses experimental results identify the proposed DLC as an effective means for reducing both voltage fluctuation and flicker in the utility grid integrated with PV systems.

Table 5.1: Voltage fluctuation and flicker before and after the use of DLC

Standard Test	Statutory Limit	Without DLC	With DLC
Voltage sensitivity curve	NA	5.75	2.66
Voltage fluctuation index	NA	0.25	0.15
Global voltage regulation	NA	2.35	1.50
Short-time flicker	1.00	**1.56**	0.84
Long-time flicker	0.65	**0.72**	0.34

5.6 Case Study 2: On-grid System

5.6.1 Description

This case study is carried out to quantify the voltage fluctuation and flicker with respect to different capacity of the PV system. For each PV capacity, the voltage magnitudes on Phase A, B and C at the point of connection where it is measured and recorded on a regular basis over a period of several weeks. The collection of data is used to calculate all the voltage fluctuation, short-time and long-time flicker indices.

Among all the short-time flicker indices, the maximum value is chosen because it represents the worst case scenario at the point of connection. The PV arrays are connected together through the array adjunction box. Then, the DC power from the PV panel is injected to the PV inverter in which the DC power is converted to the AC power output with 240 V at 50 Hz.

The generated AC power is transmitted to the distribution board with an overcurrent and earth leakage protection before feeding into the energy meter and utility grid or TNB grid. The block diagram of the Malaysian grid connected PV system is shown in Figure 5.13. The objective of this case study is to study the voltage fluctuation, the flicker index caused by the PV systems and also the background flicker caused by the changing loads. The experimental network is shown in Figure 5.14.

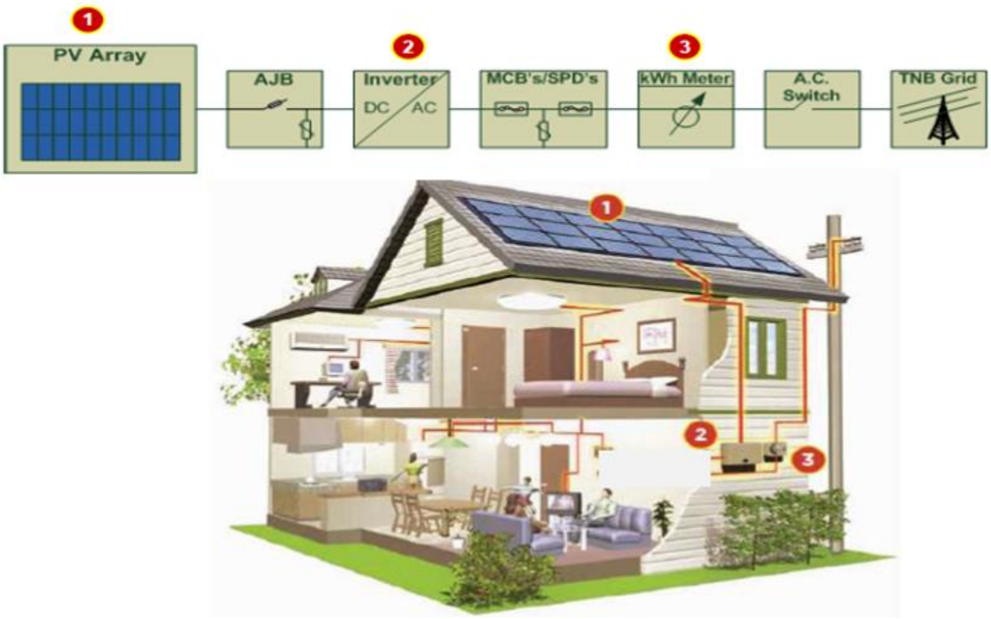


Figure 5.13: Block diagram of grid connected PV system

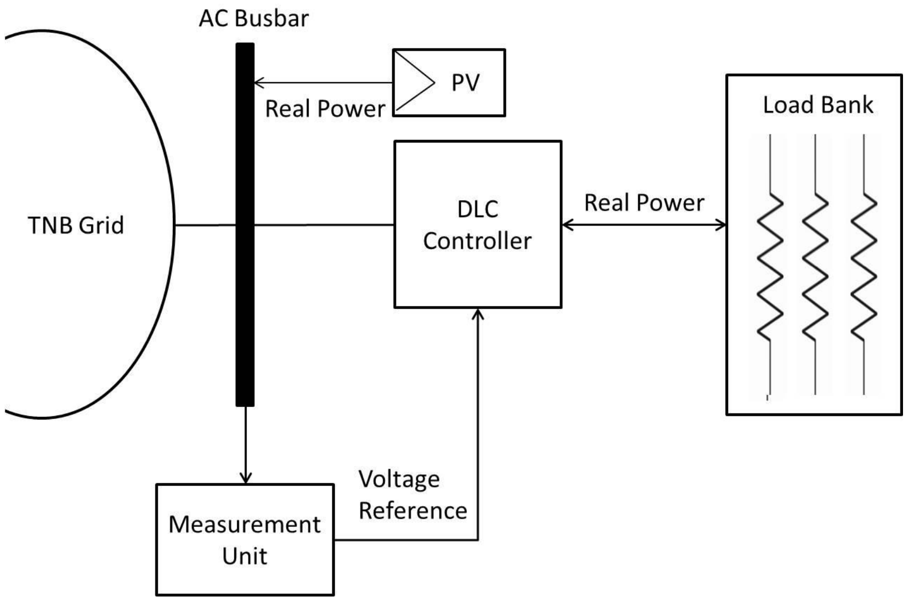


Figure 5.14: Experimental on-grid network configuration

5.6.2 Experimental Results

Figure 5.15 shows that the short-time and long-time flicker indices are 0.231 and 0.125, respectively when the PV system is not connected to the network. These values represent the background flicker indices. These back ground indices can vary depending on the activities in the university premises and changing loads. When a 1.84 kW PV system is connected to the network, the background flicker is combined with the flickers introduced by the PV system to give rise to the total short and long-time flickers of 0.922 and 0.365, respectively as shown in Figure 5.15.

As the PV capacity increases from 1.84 to 7.37 kW on Phase A, the short and long-time flickers grow from 0.922 to 1.158 and 0.365 to 0.509 respectively. The results prove that the capacity of PV system has contributed to the growth of the short and long-time flickers. It is also noticed that the short-time flicker becomes greater than the statutory limit of 1.0 when the PV capacity is 7.37 kW. The index is projected to be much higher if the PV capacity is higher than 7.37 kW.

Figure 5.16 and Figure 5.17 show a significant increase in the short and long-time flicker indices on Phase B and C even though the PV system is connected to Phase A. The flickers on Phase A have caused the flicker indices on Phase B and C to increase. This is because there is mutual coupling or capacitive linkages between the three phases. Any high magnitude of flickers and harmonic currents on one phase can propagate to the other phases through the mutual coupling.

Mutual coupling can occur in any high frequency of the AC power system when they are exposed to each other. The current on the cable or line creates electromagnetic (EM) field and this EM field induces current flow on the other cable exposed to the field. There is EM energy transfer from the first cable to the second cable whereas, the EM energy on the second cable is transferred to the third and the first cables. These experimental results show that the impacts caused by the intermittency of the PV power output can be widely spread across the distribution network. Therefore, it is very important to mitigate the flickers caused by the fluctuation of the PV power output.

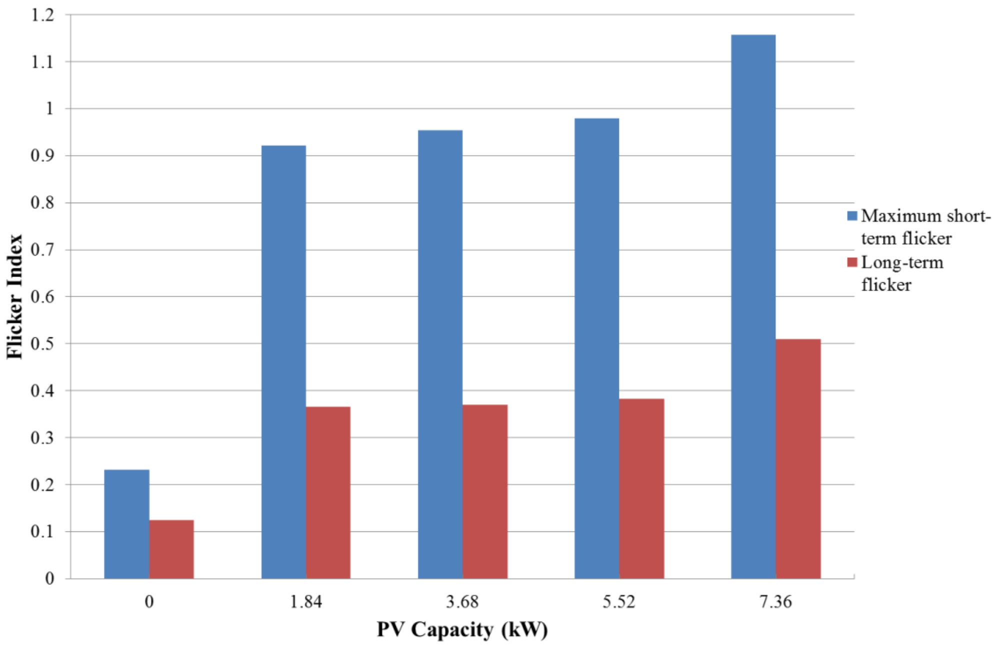


Figure 5.15: Short-time and long-time flicker indices on Phase A with respect to various capacities of PV

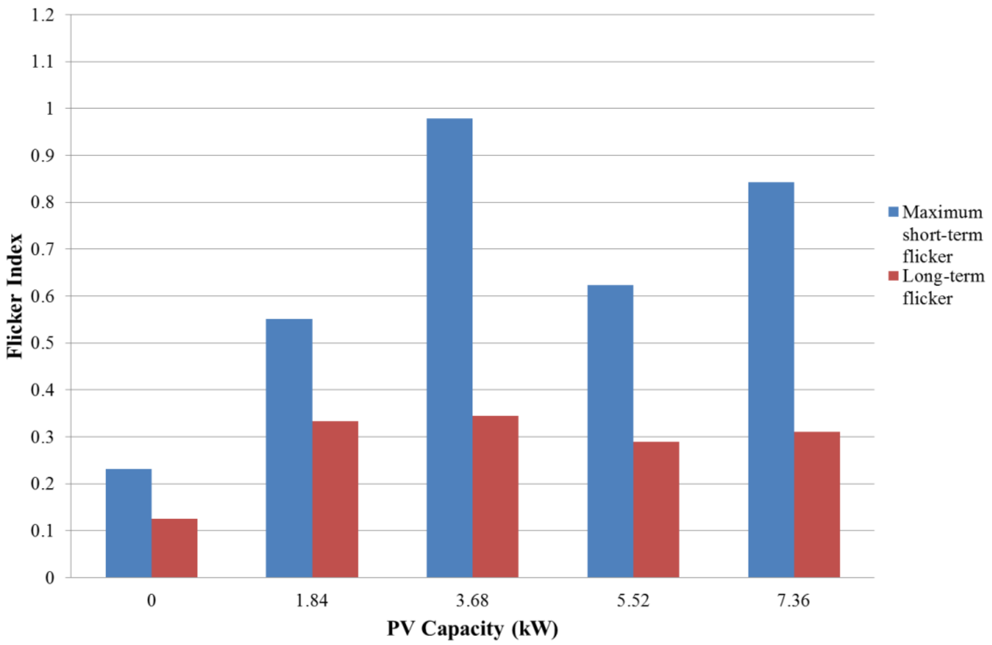


Figure 5.16: Short-time and long-time flicker indices on Phase B with respect to various capacities of PV

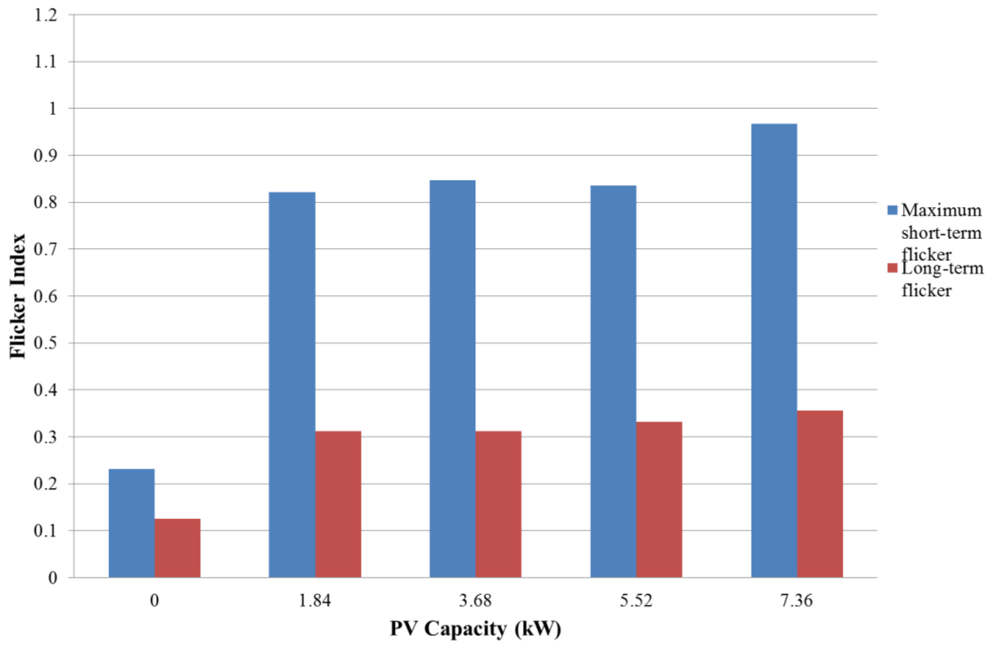


Figure 5.17: Short-time and long-time flicker indices on Phase C with respect to various capacities of PV

Figure 5.18 shows the short-time flicker index with and without DLC. It is shown that the short time flicker indices are reduced when the DLC is implemented. In this case, the flicker does not exceed the statutory limit of 1.0 because the utility grid is strong enough to cater with the small amount of PV power. However, with the increased number and capacity of PVs connected to the utility grid under the FiT scheme, the negative impacts will become more significant. This experiment shows that DLC is an effective measure for reducing the flicker in the LV distribution networks.

The voltage fluctuation and flicker indices are shown in Table 5.2. These values are quantified to evaluate the effectiveness of the proposed DLC. The voltage sensitivity gradient of 0.76 and the voltage fluctuation of 0.289V are reduced to 0.51 and 0.130V, respectively after implementing the DLC in the LV distribution network with PV systems. The global voltage regulation dropping from 1.397 to 1.229 shows the effectiveness of the DLC in reducing the voltage fluctuations caused by the intermittent PV power output. The maximum short-time flicker and long-time flicker are reduced to 0.329 and 0.17, respectively. Even though both the short and long-time flickers are well within the limit without DLC, the flicker indices are projected to increase as the PV penetration increased shown in Figure 5.16. These indices prove that the proposed DLC managed to maintain the voltage fluctuation and flicker index within the acceptable tolerance.

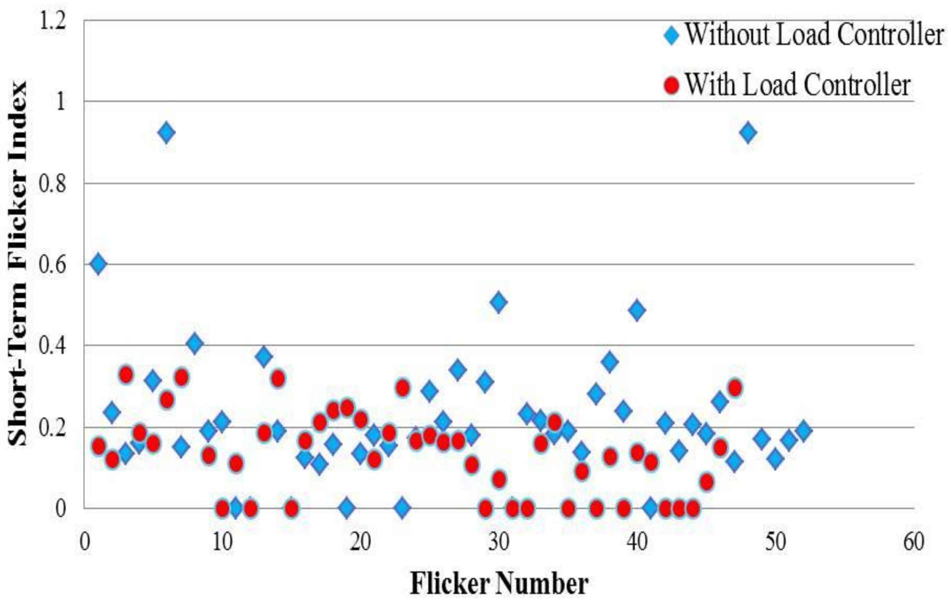


Figure 5.18: Values of short-time flickers produced by the 1.84 kW PV system connected to the utility grid

Table 5.2: Voltage fluctuation and flicker index for grid connected PV system

Standard Test	Statutory Limit	Without DLC	With DLC
Voltage sensitivity curve	NA	0.76	0.51
Voltage fluctuation index	NA	0.29	0.13
Global voltage regulation	NA	1.40	1.23
Short-time flicker	1.00	0.92	0.33
Long-time flicker	0.65	0.37	0.17

5.7 Case Study 3: Off-grid System with Battery Storage

5.7.1 Description

This case study is carried out to study the severity of voltage fluctuation and flickers induced by the PVs in an off-grid system when the battery in the off-grid system is fully charged. The proposed DLC is implemented to the off-grid system in order to mitigate and reduce the voltage fluctuation and flicker. In this case, the experimental network is configured as an off-grid system where the bi-directional inverter, SMA Sunny Island 5048, coupled with the battery bank is introduced as the supply source. The SMA Sunny Island 5048 is equipped with the grid forming capability. It is able to form the grid with 240V AC and 50Hz. A 1.84 kW PV system is connected to the experimental off grid system. The voltage magnitude is collected throughout the experiment. The experiment network setup is shown in Figure 5.19. This experiment is performed during a sunny day so that the severity of the voltage fluctuation and flicker can be analyzed.

The set point for the battery state of charge is set to be 80% in order to protect the battery from overcharge. The SMA Sunny Island will reduce the charging rate when the SOC is close to 80%. In the case of the battery SOC hitting 80%, SMA Sunny Island will adjust the network frequency to be higher resulting to the PV inverter to trip off. This is because the off-grid network frequency is out of the allowable range for the PV inverter to synchronize. The Zigor PV inverter's working range is from 49.5 Hz to 50.5 Hz which comply with the Malaysian frequency regulation. Sunny Island has the capability to instruct the PV inverter to curtail the PV power output when it detects excess power in the off-grid system. However, this feature is only available if Sunny Boy is used as the PV inverter together with Sunny Island. In this work, this feature is not possible due to different branding strategies between the bi-directional inverter and the PV inverter. Therefore, the PV inverter is disconnected when Sunny Island raises the off-grid system frequency.

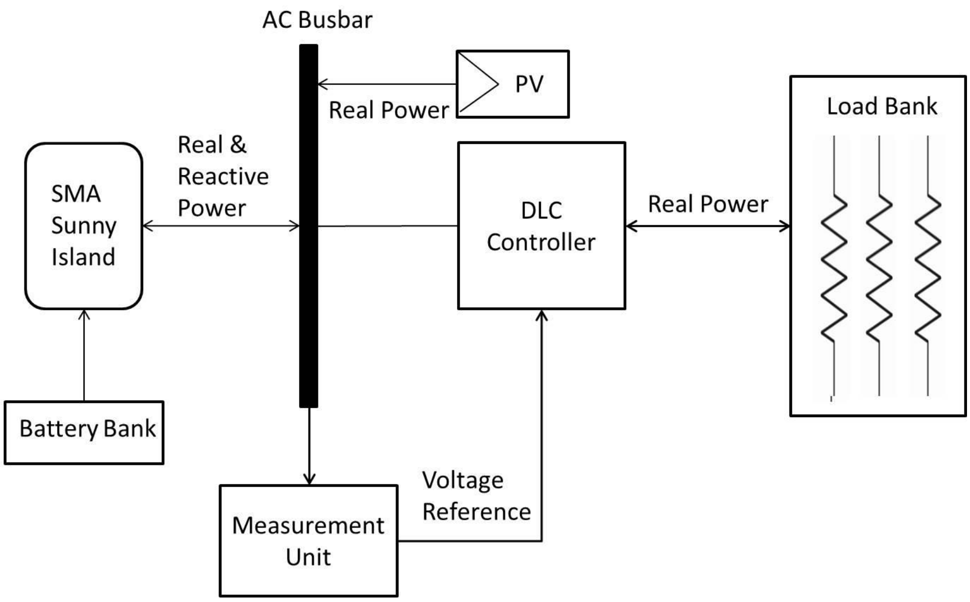


Figure 5.19: Off-grid system integrated with battery storage

5.7.2 Experimental Results

Figure 5.20 shows the network voltage profile and PV power output in the off-grid system without the DLC. Initially, the voltage magnitude remains stable at about 241 V and SOC at this time is equal to 79.6% while the PV power output is 500W. There is a sudden increase of PV power output to 1.5 kW causing the SOC to increase up to 83.2%. At this point, Sunny Island detects that the battery SOC is greater than the set-point limit, which results in the Sunny Island to increase the off-grid network frequency. Once the network frequency is increased beyond the synchronising range, the PV inverter is tripped off immediately. During a sunny day, there is always sunlight available causing the PV inverter to reconnect after it is disconnected. This is not recommended because the PV inverter disconnects and reconnects repeatedly which will reduce the life span of the inverter.

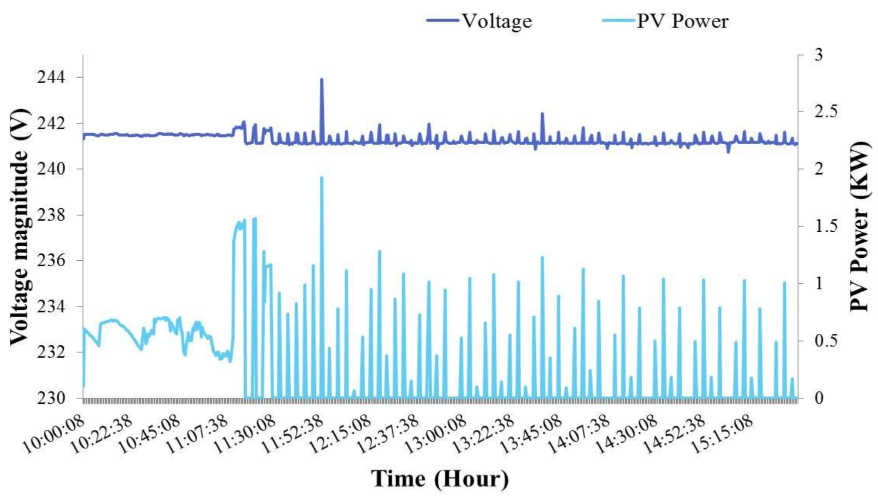


Figure 5.20: PV inverter tripped off after batteries are fully charged (without DLC)

Figure 5.21 shows the network voltage profile and PV power output in the off-grid system with DLC. Initially the SOC of the battery bank is 79.3%. The experimental result shows that the PV inverter runs smoothly throughout the experiment without a single tripping even though the battery bank is fully charged. The voltage level remains stable in between 241 V to 241.4 V. At the end of the experiment, the SOC of the battery bank is 81.6%. The proposed DLC is capable to increase the load consumption automatically to maintain the stability of the off-grid system integrated with PV systems.

In addition to solving the PV inverter tripping issues, DLC is also capable to maintain the voltage supply quality as shown in Table 5.3. The voltage sensitivity gradient is reduced from 0.65 to 0.60 when the DLC is implemented. Voltage fluctuation index of 0.10 and global voltage fluctuation of 0.78 indexes are reduced to 0.02 and 0.10, respectively. Apart from these, both short and long-time flicker indices of 0.61 and 0.33 respectively are reduced to 0.01. . Even though both the short and long-time flickers are well within the limit without DLC, the flicker indices are projected to increase as the PV penetration increase as shown in Figure 5.16.This case study has proven that the DLC is effective to reduce the voltage fluctuation and flicker caused by PV systems.

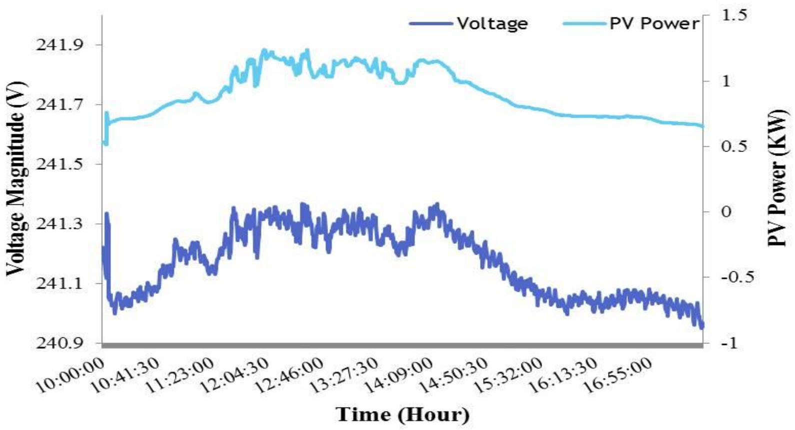


Figure 5.21: PV power output and inverter's status with the DLC

Table 5.3: Voltage quality in off-grid system integrated with PV

Standard Test	Statutory Limit	Without DLC	With DLC
Voltage sensitivity curve	NA	0.65	0.60
Voltage fluctuation index	NA	0.10	0.02
Global voltage regulation	NA	0.78	0.10
Short-time flicker	1.00	0.61	0.01
Long-time flicker	0.65	0.33	0.01

5.8 Conclusion

Malaysia is a tropical country with abundant sunlight. However, climatological data shows that Malaysia is one of the cloudiest countries in the world. This causes the solar irradiation to be highly scattered and fluctuating, hence making the PV power output to be very intermittent. A solar density chart is useful to give a quantitative impression of the PV system's performance. Each element in the solar density chart gives the number of occurrences with magnitude and duration. The Solar density charts for sunny, cloudy and rainy days in Malaysia are identified. Sunny day will have higher PV power output with short duration. The majority of PV power output in a cloudy day is intermediate with longer duration. Whilst, rainy day has a very low PV power output with long duration.

Variable PV power output causes the voltage fluctuation and flicker in the LV distribution network. The most severe voltage fluctuation occurs when the system is configured as off grid without battery storage. This is followed by the grid connected PV system and off-grid system integrated with battery storage. During off-grid configuration, the PV inverter is tripped off when the battery integrated with the off-grid system is fully charged. Short-time and long-time flickers are the highest in an off-grid system. It is seen that the collected data in an off-grid system has violated the acceptable tolerance listed in IEC 61000 3-3 as compared to the other network configurations. The proposed DLC is an effective means to mitigate the voltage fluctuation and flicker in the LV distribution networks, both on-grid and off-grid.

DLC is an effective means of reducing voltage fluctuation and flicker by switching on or off the power resistor very rapidly to compensate the sudden increase or decrease in the PV power output. The DLC activates the power resistor or load when there is an excess power in the network and vice versa. DLC works well in both on-grid and off-grid systems. Without DLC, short-time flicker index in off-grid system with PV is 1.56 whilst, long-time flicker is 0.71. These values deviate from the allowable limit set by IEC

61000-3-3 standard. The voltage fluctuation and flicker index are reduced below the statutory limit with the use of DLC.

CHAPTER 6

EVALUATION OF THE SURVEY RESULT: MALAYSIAN ENERGY EFFICIENCY INITIATIVE AND VIABILITY OF DLC IMPLEMENTATION

6.1 Introduction

The conventional direct load control is part of the demand side management by the utility company to control the peak demand on the national grid and to prevent a major blackout. A novel DLC method is proposed to mitigate the voltage fluctuation and flicker problems as described in Chapter 5. DLC involves the participation of both the utility and consumers. However, consumers play a major role in the DLC program. EE and DLC are widely recognized as an effective means of improving the power system quality and security. However, the implementation of DLC is relatively low in Malaysia. Therefore, beyond studies on the technical aspects of the DLC, it requires a transition of the electricity consumers' behavior and also the awareness of EE and DLC among them. Hence, surveys are conducted to study the social and psychological impacts of DLC. Specifically, this survey is conducted to improve the understanding on how consumers perceive, and respond to the EE and DLC implementation in Malaysia. This chapter illustrates the survey design, the Malaysian EE behavioral aspects and also DLC acceptance level. It contributes to the literature by providing a better understanding on the perceptions and behavior of the electricity consumers about the possible deployment of DLC. This is the first public survey that is carried out in Malaysia focusing on EE and DLC.

6.2 Survey Design

The designed questionnaire is distributed among the residents in Malaysia. The surveys are conducted through an online tool, namely KwikSurvey. Initially, a sample size calculator from the Creative Research Systems is utilized to determine the sample size of the survey. The sample size reflects the numbers of survey that needs to be conducted. To calculate the sample size of the survey, the Malaysian population, confidence level and error margin are the input data to the calculator. The confidence level indicates the percentage of the certainty in this survey. Therefore, a confidence level and error margin is set to be 95% and 3%, respectively. To achieve 95% of the confidence level with a 3% error margin, approximately 1000 survey are required, out of 28 million residents in Malaysia. A total of 1000 surveys are distributed. Unfortunately, 10 of the 1000 residents did not finish the survey questions. Hence the total sample collected is 990.

The questionnaire consists of two sections. The first section assessed the awareness of Malaysians on monthly electricity consumption, environmental pollution due to electricity generation and energy conservation habits. Close ended questions are listed in this part in which the respondents have a choice of yes/no to express their awareness. The second section has the questionnaire on the acceptance level of the respondents on DLC with and without incentives. The respondent is required to express his/her willingness based on a scale of one to five points. FIVE represents that they are willing to do so and totally agree with it while ONE represents that they do not agree to do so and not likely to be involved. Each question is also measured as the mean response. The mean value below three indicates a negative response while more than three indicates a positive response from the respondents.

Overall, we have 55% of female respondents and 45% male respondents in this survey. This survey analysis is based on the respondents' current location, whether they are from Peninsular Malaysia, Sabah or Sarawak. An analysis on the difference between the residents of the Western region (Peninsular Malaysia) and the Eastern region (Sabah and Sarawak) is conducted. The survey targeted youngsters as the author foresees DSM and EE as the future trends of an active management system of distribution networks. Therefore, 69% of the young respondents are between 20 to 30 years old as shown in Figure 6.1. Table 6.1 shows the respondents' details based on their current location, gender and age level. Figure 6.2 shows that 41% and 24% of the respondents are likely and very likely to participate in the energy efficiency related activities, respectively. This result shows the positive response from Malaysian youngsters to go for energy efficiency. A sample of the survey is shown in Appendix A.

Table 6.1: Respondents' detail

	Peninsular Malaysia	Sabah and Sarawak
Respondent (no. of people)	506	484
Gender (% of male)	45	45
Average age	24	29

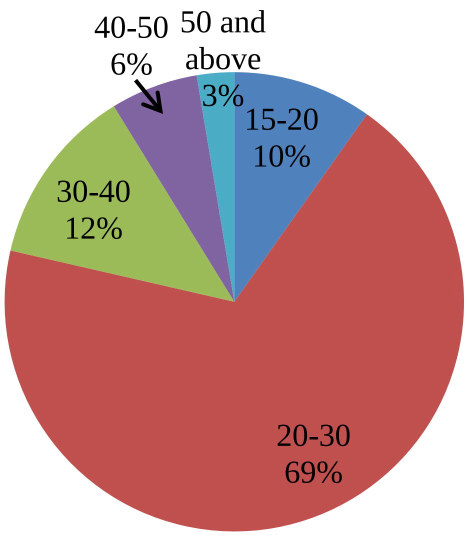


Figure 6.1: Age range of the respondents

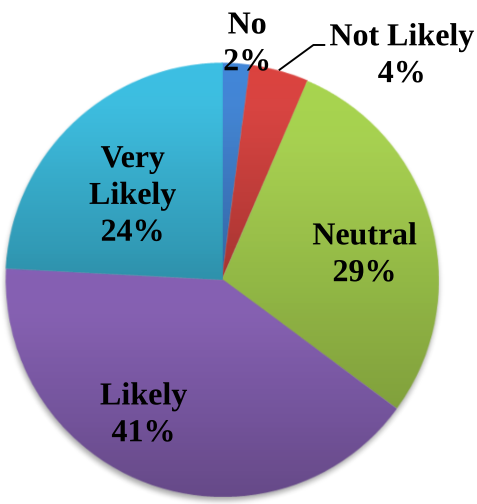


Figure 6.2: Malaysian youngsters' intention to go for energy efficiency

6.3 Malaysian Energy Efficiency Initiative

6.3.1 Awareness on Monthly Energy Bill

As a consumer, it is important to have awareness on the electricity consumption. Unnecessary usage can be reduced through the awareness. In Malaysia, the utility company has a fee structure that reflects the consumption amount in kWh and the total amount of the electricity bill. It is encouraged to be aware of our own electricity consumption, and by knowing the consumption breakdown enables consumers to reduce the electricity consumption. Table 6.2 shows the awareness of Malaysians on their electricity consumption and amount paid. The survey results show that 76% of the total respondents are aware of their electricity bill while 63% of the respondents are aware of their monthly electricity consumption. This result shows that Malaysians are more concerned about the amount to pay for electricity bill rather than the amount of energy consumed. Residents in Sabah and Sarawak are more concerned about their electricity bill as compared to Peninsula Malaysia. Figure 6.3 shows that 58% of the Malaysians are aware of the monthly electricity consumption in kilowatt-hour and money paid to the utility company. About 19% of the respondents neither know their electricity consumption nor the total amount they pay. A majority of those who know their electricity bill are aware of the energy consumption in kWh. Consequently, Malaysians have a very high awareness on the electricity consumptions and their electricity bill.

Table 6.2: Percentage of Malaysians' awareness on their monthly electricity bill

	Peninsular Malaysia	Sabah and Sarawak	Overall
Awareness on monthly electricity bill (in Ringgit Malaysia)	74%	77%	76%
Awareness on monthly electricity consumption (in kWh)	61%	63%	63%

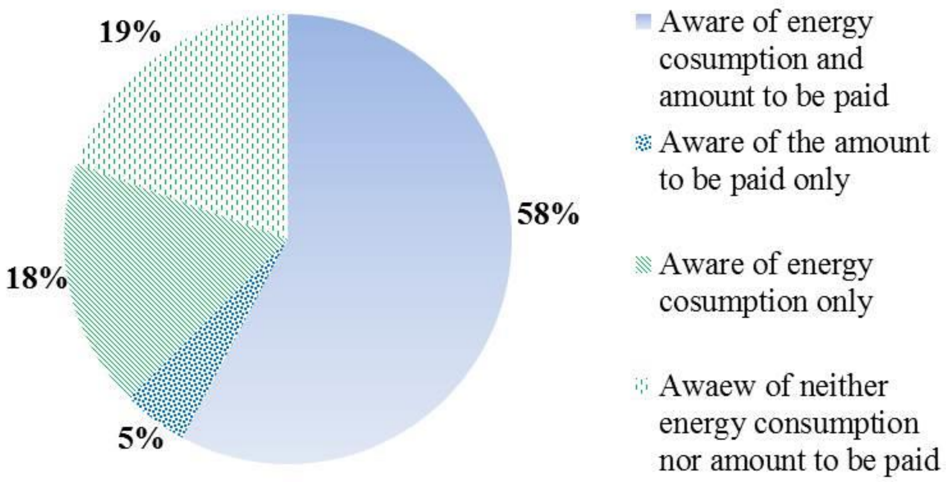


Figure 6.3: Malaysians' awareness on electricity consumption and the amount to be paid

6.3.2 Environmental Consciousness

The conventional way of power generation contributes to environmental pollution. Malaysian electricity generation mainly depends on fossil fuels such as coal, natural gas and distillate oil, which generate pollutants and categorized as non-renewable energy sources. Studies show that Malaysian electricity production emits 0.656 $kgCO_2$ per kWh (Defra/ DECC, 2012). According to the previous research by Steg, (2008), people often do not acknowledge the relationship between energy use and environmental pollution. So they fail to see the necessity of energy saving. The consciousness of Malaysians on the pollution caused by the power generation was assessed in this survey. Table 6.3 shows that 77% of the total respondents know that electric power production cause GHG emission and pollute the environment. It is noticed that people in Peninsular Malaysia have a slightly higher environmental consciousness compared to that of Sabah and Sarawak. Figure 6.4 shows that only 44% of the 77% respondents who know that electric generation produce pollutant are willing to spend additional money to purchase energy efficiency products. These results show that most of the Malaysians recognize the relationship between environmental pollution and the use of electricity but lack of initiative to purchase EE products. This might be because of the higher price of EE products compared to the conventional appliances.

Table 6.3: The environmental consciousness from the respondents in Malaysia

	Peninsular Malaysia	Sabah and Sarawak	Overall
Knowledge that electricity generation causes pollution	78%	76%	77%

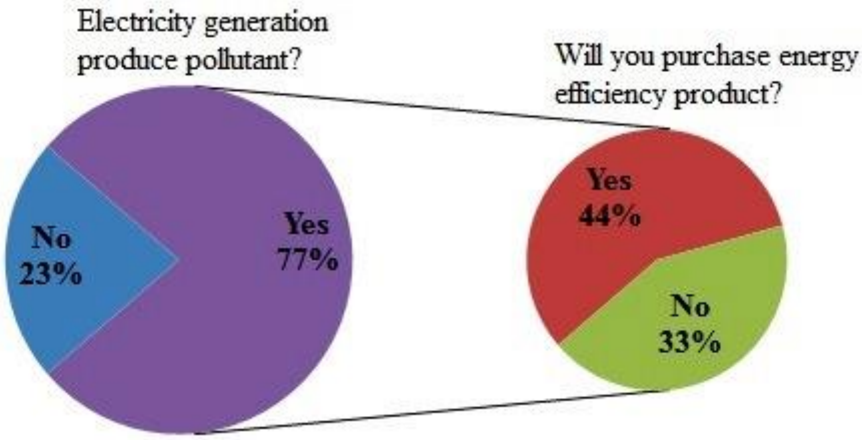


Figure 6.4: Respondents' willingness to purchase EE products with respect to environment consciousness

6.3.3 Energy Conservation Behaviour

Switch-off an appliance when it is not in use. This should be the first step for energy management. Energy conservation refers to the habit of reducing energy consumption by using less energy. Table 6.4 shows the survey results of the respondents on conservation behavior in Malaysia. The result indicates that a relatively high percentage of the respondents tend to turn off home appliances that are not in use. The percentage of energy conservation behavior is the same in the Western and Eastern regions of Malaysia which is 89%. Figure 6.5 shows a majority of the people (72% out of the 77%) who know that electricity generation causes environmental pollution have the initiative to switch off the appliances that are not in use.

Table 6.4: Malaysian behaviour on conservation of energy

	Peninsular Malaysia	Sabah and Sarawak	Overall
Turn off home appliances when it is not in use	89%	89%	89%

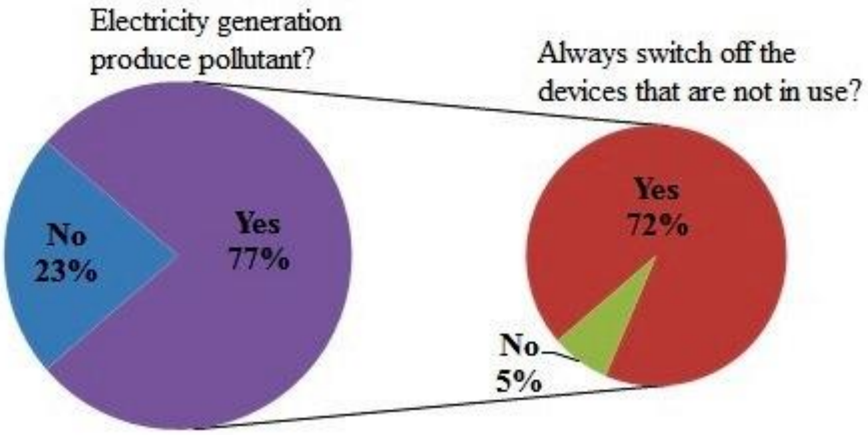


Figure 6.5: Energy conservation behaviour with respect to environmental consciousness

6.4 DLC Acceptance Level

From a utility company perspective, a DLC could help to reduce peak demand, reduce energy generation cost and hence increases organization revenue. However, the implementation of DLC depends on the willingness of electricity consumers to accept them. DLC control might have a negative impact on the consumer's comfort and convenience. A research by Zhang et al., (2011) showed that the consumer is willing to accept DLC if the effect on the consumer is insignificant, for example short interruption time. DLC refers to mechanisms to manage the customer's power demand based on the electric power grid conditions. There has been a recent upsurge in the interest and activity of smart grid, primarily due to the increasing penetration level of renewable energy resources such as solar and wind energies. The DLC enhances the connectivity between utility and customer and hence, enabling a more flexible power system.

6.4.1 DLC without Incentive

In this survey, the DLC programs refer to the programs in which utility can remotely shut down or control a customer's electrical equipment especially water heater or thermal storage to address voltage fluctuation and flicker caused by the variable power output from the PV systems. To explore the acceptability of DLC in Malaysia, a survey is conducted and the result is shown in Figure 6.6. The mean value of the point given by the respondents is calculated as follow:-

$$Mean = \frac{\sum Po\text{int } from\ respondents}{Number\ of\ respondent} \tag{12}$$

Table 6.5 shows the mean value of the Malaysian acceptance level of DLC. The survey shows that the acceptance level of DLC among the respondents in Malaysia is 2.51. This mean the value indicates that Malaysians give a negative response and are not ready for the DLC deployment. However, the survey results show that the respondents from the Peninsular Malaysia are more willing to accept the implementation of DLC as compared to that of Sabah and Sarawak.

Table 6.5: Mean value of Malaysian acceptance level of DLC

	Peninsular Malaysia	Sabah and Sarawak	Overall
Mean value of acceptance level of DLC	2.57	2.45	2.51

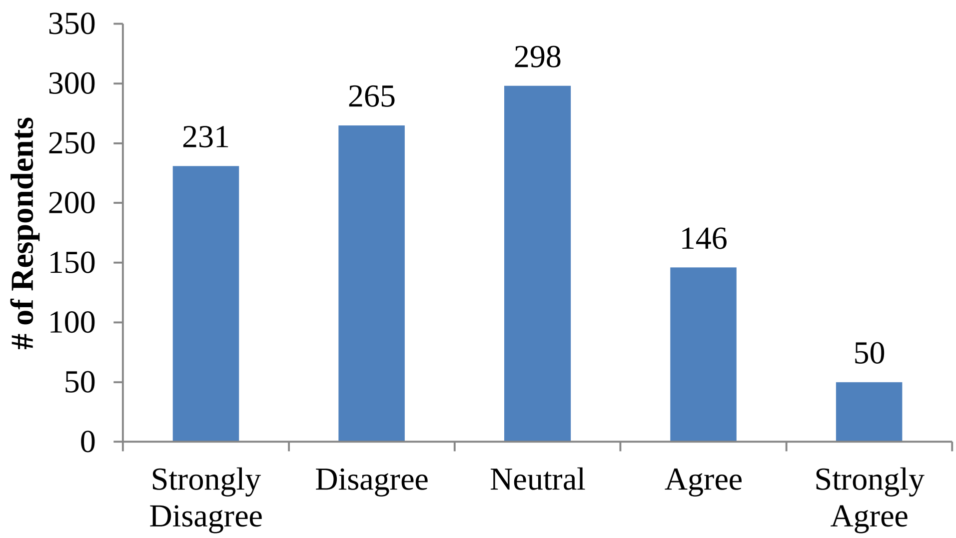


Figure 6.6: Acceptance level of DLC in Malaysia

6.4.2 DLC with Incentive

An incentive based DLC provides motivation for participating customers to allow a third party to control their home appliances, for example, water heater and thermal storage. Past research shows that fostering demand response through incentive based programs will help to improve efficiency, reliability and sustainability (William, 2009). Further questions sought to determine the user response on DLC implementation with incentive. Figure 6.7 shows that Malaysians have a positive response on the DLC implementation with incentive. A mode value of 4 indicates that consumers are willing to take part in the DLC with incentive. Figure 6.8 shows that the mean of the acceptance level in the DLC implementation is increased from 2.51 to 3.67 if the respondents are rewarded with incentive. The overall results also show that the acceptance level of the respondents from Peninsular Malaysia, Sabah and Sarawak are increased if the DLC participations are rewarded with incentive.

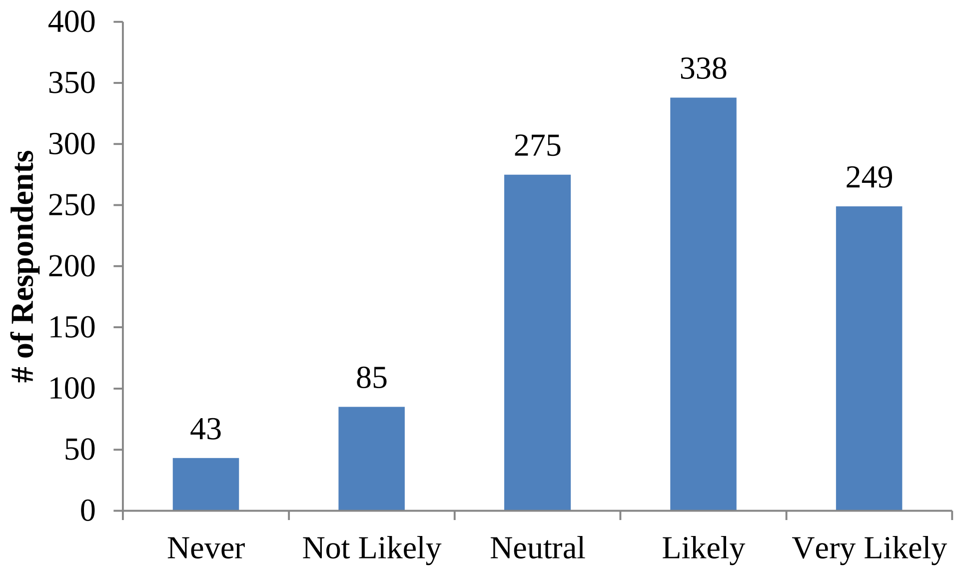


Figure 6.7: Acceptance level of DLC with incentive

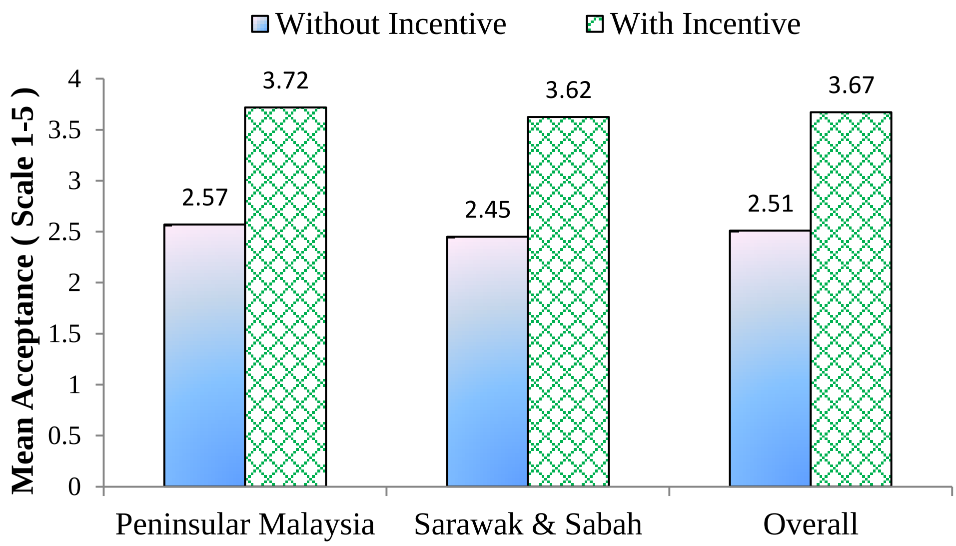


Figure 6.8: Acceptance level of DLC with and without incentive

6.4.3 DLC with lower electricity tariff

In addition to the given incentive for DLC participation, utility can opt to lower the electricity tariff for those who take part in the DLC program. This survey further studies the response to the DLC program if the electricity tariff is reduced as a reward for the DLC participation. Figure 6.9 shows that there is a positive response from the respondents on this option. Overall, the survey results show that Malaysians are willing to join the DLC program if they are rewarded with a reduced electricity tariff. Figure 6.10 shows the comparison between the acceptance level of the respondents on the DLC participation with a normal electricity tariff and a reduced tariff.

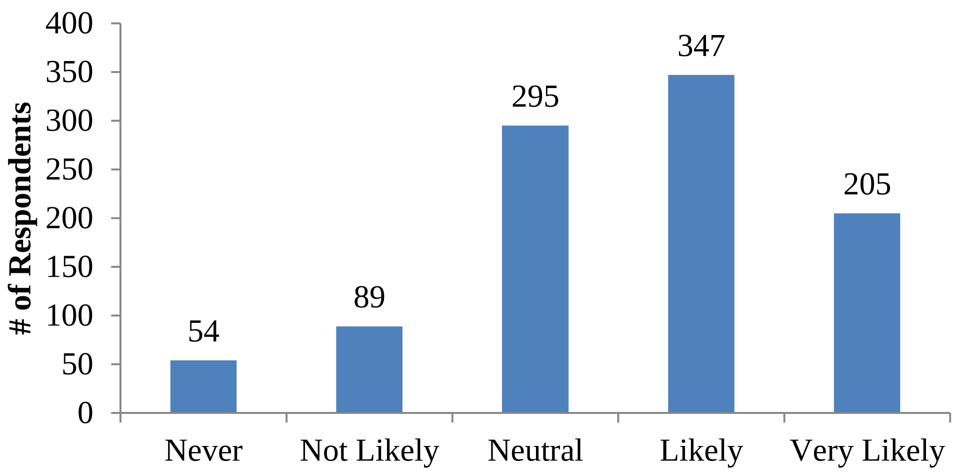


Figure 6.9: Malaysians' response to DLC implementation by giving a reduced electricity tariff

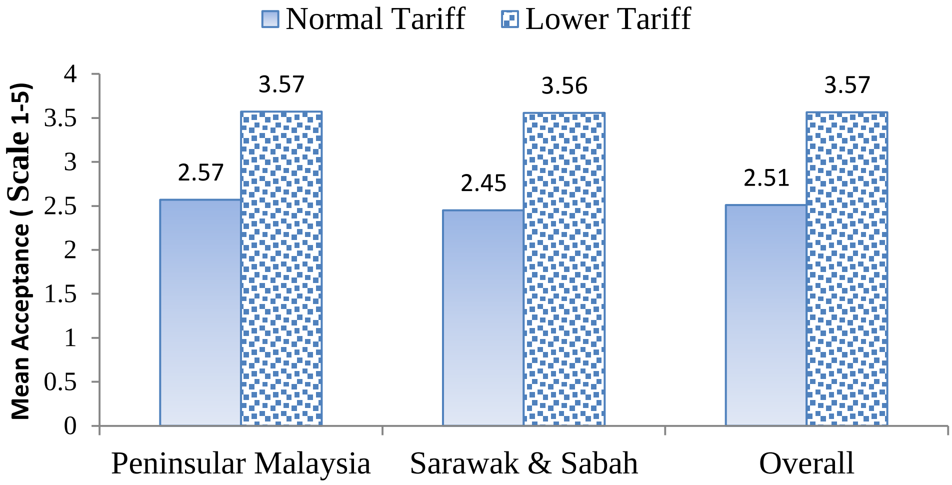


Figure 6.10: DLC implementation with normal and reduced electricity tariff

6.5 Conclusion

A survey questionnaire is designed to study the social response on Malaysians' EE consciousness and DLC acceptance level. A total of 990 samples are collected with a confidence level of 95% and an error margin of 3%. Majority of the respondents are youngsters aged between 20-30 years. The level of electricity consumption awareness is nearly the same in the western and eastern regions of Malaysia. Only 5% of the respondents are not aware of their own electricity consumption and the total amount of their electricity bill. In the context of environmental consciousness, 77% of the Malaysians are aware of the relationship between energy use and environmental pollution. 89% of the respondents have the energy conservation habit such as switch off the appliances when not in use. Overall, Malaysians have a high EE initiative, environment consciousness and energy conservation habit.

However, a mean value of 2.51, indicating negative response from the respondents, shows that majority of the Malaysians are not keen to participate in the DLC program. Introducing rewards and incentives are able to foster the DLC implementation. This is proven through the survey results where the mean value is increased from 2.51 to 3.67 if the respondents are rewarded. In addition, the mean acceptance level is increased from 2.51 to 3.57 if the utility company is willing to reduce the electricity tariff for their participation. As a conclusion, Malaysians are aware of the energy efficiency and energy conservation. However, Malaysians are not ready for DLC implementation. This program can be fostered if the utility company introduces incentives to encourage the participation.

CHAPTER 7

DISCUSSION AND CONCLUSIONS

7.1 Discussion

Photovoltaic systems are recognized as a potential renewable energy source in many countries especially in the tropical regions because of the large amount of solar irradiation available throughout the year. However, some of the tropical countries are surrounded by the sea. Therefore, an enormous amount of clouds are generated by the warm air and then carried to the main land by the seasonal winds. The passing clouds can shade the photovoltaic systems, causing the PV power output to fluctuate frequently throughout the day. The substantial fluctuation of the PV power output can cause the voltage magnitude to vary, and hence resulting in flickers to the customers. These flickers can be an issue of great concern.

The simulation result shows that non-centrally planned PV distribution can cause serious technical problems as compared to that of centrally planned PV system installation. It can also be noticed that the voltage supply quality can be degraded by the growth of PV systems without proper coordination before installation. To allow for more grid connected PV systems, a pre-installation study should be performed and planned. The allowable PV capacity that can be installed in commercial networks under centrally and non-centrally planned PV without violating any of the technical issues were found to be 8.0 kW and 3.0 kW, respectively. In the residential networks, the allowable PV capacity without violating any technical issues is 1.0 kW for non –centrally planned PV systems and 7.0 kW for centrally planned PV systems distribution.

The voltage fluctuation and flicker emission have been identified as the major concerns in the Malaysian LV distribution networks integrated with PV systems. This is because of the intermittent PV power output in Malaysia due to the passing clouds. This dissertation has proposed a method to mitigate the voltage fluctuation and flicker caused by the fluctuating PV power output.

In this research, the PV power output and the voltage magnitude are measured and recorded on a regular basis over a period of time. The collected data shows the characteristics of the PV power output in Malaysia. It is shown that majority of the peak PV power output are within short durations. The PV power output changes very frequently and rapidly. This is caused by the large number of clouds passing over the PV panel that reduces the solar irradiation substantially.

The short and long-time flickers with respect to various PV capacities and voltage fluctuations are calculated based on the collected data. The experimental results show that the severities of the flickers grow as the PV capacity is increased. Some of the short-time flickers even exceed the statutory limits. In addition, the presence of the mutual coupling establishes an electrical connection between phases. As a result, any severe flicker that occurs on one phase can propagate to the other two phases through the mutual coupling between them. Therefore, the effects of the flickers can be widely spread out across the LV distribution networks.

A novel direct load controller is proposed to mitigate the voltage fluctuations, and hence the short and long time flickers. The proposed DLC is simple, cheap and effective. It consists of several resistors and solid state relays. The DLC is designed in such a way that it provides a dynamic response to the rapid voltage change. The DLC activates and deactivates the resistors very rapidly in order to compensate the voltage fluctuation and flickers. The load controller makes use of the real power to change the network voltage because real power always has a higher influence as compared to that of the reactive power, due to the higher resistive characteristics of the network. Therefore, the reactive load does not give a big impact when comes to low voltage distribution networks.

The proposed DLC is used to mitigate the voltage fluctuation and flicker on LV distribution networks. However, the implementation needs the participation from electricity consumers. A survey is designed to investigate the response from Malaysian customers to implement such DLC to control their home appliances. This survey is important to identify whether the Malaysian market is ready for demand side management. Through the survey results, we can conclude that it is possible to implement DLC if the electricity consumers are rewarded for their participation.

7.2 Key findings

The key findings of this research study are listed as follows:-

- The technical issues caused by the non-centrally planned PV system include voltage rise, voltage unbalance and reverse power flow. However, the PV system improves the voltage profile and reduces the total network power losses if the total PV capacity does not exceed the power demand.
- Malaysia is one of the cloudiest countries in the world; many high PV power outputs occur within a short duration, less than 5 minutes. High PV power outputs drop down suddenly instead of gradually.
- The intermittent power output from PV system generates a large amount of voltage fluctuation and flicker. The voltage fluctuation and flicker are proportional to the capacity of PV system. As the capacity of PV increases, the voltage fluctuation and flicker also increase.

The voltage fluctuation and flicker reduce the power supply quality. Hence, it is important to mitigate the voltage fluctuation and flicker for on-grid and off-grid PV systems. The experimental results show that the voltage fluctuation and flicker can be effectively reduced by the proposed DLC. Short and long –time flickers are reduced within the statutory limit of 1.0 and 0.65

respectively. A DLC is proposed in this dissertation mainly because, its component is cheap, and also it is an effective means for reducing the voltage fluctuation and flicker by switching the power resistor on and off very rapidly to compensate the sudden increase or decrease in the PV power output.

Beside the technical aspect, the DLC program involves social and psychological aspects on the customer side. Hence a survey questionnaire is distributed. The survey result shows that Malaysians are aware of their electricity bill, practice energy conservation and have environmental consciousness. The DLC program is viable in Malaysia only if customers are rewarded with incentives or with a reduced electricity tariff for the participation in DLC program. 58% of the respondents are willing to participate in the DLC program if they are monetary rewarded.

7.3 Publication

The findings from this research have been published/submitted to the following journals by this author:

No	Title	Journal	Status
1.	Impacts of centrally and non-centrally planned distributed generation on low voltage distribution networks.	International Journal of Smart Grid and Clean Energy, vol. 1, no. 1, September 2012, pp. 60-66. ISSN 2315-4462	Published
2.	Grid-connected photovoltaic system in Malaysia: A review on voltage issues.	Renewable and Sustainable Energy Reviews, vol. 29, January 2013, pp. 535-545.	Published
3.	Experimental study on flicker emissions by photovoltaic systems on highly cloudy region: A case study in Malaysia.	Renewable Energy	Accepted

7.4 Future work

The current work focuses only on voltage fluctuation and flicker caused by the intermittent power output from the PV system. In addition to the PV system, future study can include the wind energy which is also a renewable energy source with intermittent characteristics. Apart from this, the harmonics from the PV inverter can be studied.

This study uses a controllable load bank to evaluate the effectiveness of the DLC to mitigate voltage fluctuation and flicker. In future, a controllable real domestic load that is suitable for this application is to be identified. Besides that, the current experiment is carried out in the lab scale LV distribution network. The proposed DLC can be tested and validated directly at utility LV distribution networks, where it matters.

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Appendix A

Survey of Energy Efficiency and Direct Load Control

1. Respondent Details

Name	(optional)	Age	
Gender	Male / Female	Date	
Current Location	Peninsula Malaysia / Sarawak / Sabah		

2. Energy Management. (Please delete whichever is not applicable Yes / ~~No~~)

Are you aware of your monthly electricity bill?	Yes / No
Are you aware of your monthly electricity consumption (kWh) or are you aware of your home appliances that are having high electricity consumption?	Yes / No
Do you know electricity production also cause environment pollution?	Yes / No
Have you ever purchase any energy efficiency product like CFL (Carbon Fluorescent Lamp) lamp?	Yes / No
Do you have the habit to switch off your home appliances when it is not usable?	Yes / No

In the following section, please rate from scale 1-5 where 1 is not willing or never do it and 5 is willing and always do it. Please circle your rating. 1 2 3 4 (5)

a) If TNB / SESCO / SESB limit your electricity consumption for a periods of time to promote energy efficiency, how willing are you to follow the instruction	1	2	3	4	5
b) Would you permit TNB/SESCO/SESB to control the usage of your home appliances? For example, they are able to switch off selected appliances to reduce the power consumption during peak hour.	1	2	3	4	5
c) How willing are you to participate in program (a) or (b)					
If you can reduce your energy consumption so to reduce the electricity bill	1	2	3	4	5
If you can save energy and help environment	1	2	3	4	5
If you are given incentive to allow utility companies (TND/SESCO/SESB) to do so	1	2	3	4	5
d) If you notice the "Energy Indicator" as shown in Figure 1, how willing are you to switch on/off your electrical appliance to improve energy efficiency.	1	2	3	4	5
e) How willing are you spend additional cost to manage your electricity consumption. For example, to install a building energy management system that indicates your energy consumption so to provide recommendation to improve energy efficiency through management.	1	2	3	4	5