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SIMULATING THE EFFECTS OF GRID-CONNECTED PV SYSTEM IN A RESIDENTIAL AREA USING OPENDSS

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SIMULATING THE EFFECTS OF GRID-CONNECTED PV SYSTEM IN A RESIDENTIAL AREA USING OPENDSS

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A report submitted in partial fulfillment of the requirements for the degree of Bachelor of Electrical Engineering (Industrial Power)

Faculty of Electrical Engineering

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

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I declare that this report entitle "*Simulating the Effects of Grid-Connected PV System in a Residential Area Using OpenDSS*" is the result of my own research except as cited in the references. The report has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

Signature : ………………………………………………………

Name : ………………………………………………………

Date : ………………………………………………………

To my beloved father, mother, family, lecturers and friends for their loving, understanding, care and support.

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Alhamdulillah, thanks to Allah S.W.T because of his blessing and truth, I finally finish my final year project report II successfully. While completing final year project II, there are a lot of people who are helping me until I successfully write a report for this project. During the process of completing my project, I faced with many problems but I can endure it because I got many references especially from my supervisor and my seniors in my faculty.

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ABSTRACT

The impact of high PV penetration into the grid, particularly at the distribution side has been extensively studied. However, most of the available research focuses on North American style systems. This project aims to investigate the effect of high PV penetration in a European-based distribution network, which is the electricity supply system Malaysia is based on. The scope for this work is limited to a residential distribution network. The modelling is done using OpenDSS. The network model used is the IEEE European Low Voltage Test Feeder which consists of 55 loads that represent a generic housing area. Each load point is then equipped with a 4 kW PV system that denotes the typical size of a PV system installation for one house. Next, PV output variability is represented by two sample days of actual irradiance variability obtained from PVSG Lab, FKE UTeM; one for clear day and another for a high variability day. The aspects analyzed were voltage unbalance, voltage rise and reverse power flow. One significant finding of this project is that voltage rise exceeds the standard of 1.05 pu during noon, when voltage at the load side is higher than the transformer secondary side. Besides that, the high variability irradiance has more impact than clear sky irradiance during reverse power flow as the fluctuation of high variability irradiance is fluctuate more often compared to clear sky irradiance.

ABSTRAK

Kesan penembusan sistem PV yang tinggi ke grid, terutamanya di bahagian pengagihan telah dikaji dengan meluas. Namun, kebanyakan hasil penyelidikan tertumpu kepada sistem Amerika Utara. Projek ini menyasarkan untuk menyiasat kesan penembusan PV yang tinggi dalam rangkaian pengagihan berasaskan Eropah, yang merupakan asas kepada sistem bekalan elektrik di Malaysia. Skop bagi kajian ini dihadkan kepada rangkaian pengagihan perumahan. Untuk mencapai objektif, model telah dibuat menggunakan OpenDSS. Model rangkaian yang digunakan adalah *IEEE European Low Voltage Test Feeder* yang terdiri daripada 55 beban yang mewakili satu kawasan perumahan yang umum. Setiap satu titik beban kemudiannya dipasang dengan sistem 4 kW PV yang mewakili saiz lazim untuk pemasangan sistem PV bagi sebuah rumah. Keluaran PV yang berubah-ubah diwakili oleh dua sampel hari sebenar di mana nilai keamatan cahaya diperoleh daripada PVSG Lab, FKE UTeM; satu untuk hari cerah dan satu lagi untuk hari yang mempunyai variasi tinggi. Aspek yang dianalisa adalah ketidakseimbangan voltan, kenaikan voltan dan aliran kuasa balikan. Satu perolehan signifikan daripada projek ini adalah kenaikan voltan melebihi piawaian 1.05 pu sewaktu tengahari, apabila voltan di bahagian beban lebih tinggi daripada voltan di bahagian sekunder pengubah. Selain itu, keamatan cahaya dengan variasi tinggi mempunyai kesan yang lebih besar berbanding dengan keamatan cerah kerana naik turun keamatan cahaya yang lebih kerap.

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CHAPTER 1

INTRODUCTION

1.1 Research Background

Malaysia is a country that is blessed with ample amount of sunlight throughout the year. The government, in their commitment to diversify the fuel resource to include renewable energy began to encourage the use of solar system among Malaysians. Solar radiation can be used to generate electricity for free as it supplies by nature and is continuous. The use of solar radiation does not bring any harm to the earth as it generate clean green energy since there is no dangerous greenhouse gas emissions produced from the process of converting the sunlight to electricity energy. Besides that, solar system is very unique because it does not need large-scale installation, requires low maintenance and does not necessitate continuous supervision. Furthermore, solar system is suitable to be installed at the urban and residential area as it generates electricity quietly. Solar system does not use any equipment that produces noise compare to other renewable energy where they use turbine which produce noise.

One of the attractive renewable energy that uses sunlight for electrical generation technologies that have been widely implemented today is photovoltaic (PV) [1]. Photovoltaic (PV) is the direct conversion of light into electricity. Photovoltaic module which is a number of solar cell electricity connected and mounted in frame is designed to supply electricity at certain voltage. Current that is produce is directly dependent on amount of light strikes the module. Several connections of PV panels can supply enough power for household, huge electric utility or industrial applications and hundreds of PV panels can be interconnected to form a single, large PV system. Photovoltaic has three common configurations which is grid connected system, stand alone system with storage and stand alone system with directly connected loads [2]. Among the three common configurations, grid-connected PV system is the lowest cost and the lowest maintenance type of residential solar electric system [3]. Grid-connected PV system is also known as “grid-tied” or “on-grid” solar system. This is because PV panels are connected to the local mains electricity grid.

Urban or residential areas that are using grid-connected PV system to supply power to their electrical appliances can use electricity power from PV solar panel or from normal mains electrical grid. During daylight hours, grid-connected PV system users can use their own electrical energy generated from their PV panels to supply their electrical appliances. But, during the night time, on cloudy time and rainy days where the generation of electricity from their panel drops or is unavailable, grid-connected PV system users get supply from the normal mains electrical grid. Electricity flows back-and-forth to and from the mains grid depend on sunlight conditions and the actual electrical demand at that time. Besides that, the main advantage that it can bring to the users is it can reduce the electricity bills [4].

PV power system can sometimes produce more electrical power than is actually needed by the users, especially during the afternoon when the penetration of sunlight on modules of PV is high and the load demand for residential area is low. The extra electrical power is either stored on batteries or most grid-connected PV system send the extra electrical power to the normal mains electrical grid. When grid connected PV system send the extra generated electrical power to the normal mains electrical grid, it can sometime give bad impact to the networks. High fluctuation of PV power with fast weather conditions does disturb the network voltage stability. Researchers in [5] prove that voltage stability issue does exist in distribution network for residential customers due to high penetrations of photovoltaic (PV). Therefore, this issue is necessary to investigate on the Malaysian distribution network.

1.2 Motivation

Since the issue on voltage instability at the distribution level does occur when the penetration of PV power is high, this issue motivates to study the effect of high PV penetration on a residential distribution network. This project can benefit local utility company, Tenaga Nasional Berhad (TNB) in accommodating higher PV penetration to the Malaysian distribution grid since the maximum penetrations of PV power that can feed to our grid without affecting the grid stability can be known. The significance of research is to study the impact or effects of different penetration of power distributed from grid-connected PV system on the Malaysia residential area distribution networks. In this project, the distribution network will simulate using Open Distribution System Simulator (OpenDSS).

1.3 Problem Statement

Researchers from other countries have proved that high PV power penetration do give negative impact on network stability. However, in Malaysia, photovoltaic (PV) power penetration on the distribution network is still low. Therefore, we do not know how high the maximum penetrations of PV power that can feed to our grid without affecting the grid stability. An investigation needs to be conducted so that we know the maximum PV power penetration level that is allowed to be fed to the grid so that the grid stability can be maintained. It is good to avoid the worst case scenario from happening as grid stability will cause serious concerns for the government and utility company.

1.4 Objectives

The objectives of this project are listed as follows:

1. To simulate a small-scale residential distribution network.
2. To simulate distributed photovoltaic (PV) power in small scale distribution network.
3. To evaluate the impact of distributed photovoltaic (PV) power penetration to the distribution network.

1.5 Scope

The scopes of this project are to investigate the impact or effects of PV power penetration by grid-connected PV systems on residential area at distribution level. A model of small scale residential distribution system will be built and simulated using Open Distribution System Simulator (OpenDSS). OpenDSS is an open-source distribution system simulator which is used specifically to simulate the distribution system. The model of small scale residential distribution will be build follows the standard of European low voltage bus network so that the simulation results are correct and can be applied to the real situation. Besides that, OpenDSS software will be used to generate the penetration of PV power. Lastly, this project analysis only on voltage characteristics effects when there is grid-connected PV systems in a residential area distribution network using OpenDSS software.

1.6 Expected Project Outcome

At the end of the project, the small scale residential distribution network of European low voltage bus network is expected successfully built and simulated using OpenDSS software. Besides that, it is expected that the distributed photovoltaic (PV) power in small scale distribution network is simulated by using OpenDSS software. Furthermore, at the end of the project the impact on voltage characteristics and current of distributed photovoltaic (PV) power penetrates at the distribution network is expected to be evaluated.

CHAPTER 2

LITERATURE REVIEW

2.1 Theory and Basic Principles

Based on problem statement, objective and scope in Chapter 1, a study on the theory and basic principles is done in order to fully understand the project. The necessary theories that related to photovoltaic (PV) effects on grid which are voltage unbalanced, reverse power flow, voltage rise or issues, protection coordination and lastly, flicker and harmonics are included in this sub-topic of Chapter 2. Besides that, details information on Open Distribution Simulator System (OpenDSS) software, OpenDSS architecture model and comparison between European and North American distribution network are stated in this sub-topic of Chapter 2.

2.1.1 Voltage Unbalance

Voltage unbalance happens when voltage magnitude of each phase of three phase network is dissimilar or the phase angle between two phases of the three phase network is different [6]. As an example, when there is high penetration of PV power at phase-A compared to phase-B and phase-C, voltage will be higher at phase-A than other phases. As the voltage magnitude is not the same at each of the phases, the voltage is unbalanced and overvoltage is occur at phase-A. The case of the example is occurred when the installation of integrated PV to the grid is not controlled at each phases. This scenario is supported by [7] and [8] where in the investigation, the researchers found that the uncontrolled installation of integration PV on grid on each phases at distribution network does make the grid became unbalanced. This situation creates uneven voltage rise as PV penetration on each of the phases is distribute unequally. Therefore, voltages are unbalanced in the network and disrupt the stability of the grid.

In small region, PV power swing fast followed the fast changing of weather conditions and cloud movement, as a result uneven voltage rise at the distribution level creates even worst condition on grid stability. According to [9] the unbalanced voltage at the phases can be reducing by distribute PV power in each of the phases equally. When same researcher in [7] extended investigation on voltage stability problem at residential area in [5], found that voltage instability occurred at 40% PV power penetration at distribution level. Throughout the investigation, a PV inverter reactive power support scheme is developed to solve the voltage stability problem instead of installing extra devices to solve the problem. Before, in [7] reactive power is not considered as the reactive power will increase the voltage variation in the investigation.

In the research [5] reactive power is included in the analysis as the voltage variation need to be increase so that voltage stability can be achieve. Researcher in [1] also found that 40% is the highest PV penetration that is allowed to penetrate on grid when penetrate the PV on unbalanced network at distribution level. The analysis is conducted in mathematical form on unbalanced voltage variation by using voltage variation sensitivity matrix and observed approximate linearity. Researchers in [5] and [7] both using the different methods in investigate the voltage characteristics, but found the same maximum level of PV penetration that is allowed to distribute among the consumer.

The level penetration of PV power that is found by the researchers can be used in this project to find out what are the effects on Malaysia distribution network. Furthermore, [5] suggested that the location of install the source storage of PV should be at the downstream feeder because according to the investigation, voltage instability problem can also be solve by properly choosing the right location of storage. This action can reduce voltage drop along the distribution line. The suitable types of load to install the right quantity of integrated PV on grid in analyze the unbalanced voltage is better in dynamic load rather than static load.

2.1.2 Reverse Power Flow

Reverse power flow occurs on the grid when the power generates on grid by PV is higher and during that period the load is low. This is the moment that the grid operation at the distribution side becomes most challenging [10]. In the traditional distribution system, the generated power distribute in one way which is from feeder to customer where voltage at the feeder is higher than the connection point at the customer side which is at the load side. But, during the period of high penetration of PV power on grid when the sun irradiation is the highest, PV generate an excessive power which is more than consumer needed.

Therefore, the voltage at the load side is higher than the feeder. As a result, direction of power flow is reversed as most of the time the grid-connected PV system will send the extra electrical power back to the normal mains electrical grid rather than stored the extra power on batteries. Now power flows from the connection point at the load side to the feeder. This situation creates over voltage at the feeder and according to [11] and [12], when over voltage occurred at feeder due to reverse power flow, voltage regulator and protection device coordination is affected during their analysis on voltage characteristics due to high PV penetration at distribution system.

Besides that, the relationship between power and voltage is directly proportional, researcher in [13] found that if the excessive power is distribute to the connected electrical equipments of the household, it can damages the equipments due to voltage is more than needed by the equipments. The excessive power generates by PV lead to many impacts. The reverse power flow on grid leads to overvoltage where it is not acceptable by the regulation as it is affect the behavior of the low voltage grid. Furthermore, as the direction of power flow reverse, the voltage profile also reverses [10].

2.1.3 Voltage Rise Issues

Voltage rise issue arises at both urban and residential areas. Many researchers have investigate on this issues as it bring concern when the penetration of PV on grid expected to be high due to the price of PV falls every year [7]. Voltage rise is happened when the penetration of PV power suddenly goes high in the short period of time. This is due to the fast changing of weather condition. PV power fluctuation depends on weather conditions and affects the voltage fluctuation in distribution networks. Therefore, voltage rise occurs due to fluctuation of voltage on grid.

Usually, in the traditional distribution network, the voltage should fluctuate in the range of 0.95 pu to 1.05 pu. But, the moment the PV power penetrate high, the voltage fluctuate more than 1.05 pu where voltage rise occurred. This statement have been proved by [14], where in the investigation, when there is no penetration of PV on the network, the voltage magnitude is constant which is 0.9690 pu. When there is penetration of PV, the magnitude voltage rise and fall between 1.02 pu to 1.14 pu in each hour. It shows that voltage rise occurred because of PV penetration.

There is a lot of voltage control methods can be used to mitigate this issue where PV and voltage control devices need to incorporate communication to reduce the voltage raise issues [11]. The methods of voltage control that have been proposed by several researchers to deal with voltage variations brought by PV generation are PV power curtailment [15], storage management [16], PV reactive power injection [17-19] and communication based coordination and intelligent control [20-22]. Unfortunately, not one of these methods is implemented as PV system only produce real power and do not accept any of the control voltage methods.

According to [7], to realistically simulate effects of high PV penetration in a distribution network, an unbalanced system must be used. The researchers argue that if a balanced system is used, the outcome on the voltage increment will be wrong, leading to incorrect PV power curtailment or implementation of expensive supporting equipment. Furthermore, different voltage drop levels might occur. To prove this, the researchers developed an unbalanced distribution network using a generic IEEE 13 bus system built using PSCAD and MATLAB/SIMULINK and compared the simulation with a balanced network.

The results of the simulation proved that for an unbalanced network, each phases react differently to changing PV power output. Therefore, one phase can have a voltage rise that exceeds the critical value while the other two remain stable. This cannot be seen in balanced network where the bus voltage is assumed to be high and voltage variation can be ignored.

Besides that, the researcher created method of estimating voltage variations special assumption that can be used for unbalanced network analysis because the results of voltage variations using the three phase balanced assumption cannot be used for unbalanced network as the result leads to wrong conclusion. By using the method created, the researcher founds that voltage rise is not serious and even additional PV can be install into the network which is far from perception. Therefore, the balanced network or assumption cannot be used in analyzed the unbalanced network.

For [23], to investigate on the voltage rise, the worst case must be used which is lets the load be at minimum because load also affect the incremental of voltage in the network. What is found in the investigation is, with the low load, voltage rise will happened at upstream and this situation created even higher voltage rise at low voltage side. Throughout investigation in [24] by using method of OpenDSS to simulate the distribution network, the researcher from United State found that voltage rise occurred when the PV power penetration on the network is more than 30% but the researcher increase the PV penetration to 50% and found that with that level of PV penetration issue voltage rise still can endured.

2.1.4 Protection Coordination

Traditional distribution network operation, control and protection tend to be affected by the negative impacts of PV like voltage rise and reverse power flow. The over voltage and over current created from both of the impacts of PV let the protection device's coordination interrupted. The protection equipments started to lose the direction in determining the time of trip amongst them when both over voltage and over current occur on feeder since voltage rise and reverse power flow happen in accordance with weather conditions where the PV penetration can rise and fall unexpectedly.

Above findings is consistent with the study by [11], through the investigation by using DIGSILENT power factory software, among impacts of PV on grid, reverse power flow is the reason why the protection coordination is affected. In the investigation, the coordination of the over current protection device is interrupted as the current at the feeder is affected by the occurrence of reverse power flow. The excessive power that is fed back into the grid created over current at the feeder. Therefore, the coordination between the over current protections is interrupted on the feeder. Similarly, researcher in [25] also provided the same result as [7] which is the coordination between the protection devices on the feeder is affected by PV penetration.

Researcher in [25] added that fault current creates challenging situation and even more complex situation to the protection coordination. Besides that, researcher in [25] found that operating time of protection devices unlikely affected by the penetration of PV when researcher in [25] used a prototype to investigate on operation and protection issue at distribution level. This might be because PVs is designed as inverter interface system where any fault current occurred can be limit. Therefore, from research in [7] and [25], high PV power penetration can affect the coordination of protection devices on grid which are installed on the feeder.

2.1.5 Flicker and Harmonic

Flicker is happened due to the variation of voltage on the grid caused by PV [26]. Where the variation of voltage is occurred due to PV power are fluctuates follow the fast changing of weather conditions. Flicker is produce at the feeder. When the voltage at the feeder is high, it creates flicker and when the voltage is low, and then there is no flicker occurs at the feeder even with the connection of PV. As PV power fluctuation follows the condition of weather either sunny, cloudy or rainy day, but the investigation in [13], the researcher gives attention to cloud movement.

The analysis that has been done shown that, large amount of flicker is created at the feeder due to variation of voltages occurred due to PV power output rise and fall depending on the cloud movement. Besides that, researcher in [13] stated that flicker normally did not occur at low voltage side, it usually happened at high voltage side. In case flicker does arise at low voltage side, it will occur in the short period of time. Furthermore, if flicker occurs too often, it will give bad impact on the efficiency of connected machines and throughout the investigation, researcher highlight the findings on the maximum short term and long term flickers created which are 2.0 and 0.78 respectively.

In contrast, the study in [24] indicated that, flicker will created at the feeder if the feeder is weak while the penetration of PV power is high. If the penetration of PV power is at low, the flicker is unlikely occurred although the feeder is weak. But, this scenario needs further study. In this study, the researcher found that the distance between where the flicker is occurred and the regulator play the important role in the generation of flickers. Flicker is at high stage when the distance where the flicker is occurred and the regulator are far from each other and on that time, high penetration of PV power output is generated from the PV.

Fortunately, through this investigation, all the calculated values of flicker do not exceed the IEEE 1453 limits. Therefore, flicker occurred in this investigation due to high penetration of PV is assume not lead to any negative impact on the distribution feeder. Harmonic is also one of the effects of high penetration of Grid-connected PV system on grid. Harmonics is happened due to conversion of direct current to alternating current in order to synchronize with the alternating current of main supply by utilizing inverter of PV. The harmonic distortion of current and voltage waveform is becoming an essential concern due to the penetration of PV systems in the distribution network.

Current harmonic can results in voltage harmonic and Total Harmonic Distortion (THD) in the system. These harmonics bring negative impact to the low voltage side of grid as they contribute to increasing losses in distribution system through heating [6]. According to [6], the relationships between powers penetrate to the low voltage side of the grid and PV output current is directly proportional. The higher the generation of PV power output, the higher the PV current output, therefore the higher the current harmonic injected into the grid.

This relationship is supported by the results that have been obtained in the investigation where during the afternoon, PV penetrate power at the highest level, so the results show that the amplitude of the 3rd order harmonic is about 40-50% of the amplitude of the fundamental current. This percentage of amplitude is considered high. But then, in this investigation, the results of harmonic do not surpass the limit as determined by IEEE 1547. In addition, PV inverters are the main equipment to inject current harmonics into the distribution system [26].

2.1.6 Open Distribution System Simulator (OpenDSS) Software

Open Distribution System Simulator (OpenDSS) software is a comprehensive electrical system simulation tool for electric utility distribution systems developed by the Electric Power Research Institute (EPRI). It is technically referred to open-source execution of DSS [27]. Basically all steady-state analysis for utility distribution systems is support by OpenDSS. OpenDSS makes possible to define the different components of the electrical distribution network like transformer, cables, lines, voltage regulators, capacitors and loads. It allows all functions to be done by a text based script. Therefore, it makes any complicated circuit can be easily construct to a variety of data transfer format using DSS script.

Each component that will be build in OpenDSS software has specific syntax and parameter where users can write the script command of the components in any random arrangement and OpenDSS compiler will process the command in positional order and build the component structure. Therefore, users do not need to worry about the arrangement of the script command of DSS. OpenDSS software is designed to be driven from variety of existing software platforms since it is implemented as a stand-alone executable program and an in-process component object model (COM) server DLL as shown in Figure 2.1.

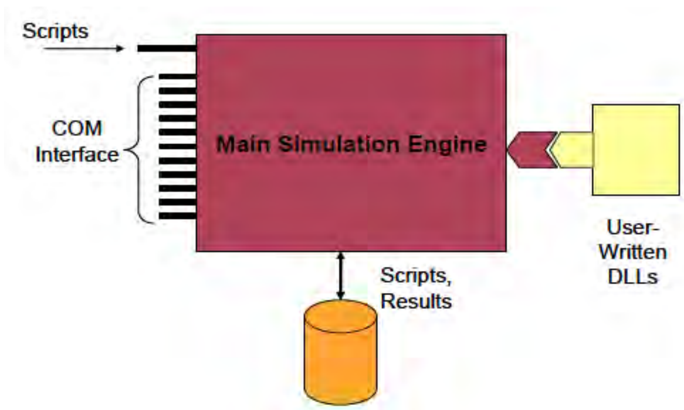

Figure 2.1: DSS Structure [27]

Stand-alone executable program version consists of basic user interface which is text scripting stand-alone user interface on the DSS solution engine help users develop scripts and view solutions. It is sufficient for most of the analysis. Through the COM interface, design and execute custom solution modes and features of the simulator from any third party analysis programs like MATLAB, VBA, C#, Python and other analysis programs can be done. Besides that, COM interface also provides direct access to the text-based command interface. OpenDSS can be expanded by integrating user developed DLL's to the solution engine to meet future needs. The most important benefit of OpenDSS software is that it supports study with distributed generation integration and time series power flow.

The OpenDSS program has been used for [28]:

- Distribution Planning and Analysis
- General Multi-phase AC Circuit Analysis
- Analysis of Distributed Generation Interconnections
- Annual Load and Generation Simulations
- Wind Plant Simulations
- Analysis of Unusual Transformer Configurations
- Harmonics and Inter harmonics analysis
- Neutral-to-earth Voltage Simulations
- Development of IEEE Test feeder cases and DG models
- Loss evaluations with unbalanced loadings
- Transformer frequency response analysis
- Open conductor fault conditions with a variety of single phase and three phase banks

2.1.7 OpenDSS Architecture Model

The main simulation engine consists of OpenDSS executive function as controls the distribution system simulation. There are five classes for various distribution components which are Power Delivery (PD) elements, Power Conversion (PC) elements, Controls, Meters, and General. Figure 2.2 shows an overview of the architecture for the main simulation engine of the OpenDSS program.

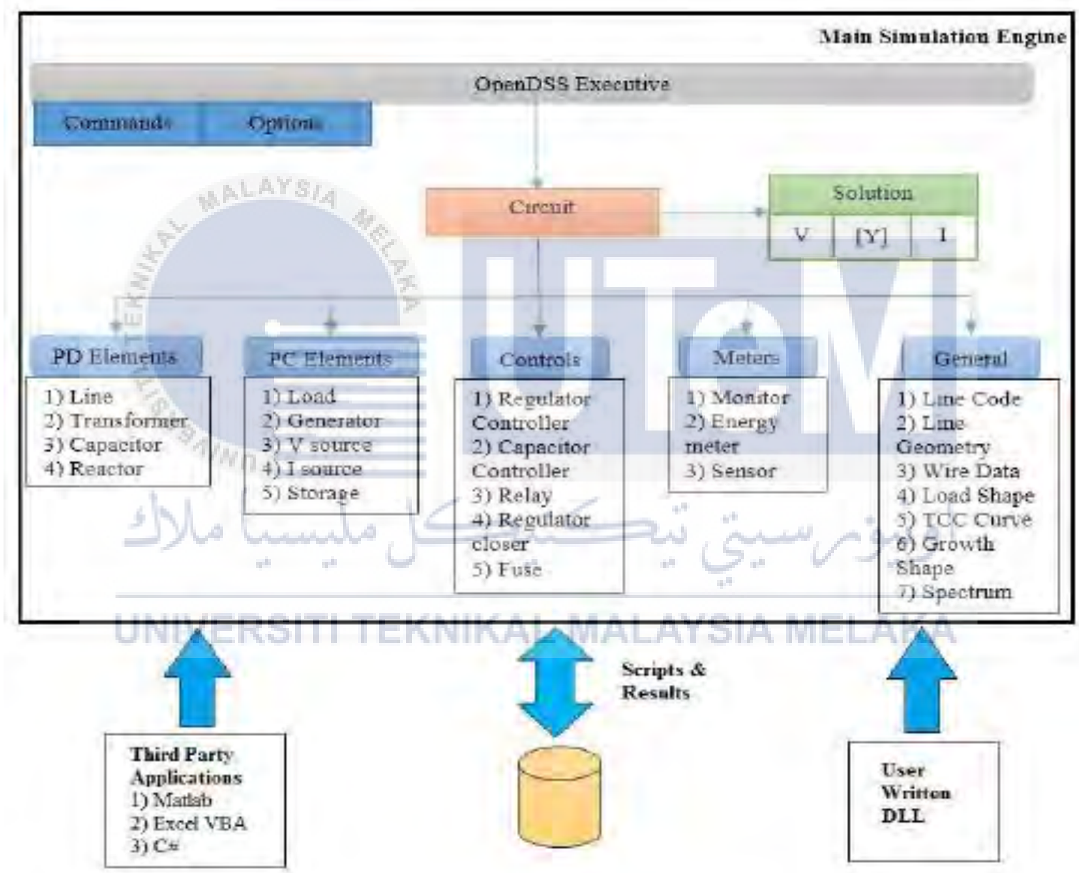

Figure 2.2: OpenDSS Architecture Model [28]

PD elements are the elements that can transport the electrical power from one node to another and the elements are multi-phased. Most common PD elements are transmission lines and transformers. PC elements convert the electrical energy from one form to another form. The PC elements are the components that can store energy temporarily and most of them have a single connection to the power system. Common PC elements such as generators and loads are modeled by characterizing their impedance and current injections by using a set of differential equations. Common components of General class are line geometry and wire data. The OpenDSS executive controls the collection of results through the Meter elements and the execution of the control elements.

Furthermore, the OpenDSS simulator can directly execute the main simulation engine either by sending text command through generating scripts or by the COM interface. Otherwise, user-written DLL programs can also perform several executions at the same time. Generally, the result (output) files will be exported as a Comma-Separated Value (CSV) format, which redirected through third-party applications that facilitates the use of MATLAB and Excel VBA.

2.1.8 Comparisons between European and North American System

Distribution systems around the world have evolved into different forms. The two main designs are North American and European. For both designs, hardware is much the same like conductor, cables, insulators, arresters, regulators and transformer are the very alike. Both systems are radial, voltage and power carrying capabilities are similar. The main different between the two main distribution systems are in layouts, configurations and applications. Figure 2.3 shows the different between North American and European Distribution Systems.

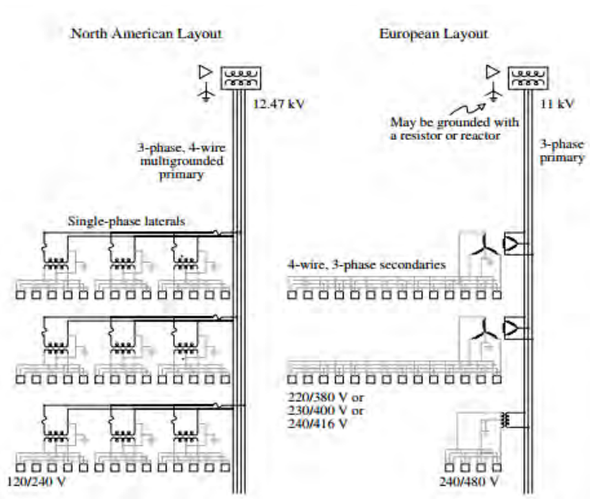

Figure 2.3: North American versus European Distribution Layouts [29]

European systems have larger transformers and more customers per transformer. Most European transformers are three-phase and on the order of 300 to 1000 kVA, much larger than typical North American 25 kVA or 50 kVA single-phase units. Besides that, secondary voltages have caused many of differences in distribution systems. North American has standardized on a 120/240 V secondary system where voltage drop limits how far utilities can run secondary typically no more than 250 feet which is 0.0762 km. In European designs, higher secondary voltages allow utilities run secondary almost one mile which is 1.609344 km.

Moreover , European secondary is mostly three-phase and most European countries have a standard secondary voltage of 220, 230, or 240 V, twice the North American standard. As the voltage is twice, a circuit feeding the same load can reach four times the distance and because three-phase secondary can reach over twice the length of a single-phase secondary, overall, a European secondary can reach eight times the length of an American secondary for a given load and voltage drop. Although it is rare, some European utilities supply rural areas with single-phase taps made of two phases with single-phase transformers connected phase-to-phase.

Furthermore, in the European design, secondary are used much like primary lateral in the North American design. In European designs, the primary is not tapped frequently, and primary-level fuses are not used as much. European utilities also do not use reclosing as religiously as North American utilities. Some of the differences in designs center is on the differences in loads and infrastructure. In Europe, the roads and buildings were already in place when the electrical system was developed, so the design had to “fit in.” Secondary is often attached to buildings where as in North America, many of the roads and electrical circuits were developed at the same time. Also, in Europe houses are packed together more and are smaller than houses in America. Each type of system has its advantages.

In addition, both of the distribution systems are differ in term of cost where the European system is generally more expensive than the North American system. This is because, European primary equipment is generally more expensive, especially for areas that can be served by single-phase circuits. Besides that, European and North American distribution systems is differ in term of flexibility where the North American system has a more flexible primary design while the European system has a more flexible on the secondary design. For urban systems, the European system can take advantage of the flexible secondary. For example, transformers can be sited more conveniently. For rural systems and areas where load is spread out, the North American primary system is more flexible. The North American primary is slightly better suited for picking up new load and for circuit upgrades and extensions.

In term of safety, North American is safer than European system as the multigrounded neutral of the North American primary system provides many safety benefits which are protection can more reliably clear faults, the neutral acts as a physical barrier, as well as helping to prevent dangerous touch voltages during faults. The European system has the advantage that high-impedance faults are easier to detect. Lastly, North American designs are more reliable than European designs since North American designs result in fewer customer interruptions. This is because, although European systems have fewer primaries, almost all of it is on the main feeder, loss of the main feeder results in an interruption for all customers on the circuit. European systems need more switches and other gear to maintain the same level of reliability [29].

CHAPTER 3

METHODOLOGY

3.1 Introduction

This chapter describes the methodology used to analyze the impact or effects of penetration of distributed PV power on grid in a residential area using OpenDSS. The sequence on how to simulate the distributed photovoltaic (PV) power in distribution network by using OpenDSS software is shown in this chapter. Besides that, the sequence of modeling the distribution network to represent a generic small-scale Malaysian residential distribution system for this project is also shown in this chapter where Open Distribution System Simulator (OpenDSS) software is used to model the network and perform the power flow analysis. In addition, the modeling of various components that are used to build the model of distribution network are stated and the commands are explained. Lastly, the details on model of distribution network using IEEE European Low Voltage test feeder is explained in this chapter.

3.2 Modeling Distribution Network with PV Power Penetration using OpenDSS Software

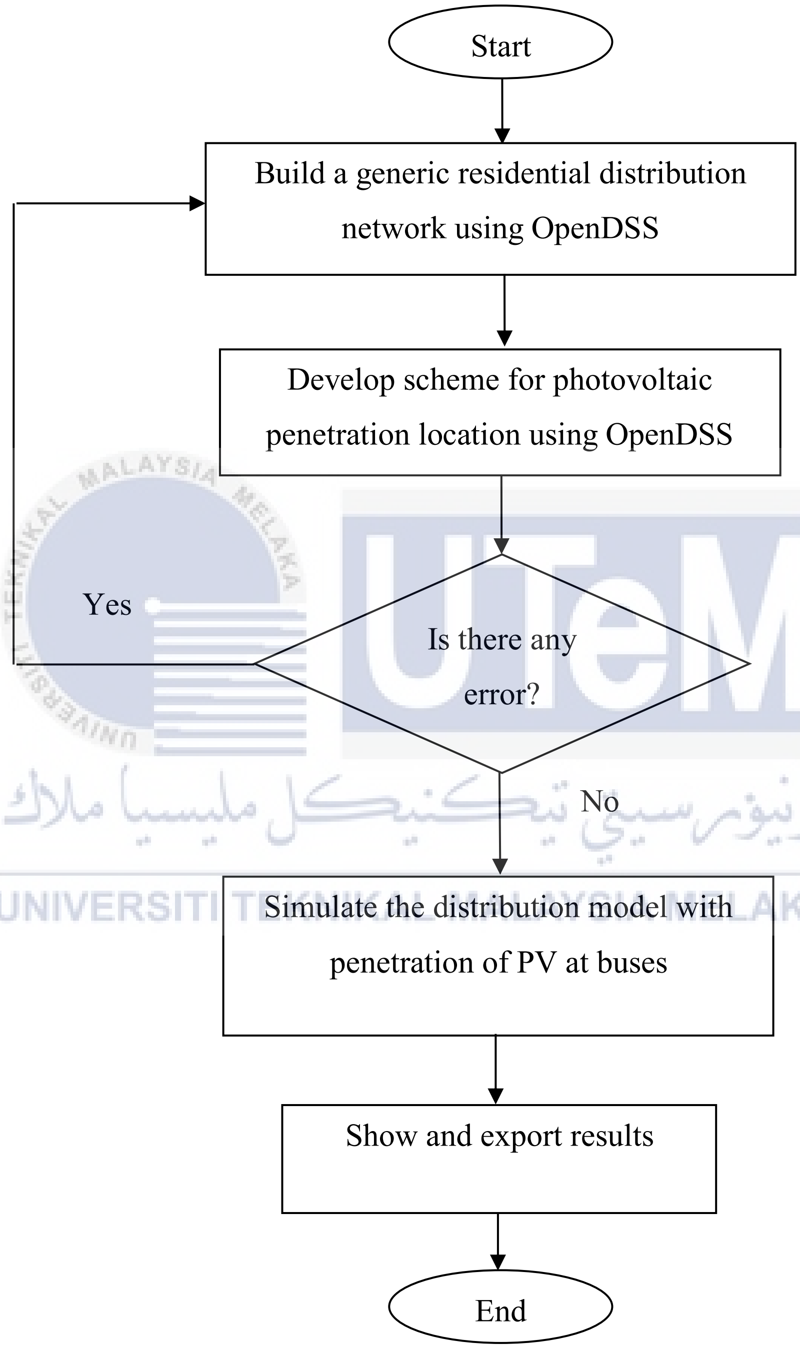

Figure 3.1: Flow Chart of Modeling Distribution Network with PV Power Penetration

3.2.1 Build a Generic Residential Distribution Network using OpenDSS

OpenDSS program is used to design balanced and unbalanced three phase distribution network for residential areas. The steps and the elements that are needed to build the balanced and unbalanced distribution network are shown in Figure 3.4 in section 3.3. IEEE European Low Voltage test feeder, as shown in Figure 3.2 is used to build small scale distribution network for residential area.

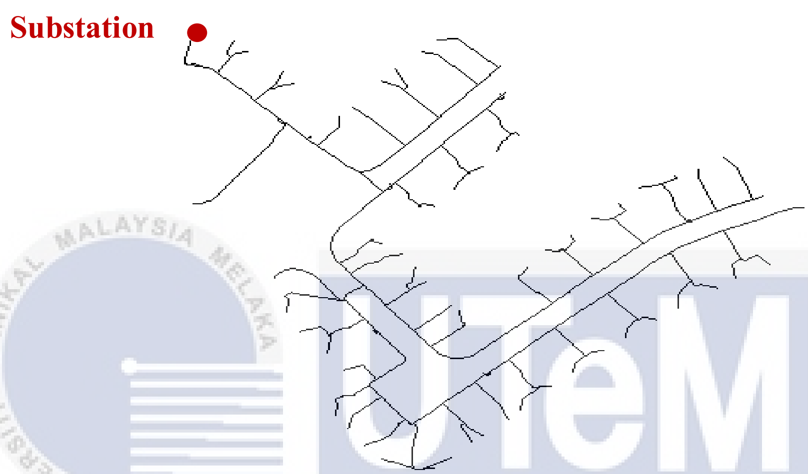

Figure 3.2: One-line Diagram of the European Low Voltage Test Feeder

3.2.2 Develop Scheme for Photovoltaic Penetration Location

OpenDSS software is used to generate photovoltaic (PV) penetration on selected feeders or buses. There will be two cases to penetrate PV on selected feeders or buses to analyze variation of voltages at the distribution network for residential areas. First, maximum 100% PV penetration distribute into all three phases on different buses with clear sky irradiance PV profile. Second, maximum 100% PV penetration distribute into all three phases on different buses with high variability irradiance PV profile. Figure 3.3 shows a PV is connected at Bus 632. This is the example on how the connection between PV and selected feeder or bus of the distribution network will be done.

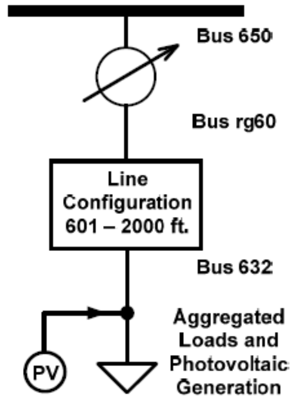

Figure 3.3: The Simplified Node Test Feeder [7]

3.2.3 Simulate Distribution Network with Penetration of PV

Different levels of PV power penetration which are clear sky irradiance and high variability irradiance will penetrate on selected buses or feeders as shown in Figure 3.3 for simulate. There are 55 buses or feeders that penetrated with PV power in this project which already have their own load profile.

3.2.4 Show and Export Results

Show and export is the word that is used to display simulation results on the impact of PV penetration in term of real-time variation of voltages on the distribution network for residential area in OpenDSS program. The analysis is only on voltage characteristics. The other impact like protection coordination, flicker and harmonic will not be studied in this project. When the command is written as “show”, the simulation results are shown in notepad. If the command is written as “export”, the simulation results are exported and displayed in the Excel file. Users can choose to display the results by written the command as show or export.

3.3 Flow Chart of Distribution Network Modeling

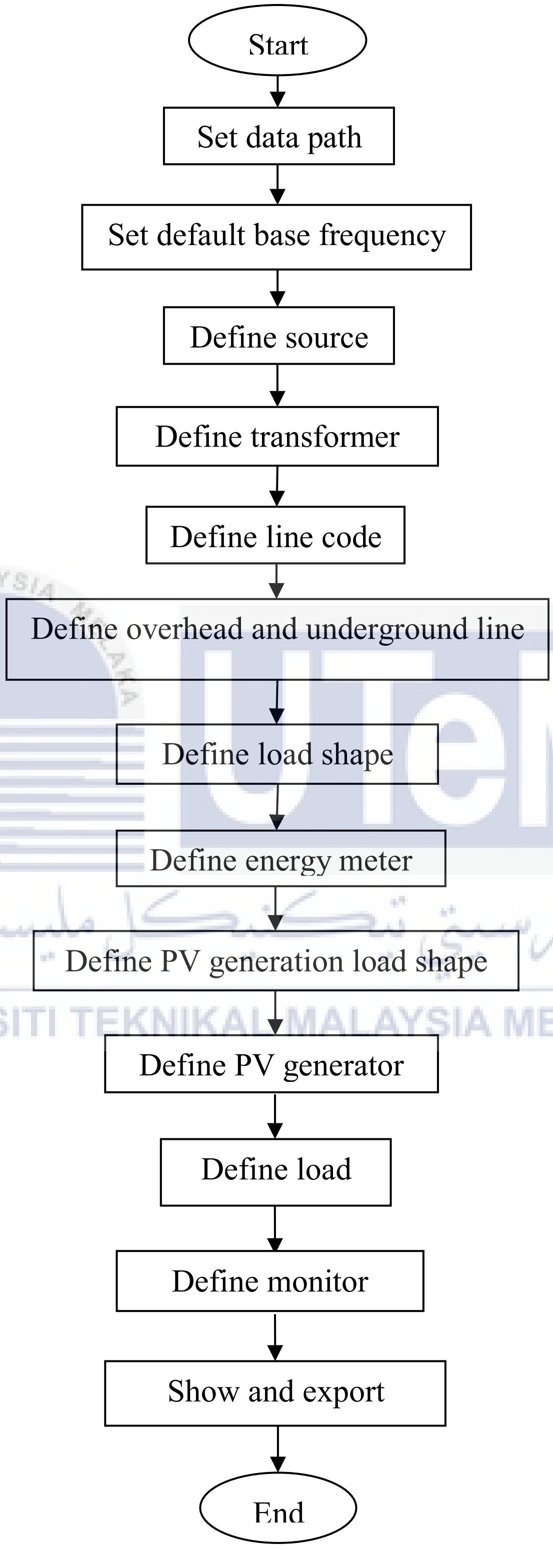

Figure 3.4: Flow Chart of Distribution Network Modeling

3.3.1 Set Data Path

Data path need to be set at the beginning of the script command so that any simulation results or data can be transfer straightly and save in the specific folder or location that has been set. Therefore, users know where to fine the results or the data later on.

3.3.2 Set Default Base Frequency

OpenDSS can be simulates by two default base frequencies which is 50 Hz and 60 Hz. Since Malaysia use frequency of 50 Hz, the frequency use in the simulator is 50 Hz. Make the selection between this two frequencies is important because it can affect the simulation results as it is use by all impedance quantities.

3.3.3 Define Source

Source that is defined in OpenDSS is voltage source. It is used as a reference value for the circuit. Besides that, it is used to initialize the power flow solution and all other injection sources are set to zero. Figure 3.5 shows the format on how to write a script command of voltage source for OpenDSS compiler to process.

```
New Circuit.<name> basekv=12.47 pu=1.045 angle=0 Bus1=130 R1=0.193 X1=1.79 R0=0.13
X0=1.582
```

Figure 3.5: Format of Define Source in OpenDSS [28]

The word "new" in the format tells the main DSS command that it is a new command and need to build by the OpenDSS. The 'basekv" represents the rated line-line base voltage for the circuit. While "pu" represents the value of actual per unit at which the source is operating. Degree of the first phase of the circuit or base angle is represent by syntax "angle".

"Bus1" is used in the format to state at which bus the source is connected. The values of positive sequence reactance and resistance of the source are specified by "x1"and "r1" in ohms while "x0" and "r0" properties represent the values of zero sequence reactance and resistance of the source in ohms. Table 3.1 shows the other properties of the voltage source that can be use in the format of writing the script command of the source to build the network.

Table 3.1: Property of Source [28]

Property	Description
Frequency	Frequency of the source
Phases	Number of phases of the source
MVASC3/ MVASC1	3 phase and 1 phase short circuit MVA

3.3.4 Define Transformer

The transformer consists of two or more windings and the parameters of each winding are specified individually. Figure 3.6 shows the format to write the command to build transformer in the OpenDSS program.

```
New Transformer.<name> phases=1 windings=2 buses=(<name>.1,<name>.1) conns=(wye,wye)
kvs=(7.2,7.2) kvas=(333,333) xhl=0.001 %loadloss=0.0001
```

Figure 3.6: Format of Define Transformer in OpenDSS [28]

Number of phases and number of windings of the transformer represent by "phases" and "windings" respectively. "buses" describe which winding of the transformer is connected to which bus in the network. "conns" describe the connection of transformer winding is wye or delta connection. Besides that, in the command it is important to state the base kVA rating and rated voltage of the winding. "xhl" represent the percent reactance high-to-low winding. Lastly, property of load loss in percentage represents load loss at rated load.

3.3.5 Define Line Code

Distribution lines are defined by line codes and their length. Line code is used to state the impedance characteristics for the lines and cables in OpenDSS program. The line code specifies the symmetrical impedance characteristics for underground cables as OpenDSS program do not have an inbuilt impedance calculation module for underground cables yet.

The impedance characteristics of a line in the network are described by its series impedance and nodal capacitive admittance matrix where the matrixes as shown in Figure 3.7 may be specified directly or can be generated by specifying the symmetrical component data [28].

Line Codes defined by matrix values

Name	nphases	R1	X1	R0	X0	C1	C0	Units
2c_.007	3	3.97	0.099	3.97	0.099	0	0	km
2c_.0225	3	1.257	0.085	1.257	0.085	0	0	km
2c_16	3	1.15	0.088	1.2	0.088	0	0	km

Ohms, Series Impedance form

nF, Nodal Admittance

Figure 3.7: Series Impedance and Nodal Capacitive Admittance Form

Figure 3.8 shows the format on writing the command to describe the impedance characteristics in the network. In the format, “code4” is the identifier that describes line code for an underground cable. OpenDSS users free to rename the identifier but then the same name need to be use when write the command to build overhead and underground line. If not, there will be error in the simulation process.

```
New Linecode.code4 nphases=3 r1=0.3489 x1=0.426198 r0=0.588811 x0=1.29612
c1=10.4308823411236 c0=4.48501282215346 units=km baseFreq=60 normamps=310
emergamps=310
```

Figure 3.8: Format of Define Line Code in OpenDSS [28]

The used of “nphases” represent the number of phases. “r1” and “x1” is represents the positive sequence resistance and reactance in ohms per unit length for the lines and cables in the network. While “r0” and “x0” is represents the zero sequence resistance and reactance in ohms per unit length for the lines and cables in the network. “c1” and “c0” properties describe the positive and zero sequence capacitances in nano-farads per unit length. “units” property written in the command represent unit used either in kilometer (km), meter (m), feet (ft), mile (mi), inch (in) or centimeter (cm) to model the line code. The “baseFreq” in the command is used for calculation of impedances.

Lastly, the “normamps” and “emergamps” describe normal and emergency current carrying capacity of the line. Both “normamps” and “emergamps” not used when written the line code command as the data is not provided by the IEEE Distribution System Analysis Subcommittee. Without normal and emergency current carrying capacity, the line code can be model finely.

3.3.6 Define Overhead and Underground Lines

Modeling lines in OpenDSS require detail information or data on wire data, line geometry or line code and actual line definition where the data is then used to model the overhead lines. The impedance of the underground cables is specified in symmetrical components because for now OpenDSS does not have an inbuilt impedance calculation module for underground cables as mentioned in section 3.3.5. Figure 3.9 shows the format to write the command to build the overhead line.


```
New Line. <line name> bus1=<bus1name>.2.4 bus2=<bus2name>.2.4 length=586.923 units=ft
geometry=geom4 (or linecode=code4)
```

Figure 3.9: Format of Define Overhead Line in OpenDSS [28]

In the command format writing, "line name" represent the name of the line that describe the overhead line. "bus1" and "bus2" describe from which node to which node the line will be connect in the network. "length" and "units" represent length of the line and its corresponding unit. "geometry" or "linecode" property is used to call back the identifier of line geometry or line code as to build the line, line geometry or line code data is needed.

3.3.7 Define Load Shape

Load shape is defined for time-series simulation defining load curve data. Load shape with a one-minute time resolution over 24 hours is provided for time-series simulation. Data for load shapes are given in *LoadShapes.csv* files where "csv" is comma separated value. Each load shape is linked to a .csv file that defines the load profile as shown in Figure 3.10.

Load Profiles

# Load Shapes				
Name	npts	minterval	File	useactual
Shape_1	1440	1	Load_profile_1.csv	TRUE
Shape_2	1440	1	Load_profile_2.csv	TRUE
Shape_3	1440	1	Load_profile_3.csv	TRUE

Figure 3.10: Load Shape Linked to Load_profile.csv File

Load profiles are defined by a matrix with two columns. The first column specifies the time, while the second column state the multiplier values. A portion of the *Load_profile_1.csv* file is shown in Figure 3.11.

Multiplier

time	mult
0:01:00	0.036
0:02:00	0.036
0:03:00	0.036
0:04:00	0.036
0:05:00	0.036

Figure 3.11: *Load_profile_1.csv* File

The kW value of a load at a specific time is determined by its base kW and multiplier values. Take LOAD1 as an example, its base kW value is 1 and the value of multiplier at time 00:01:00 is 0.036. Therefore, the kW value of LOAD1 at time 00:01:00 is 1×0.036=0.036 kW. Figure 3.12 below shows the format on writing the command to describe the load shape.

```
New Loadshape.<name>  npts=1440   interval=0  hour=(file=<name>)
mult=(file=<name>)   cvsfile = <name>  action=normalize !Use normalization when
needed
```

Figure 3.12: Format of Define Load Shape in OpenDSS

Every load shapes need to have name so that OpenDSS program can differentiate each load shape. “npts” property is represents a one-minute time resolution over 24 hours where it is maximum number of points to expect in load shape vectors. “interval” property represent time interval for fixed interval data in hours. “hour” property is used to define array for hour values. Whereas “mult” property is used to define array for multiplier values for active power, P. “csvfile” containing (hour, mult) points or simply (mult) values for fixed time interval data.

In addition, the load shape command also can be written without “hour” and “mult” properties as “csvfile” is stated in the command. Command of load shape should be added after “New Circuit” and before the “New Load”. Table 3.2 shows the properties that are use to define the load shape with additional description.

Table 3.2: Property of Load Shape

Property	Description
Interval	Default = 1 If interval = 0, then time data (in hours) maybe at irregular intervals and time value must be specified using either the Hour property or Input files. minterval = 1, specify fixed interval in minutes. Alternate way to specify interval property.
Hour	If the data are fixed interval, do not use this property. hour = (file=filename) for text file one value per line hour = (dblfile=filename) for packed file of doubles hour = (sngfile=filename) for packed file of single
mult	mult = (file=filename) for text file one value per line mult = (dblfile=filename) for packed file of doubles mult = (sngfile=filename) for packed file of single

3.3.8 Define Energy Meter

Energy meter is used in the network to measure energy at certain node or bus. The result can be shown in hourly and by year. The results of energy consume (kWh) and the energy demand (kW) is shown in Excel file. Figure 3.13 shows the format on writing the command to describe the energy meter.

```
New Energymeter.<Name>   Element=transformer.<name>   Terminal=1
```

Figure 3.13: Format of Define Energy Meter in OpenDSS

Each energy meter needs to be name in the command so that the energy meters defined can differentiate by OpenDSS. It is better that every energy meter have different names. The way on defining the energy meter is no other different than defining monitor where in the format of define energy meter there is no property of “mode”. Property of “element” refers to which component the energy meter is connected. Whereas, property of “terminal” refer to consideration on load current as positive or negative, where currents will either flow to the right or left.

3.3.9 Define Photovoltaic (PV) Generation Load Shape

Photovoltaic penetration on selected bus or feeder in the modeling of distribution network is defined by photovoltaic (PV) generation load shape or load curve data taken from FKE Lab, UTeM. The taken data used in this simulation is the actual data. Before the data of PV irradiance is use in the simulation, the data have to be converted to normalize values so that the peak of multipliers is 1.0. Figure 3.14 shows the format on writing the command to describe the load shape of photovoltaic generation.

```
New Loadshape.<name>    npts=1440    interval=1m    cvsfile = <name>.txt
```

Figure 3.14: Format of Define Photovoltaic (PV) Generation Load Shape in OpenDSS

Property of “npts” refers to maximum number of points to expect in the load shape vector. This property gets reset to the number of multiplier values found in files only if less than specified. The property of “interval” represent time interval for fixed interval data in hours. In the simulation, the property of “minterval” is used where this property will specify fixed interval in minutes. The property of “csvfile” will call the CSV text file containing load shape data (hour, mult) points or simply (mult) values for fixed time interval data, one per line.

In this project, there are two conditions of photovoltaic generation used in the simulation to evaluate the impact of distributed photovoltaic (PV) power penetration to the small scale residential distribution network which is clear sky irradiance and high variability profile of photovoltaic generation. The two load shapes of photovoltaic generation are shown in Figure 3.15 and Figure 3.16 where both of the figures show the graph of generated photovoltaic actual data that been normalize so that the peak of the multipliers is 1.0 and can be use in OpenDSS simulation.

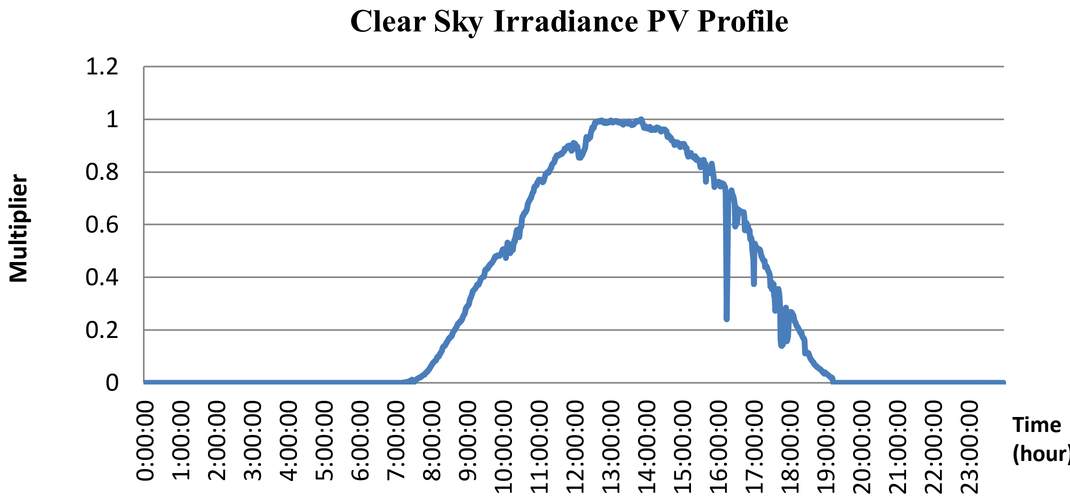

Figure 3.15: Load Shape of Clear Sky Irradiance of Photovoltaic Generation

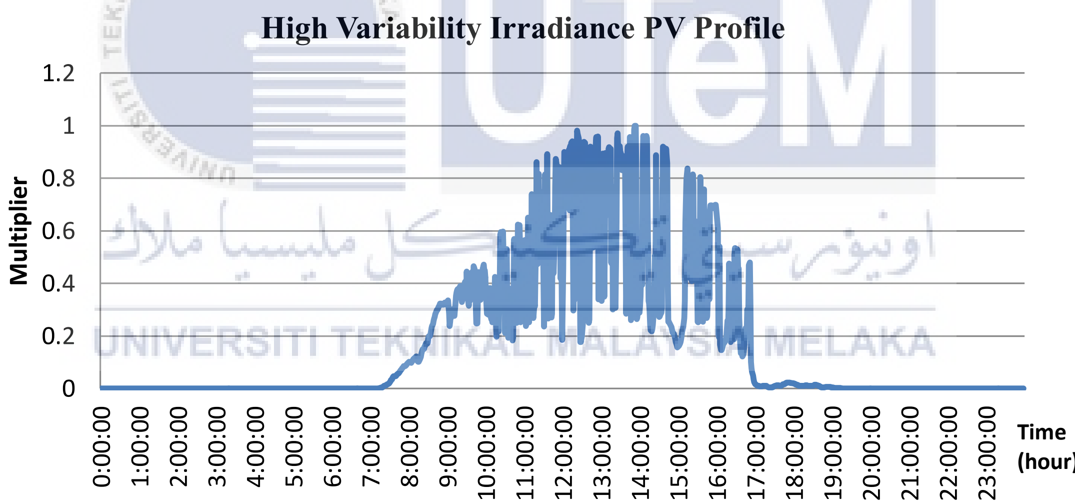

Figure 3.16: Load Shape of High Variability Irradiance of Photovoltaic Generation

3.3.10 Define Photovoltaic (PV) Generator

Photovoltaic generator need to be built in the OpenDSS so that the load shape of photovoltaic generation in section 3.3.9 can be applied. Figure 3.17 shows the format on writing the command to describe the photovoltaic generation.

```
New Generator.<name>   bus1=<name>   phases=1   kV=(0.4  3 sqrt /)   kW=30   pf=1
model=1    status=variable    daily=<name>
```

Figure 3.17: Format of Define Photovoltaic (PV) Generation in OpenDSS

Each generator need name so that OpenDSS can differentiate each of the generator built in the program. "bus1" property defined at which bus the generator is connected. Property of "phases" represents number of generator phases where power is evenly divided among phases. "kV" property represents the voltage value of a generator. While the property of "kW" represents total base power for the generator and property of "pf" represents the generator power factor. Property of "model" represents the integer code for the model to use for generation variation with voltage. "status" property will represents the condition of generator whether the generator will follow the data curves or not. Lastly, property of "daily" represents the load shape to use for daily simulations. The load shapes of 24 hours must be previously defined.

3.3.11 Define Load

A load is an element of power conversion where it is the core of all power flow and voltage analysis. Loads are modeled as constant PQ ones. For each load, the base load is specified using kW and power factor (PF). Figure 3.18 shows that data for loads given in the *Loads.csv* file and each load is linked with the one load shape.

Load Shapes

# Loads									
# Model 1 is constant PQ									
Name	numPhase	Bus	phases	kV	Model	Connectic	kW	PF	Yearly
LOAD1	1	34	A	0.23	1	wye	1	0.95	Shape_1
LOAD2	1	47	B	0.23	1	wye	1	0.95	Shape_2
LOAD3	1	70	A	0.23	1	wye	1	0.95	Shape_3

Figure 3.18: Load Linked to Load Shape, shape.csv File

Figure 3.19 shows how the command is written to define load in the network. “phases” represent the number of phases for the load. “bus1” describe at which bus the load is connected. “class” represent the integer number that separates the load according to a particular class. “conn” describe the connection of the load whether wye or delta connection. “kV”, “XfkVA” and “kva” represent base voltage of the load in kV, rated kVA of the service transformer for allocating the load based on connected kVA at the bus and define the base load in kVA.

```
New Load.<load name> phases=1 bus1=<node>.2 class=1 Conn=wye kV=7.2 XfkVA=10
AllocationFactor=1 model=1 kva=2.037 pf=0.982 NumCust=1
```

Figure 3.19: Format of Define Load [28]

The allocation factor is written in the command as it describe for allocating the loads based on the connected kVA at the bus. “model=1” defines how the load will vary with the voltage and the load is the normal load flow type with constant active power and reactive power. “pf” represent nominal power factor for the load. Lastly, “numcust” represent the number of consumers to be served by the load. Table 3.3 shows the other properties that can be used to define the load.

Table 3.3: Property of Load [28]

Property	Description
KW/KVAR	Nominal real power and reactive power for the load.
Vminpu	Minimum pu voltage for which the model is assumed to apply.
Vmaxpu	Maximum pu voltage for which the model is assumed to apply.
Status	Fixed or Variable, to be modified by multiplier.
Daily	To call the load shape where the command can be write as below **daily=shape_1**

3.3.12 Define Monitor

Monitor is used to captures selected quantities at a point where it is connected in the distribution network. Figure 3.20 shows the format to write the command to build monitor in the OpenDSS program.

```
New Monitor.<Name>   Element=transformer.<name>    Terminal=1    mode=1
```

Figure 3.20: Format of Define Monitor

Name of each of new monitor must have name differently so that program can read differentiate between one monitor to another. Property of "element" is used in the command to name the object of which the monitor is connected. Figure 17 shows that the monitor is being placed at transformer. "terminal" property represents the load current as positive or negative where currents flowing to the right or to the left of the monitor.

Command shown in Figure 3.20 describe that the monitor is place at terminal 1 of the transformer and the current is flowing to the right. If the command is written in *terminal=2* the monitor is place at terminal 2 of the transformer and the current is flowing to the left. Property "mode" represents which quantity should the monitor capture at a point in the circuit. Table 3.4 shows the types of monitor mode.

Table 3.4: Monitor modes

Property	Description
Mode	0= Voltages and currents 1= Powers 2= Tap position (transformer only) 3= State variables (PC elements only) 4= Flicker level and severity index for voltages

3.3.13 Show and Export Results

As stated in section 3.2.4, "show" and "export" is the word command for OpenDSS program to display simulation results either in notepad or in Excel file.

3.4 IEEE 4-bus Test Feeders

For better understanding of distribution systems modeling by OpenDSS platform, 4-Bus test feeders have been built and simulated. It is a simple trial for the beginner to learn about OpenDSS program. Basically, beginner learns how to write the script command to build a model of system using the 4-bus test feeder. Figure 3.21 shows the 4-bus test system diagram that is used in testing transformer models.

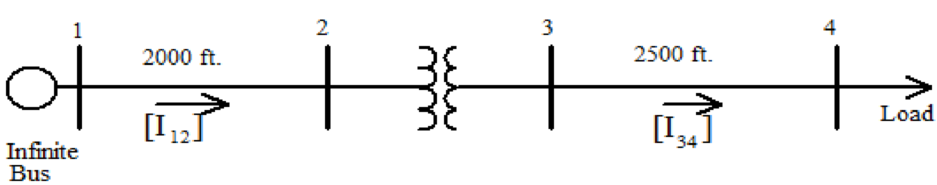

Figure 3.21: IEEE 4-Bus Test Feeder [30]

The system has an infinite bus with 12.47 kV line-to-line voltage, 6000 kVA step-down transformer (12.47 kV/ 4.16 kV) or step-down transformer (12.47 kV/ 24.9 kV) which can connect in the connection of Wye-Wye, Wye-Delta, Delta-Wye and Delta-Delta with balanced load with 1800 kW and power factor of 0.9 lagging. Other data that are used to build the 4-bus test system are provided in Appendix A.

The rating of the transformer shows that the 4-bus test system is the North American distribution network as OpenDSS test cases focused on North American style systems while Malaysia distribution system used the European distribution network. Therefore, IEEE 4-bus test feeders will not be used in this project to evaluate the impact of distributed photovoltaic (PV) power penetration to the small scale residential distribution network. So, IEEE European Low Voltage Test Feeders will be use to evaluate the impact of distributed photovoltaic (PV) power penetration to the small scale residential distribution network.

3.5 IEEE European Low Voltage Test Feeders

The Test Feeders working group of the IEEE Distribution System Analysis Subcommittee has provided a benchmark for researchers who want to study low voltage feeders. The European low voltage test case was developed to meet the needs which have the features as follow, first, the test feeder is at the voltage level of 416 V (phase-to-phase), which is typical in the European low voltage distribution systems. Second, load shapes with a one-minute time resolution over 24 hours are provided for time-series simulation and lastly, time-series simulation results over a one-day period and static power flow calculation results at some key moments are provided.

The low voltage test feeder is a radial distribution feeder with a base frequency of 50 Hz. The feeder is connected to the medium voltage (MV) system through a transformer at substation. The transformer steps the voltage down from 11 kV to 416 V. The main feeder and laterals are at the voltage level of 416 V. The one-line diagram of the test feeder used to build small scale distribution network for residential area is shown in Figure 3.22.

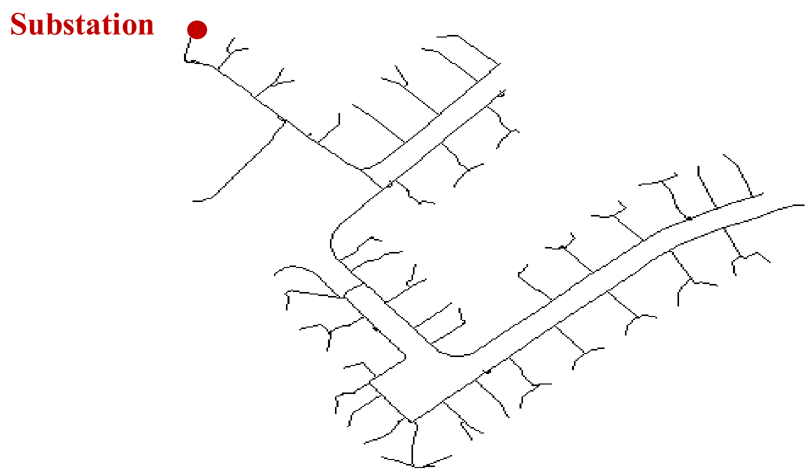

Figure 3.22: One-line Diagram of the European Low Voltage Test Feeder

The MV system is modeled as a voltage source with impedance as shown in Figure 3.23. The data for the source is given in the *Source.csv* file. The impedance is specified by short circuit currents.

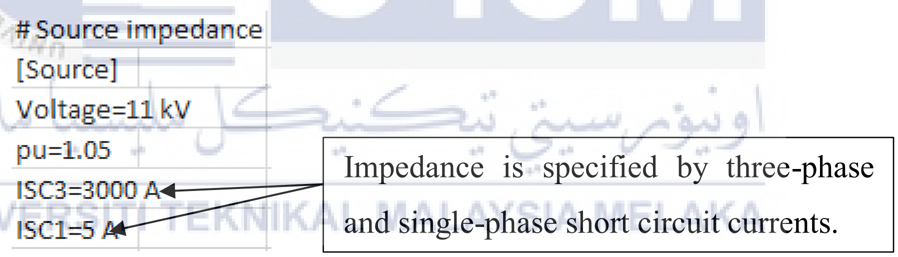

Figure 3.23: Source Impedance Data

The three-phase transformer at substation has a rated MVA of 0.8, rated voltages of 11/0.416 kV, and a Delta/grounded-Wye connection. The resistance and reactance of the windings are 0.4% and 4% (use the kVA and kV base of the high-voltage winding), respectively. There are 205 lines, 906 buses and all load in distribution network are connected in single phase with 0.23 kV, 0.95 power factor in Wye-connection. The data that have been provided by the Distribution System Analysis Subcommittee is in raw. The data is then used in this project to build the low voltage distribution network by using OpenDSS.

3.6 Gantt Chart of the Research

Table 3.5: Gantt Chart Table

Milestone	Tasks	Week													
		1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Investigation on raw data provided by IEEE committee.														
2	Analysis on the type of PV power penetration.														
3	Construct the distribution network and PV penetration using OpenDSS.														
4	Verify the simulation results of OpenDSS software.														
5	Preparation for report writing and presentation slide.														

CHAPTER 4

RESULTS

4.1 Results of IEEE 4-bus Test Feeders

Validation of the software simulation results should be checked to prove that OpenDSS program can be used to simulate Malaysia distribution network in this project. The process to check the validation is conducted by comparing the OpenDSS results of simulation with published results by the IEEE Distribution System Analysis Subcommittee. Preliminary result of this project is on proof the validation of OpenDSS simulation results where 4-bus test feeder with difference types of transformer model is simulated as mentioned in section 3.4.

Table 4.1, Table 4.3, Table 4.5, Table 4.7, Table 4.9 and Table 4.11 show the percentages of error between simulation results of OpenDSS with IEEE test results for voltage values while Table 4.2, Table 4.4, Table 4.6, Table 4.8, Table 4.10 and Table 4.12 show the percentages of error between simulation results of OpenDSS with IEEE test results for current values. Whereas, Figure 4.1 until Figure 4.5 show the script command that is used in built each of step-down three-phase transformer models with balanced load, while Figure 4.6 shows the script command that is used in built each of step-up three-phase transformer models with balanced load.

4.1.1 Step-down 4-Bus Ground Wye- Ground Wye Balanced Load

```
Set datapath=C:\OpenDSSAliahsWorks\4buses
!set Datapath
New Circuit.4BusYYbal basekV=12.47 phases=3 mvasc3=200000 200000
!define Source
New wiredata.conductor Runits=mi Rac=0.306 GMRunits=ft GMRac=0.0244 Radunits=in Diam=0.721
!define Wire Data
New wiredata.neutral Runits=mi Rac=0.592 GMRunits=ft GMRac=0.00814 Radunits=in Diam=0.563
!define Wire Data
New LineGeometry.4wire nconds=4 nphases=3 reduce=yes
~ cond=1 wire=conductor units=ft x=-4 h=28
~ cond=2 wire=conductor units=ft x=-1.5 h=28
~ cond=3 wire=conductor units=ft x=3 h=28
~ cond=4 wire=neutral units=ft x=0 h=24
!define Line Geometry
New line.line1 geometry=4wire length=2000 units=ft bus1=sourcebus bus2=bus2
!define Overhead and Underground Lines
New transformer.T1 xhl=6
~ wdg=1 bus=bus2 conn=wye kV=12.47 kVA=6000 %r=0.5
~ wdg=2 bus=bus3 conn=wye kV=4.16 kVA=6000 %r=0.5
!define Transformer No.1
New line.line2 geometry=4wire length=2500 units=ft bus1=bus3 bus2=bus4
!define Overhead and Underground Lines
New load.load1 phases=3 bus1=bus4 conn=wye kV=4.16 kW=5400 pf=0.9 model=1 vminpu=0.75
!define Load at bus 4
New energymeter.busbar element=line.line2 terminal=1

Set voltagebases=[12.47, 4.16]
calcvoltagebases
solve
show voltages LN node
show currents
Export currents
Export meters
```

Figure 4.1: Script Command of Step-down 4-bus Ground Wye-Ground Wye Balanced

Table 4.1: Voltage Validation Results of OpenDSS Step-down 4-bus Ground Wye-Ground Wye Balanced with IEEE Test

Connection	IEEE Test Results (V)	OpenDSS Results (V)	Percentage of Error (%)
Node 2			
V1	7107	7120.5	0.19
V2	7140	7145.1	0.07
V3	7121	7131.6	0.15
Node 3			
V1	2247.6	2258.9	0.50
V2	2269	2273.8	0.21
V3	2256	2264.9	0.39
Node 4			
V1	1918	1975.9	3.02
V2	2061	2082.4	1.04
V3	1981	2025.2	2.23

Table 4.2: Current Validation Results of OpenDSS Step-down 4-bus Ground Wye-Ground Wye Balanced with IEEE Test

Connection	IEEE Test Results (A)	OpenDSS Results (A)	Percentage of Error (%)
Current 1-2			
I_a	347.9	337.64	2.95
I_b	323.7	320.42	0.01
I_c	336.8	329.42	2.19
Current 3-4			
I_a	1042.8	1012.1	2.94
I_b	970.2	960.51	1.00
I_c	1009.6	987.49	2.19

Refer to Table 4.1 and 4.2, the percentages of error between OpenDSS simulation results with IEEE test results of phase voltages and currents are not high. The highest percentage of error is 3.02% detected at node 4 which is considered low.

4.1.2 Step-down 4-Bus Wye-Delta Balanced Load

```
Set datapath=C:\OpenDSSAliahsWorks\4bYDbal
!set Datapath
New Circuit.4BusYDbal basekV=12.47 phases=3 mvasc3=200000 200000
!define Source
New wiredata.conductor Runits=mi Rac=0.306 GMRunits=ft GMRac=0.0244 Radunits=in Diam=0.721
!define Wire Data
New wiredata.neutral Runits=mi Rac=0.592 GMRunits=ft GMRac=0.00814 Radunits=in Diam=0.563
!define Wire Data
New LineGeometry.4wire nconds=4 nphases=3 reduce=yes
~ cond=1 wire=conductor units=ft x=-4 h=28
~ cond=2 wire=conductor units=ft x=-1.5 h=28
~ cond=3 wire=conductor units=ft x=3 h=28
~ cond=4 wire=neutral units=ft x=0 h=24
!define Line Geometry
New line.line1 geometry=4wire length=2000 units=ft bus1=sourcebus bus2=bus2
!define Overhead and Underground Lines
New transformer.T1 xhl=6
~ wdg=1 bus=bus2.1.2.3.4 conn=wye kV=12.47 kVA=6000 %r=0.5  ! Float the neutral of wye winding
~ wdg=2 bus=bus3 conn=delta kV=4.16 kVA=6000 %r=0.5
!define Transformer No.1
New line.line2 geometry=4wire length=2500 units=ft bus1=bus3 bus2=bus4
!define Overhead and Underground Lines
New load.load1 phases=3 bus1=bus4 conn=delta kV=4.16 kW=5400 pf=0.9 model=1 vminpu=0.75
!define Load at bus 4
New energymeter.busbar element=line.line2 terminal=1

Set voltagebases=[12.47, 4.16]
calcvoltagebases
solve
show voltages LN node
show currents
Export currents
Export meters
```


Figure 4.2: Script Command of Step-down 4-bus Wye-Delta Balanced

Table 4.3: Voltage Validation Results of OpenDSS Step-down 4-bus Wye-Delta Balanced with IEEE Test

Connection	IEEE Test Results (V)	OpenDSS Results (V)	Percentage of Error (%)
Node 2			
V1	7112	7123.6	0.16
V2	7133	7140.3	0.10
V3	7124	7133.1	0.13
Node 3			
V1	3906	3921.2	0.39
V2	3915	3928.7	0.35
V3	3909	3924.4	0.39
Node 4			
V1	3437	3509.2	2.10
V2	3497	3558.0	1.74
V3	3388	3469.4	2.40

Table 4.4: Current Validation Results of OpenDSS Step-down 4-bus Wye-Delta Balanced with IEEE Test

Connection	IEEE Test Results (A)	OpenDSS Results (A)	Percentage of Error (%)
Current 1-2			
I_a	335.8	328.92	2.05
I_b	335.9	329.04	2.04
I_c	335.9	329.02	2.05
Current 3-4			
I_a	1006.6	986.07	2.04
I_b	1006.7	986.13	2.04
I_c	1007.2	986.42	2.06

The percentages of error between OpenDSS simulation results and IEEE test results of voltages and currents shown in Table 4.3 and Table 4.4 are not high too. The percentage of error is considered low. The highest percentage of error is 2.40% at node 4 which is low and even lower than step-down 4-bus Ground Wye-Ground Wye balanced highest percentage of error.

4.1.3 Step-down 4-Bus Ground Wye-Delta Balanced Load

```
Set datapath=C:\OpenDSSAliahsWorks\4bGrdYDbal
!set Datapath
New Circuit.4BusGrdYDbal basekV=12.47 phases=3 mvasc3=200000 200000
!define Source
New wiredata.conductor Runits=mi Rac=0.306 GMRunits=ft GMRac=0.0244 Radunits=in Diam=0.721
!define Wire Data
New wiredata.neutral Runits=mi Rac=0.592 GMRunits=ft GMRac=0.00814 Radunits=in Diam=0.563
!define Wire Data
New LineGeometry.4wire nconds=4 nphases=3 reduce=yes
~ cond=1 wire=conductor units=ft x=-4 h=28
~ cond=2 wire=conductor units=ft x=-1.5 h=28
~ cond=3 wire=conductor units=ft x=3 h=28
~ cond=4 wire=neutral units=ft x=0 h=24
!define Line Geometry
New line.line1 geometry=4wire length=2000 units=ft bus1=sourcebus bus2=bus2
!define Overhead and Underground Lines
New transformer.T1 xhl=6
~ wdg=1 bus=bus2.1.2.3.0 conn=wye kV=12.47 kVA=6000 %r=0.5    ! Ground the neutral of wye winding
~ wdg=2 bus=bus3 conn=delta kV=4.16 kVA=6000 %r=0.5
!define Transformer No.1
New line.line2 geometry=4wire length=2500 units=ft bus1=bus3 bus2=bus4
!define Overhead and Underground Lines
New load.load1 phases=3 bus1=bus4 conn=delta kV=4.16 kW=5400 pf=0.9 model=1 vminpu=0.75
!define Load at bus 4
New energymeter.busbar element=line.line2 terminal=1
Set voltagebases=[12.47, 4.16]
calcvoltagebases
solve
show voltages LN node
Export currents
```

Figure 4.3: Script Command of Step-down 4-bus Ground Wye-Delta Balanced

Table 4.5: Voltage Validation Results of OpenDSS Step-down 4-bus Ground Wye-Delta Balanced with IEEE Test

Connection	IEEE Test Results (V)	OpenDSS Results (V)	Percentage of Error (%)
Node 2			
V1	7113	7124.4	0.16
V2	7132	7140.1	0.11
V3	7123	7132.5	0.13
Node 3			
V1	3906	3921.3	0.39
V2	3915	3928.7	0.35
V3	3909	3924.4	0.39
Node 4			
V1	3437	3509.2	2.10
V2	3497	3558.0	1.74
V3	3388	3469.4	2.40

Table 4.6: Current Validation Results of OpenDSS Step-down 4-bus Ground Wye-Delta Balanced with IEEE Test

Connection	IEEE Test Results (A)	OpenDSS Results (A)	Percentage of Error (%)
Current 1-2			
I_a	334.8	328.16	1.98
I_b	335.4	328.54	2.04
I_c	337.4	330.27	2.11
Current 3-4			
I_a	1006.6	986.07	2.04
I_b	1006.7	986.13	2.04
I_c	1007.2	986.42	2.06

Refer to Table 4.5 and Table 4.6, the highest percentage of error between the simulation results and test results is 2.40% which is same as step-down 4-bus Wye-Delta with balanced load. Therefore, the percentage is also considered low.

4.1.4 Step-down 4-bus Delta-Delta Balanced Load

```
Set datapath=C:\OpenDSSAliahsWorks\4bDDbal
!set Datapath
New Circuit.4BusGrdDDbal basekV=12.47 phases=3 mvasc3=200000 200000
!define Source
New wiredata.conductor Runits=mi Rac=0.306 GMRunits=ft GMRac=0.0244 Radunits=in Diam=0.721
!define Wire Data
New wiredata.neutral Runits=mi Rac=0.592 GMRunits=ft GMRac=0.00814 Radunits=in Diam=0.563
!define Wire Data
New LineGeometry.4wire nconds=4 nphases=3 reduce=yes
~ cond=1 wire=conductor units=ft x=-4 h=28
~ cond=2 wire=conductor units=ft x=-1.5 h=28
~ cond=3 wire=conductor units=ft x=3 h=28
~ cond=4 wire=neutral units=ft x=0 h=24
!define Line Geometry
New line.line1 geometry=4wire length=2000 units=ft bus1=sourcebus bus2=bus2
!define Overhead and Underground Lines
New transformer.T1 xhl=6
~ wdg=1 bus=bus2 conn=delta kV=12.47 kVA=6000 %r=0.5
~ wdg=2 bus=bus3 conn=delta kV=4.16 kVA=6000 %r=0.5
!define Transformer No.1
New line.line2 geometry=4wire length=2500 units=ft bus1=bus3 bus2=bus4
!define Overhead and Underground Lines
New load.load1 phases=3 bus1=bus4 conn=delta kV=4.16 kW=5400 pf=0.9 model=1 vminpu=0.75
!define Load at bus 4
New energymeter.busbar element=line.line2 terminal=1
Set voltagebases=[12.47, 4.16]
calcvoltagebases
solve
show voltages LN node
Export currents
```


Figure 4.4: Script Command of Step-down 4-bus Delta-Delta Balanced

Table 4.7: Voltage Validation Results of OpenDSS Step-down 4-bus Delta-Delta Balanced with IEEE Test

Connection	IEEE Test Results (V)	OpenDSS Results (V)	Percentage of Error (%)
Node 2			
V1	12339	12355	0.13
V2	12349	12364	0.12
V3	12321	12341	0.16
Node 3			
V1	3911	3925.2	0.36
V2	3914	3928.4	0.37
V3	3905	3920.8	0.40
Node 4			
V1	3442	3513	2.06
V2	3497	3558	1.74
V3	3384	3465.6	2.41

Table 4.8: Current Validation Results of OpenDSS Step-down 4-bus Delta-Delta Balanced with IEEE Test

Connection	IEEE Test Results (A)	OpenDSS Results (A)	Percentage of Error (%)
Current 1-2			
I_a	335.8	328.95	2.04
I_b	335.8	328.95	2.04
I_c	336.0	329.07	2.06
Current 3-4			
I_a	1006.7	986.09	2.05
I_b	1006.7	986.09	2.05
I_c	1007.2	986.44	2.06

Refer to Table 4.7 and Table 4.8, the calculated percentages of error are low too. The highest percentage of error between OpenDSS simulation results with IEEE test of voltages and currents is 2.41% detected at node 4.

4.1.5 Step-down 4-Bus Delta-Ground Wye Balanced Load

```
Set datapath= C:\OpenDSSAliahsWorks\4bDYbal
!set Datapath
New Circuit.4BusDYbal basekV=12.47 phases=3 mvasc3=200000 200000
!define Source
New wiredata.conductor Runits=mi Rac=0.306 GMRunits=ft GMRac=0.0244 Radunits=in Diam=0.721
!define Wire Data
New wiredata.neutral Runits=mi Rac=0.592 GMRunits=ft GMRac=0.00814 Radunits=in Diam=0.563
!define Wire Data
New LineGeometry.4wire nconds=4 nphases=3 reduce=yes
~ cond=1 wire=conductor units=ft x=-4 h=28
~ cond=2 wire=conductor units=ft x=-1.5 h=28
~ cond=3 wire=conductor units=ft x=3 h=28
~ cond=4 wire=neutral units=ft x=0 h=24
!define Line Geometry
New line.line1 geometry=4wire length=2000 units=ft bus1=sourcebus bus2=bus2
!define Overhead and Underground Lines
New transformer.T1 xhl=6
~ wdg=1 bus=bus2 conn=delta kV=12.47 kVA=6000 %r=0.5
~ wdg=2 bus=bus3 conn=wye kV=4.16 kVA=6000 %r=0.5
!define Transformer No.1
New line.line2 geometry=4wire length=2500 units=ft bus1=bus3 bus2=bus4
!define Overhead and Underground Lines
New load.load1 phases=3 bus1=bus4 conn=wye kV=4.16 kW=5400 pf=0.9 model=1 vminpu=0.75
!define Load at bus 4
New energymeter.busbar element=line.line2 terminal=1

Set voltagebases=[12.47, 4.16]
calcvoltagebases
solve
show voltages LN node
show currents
Export currents
Export meters
```


Figure 4.5: Script Command of Step-down 4-bus Delta-Ground Wye Balanced

Table 4.9: Voltage Validation Results of OpenDSS Step-down 4-bus Delta-Ground Wye Balanced with IEEE Test

Connection	IEEE Test Results (V)	OpenDSS Results (V)	Percentage of Error (%)
Node 2			
V1	12340	12356	0.13
V2	12349	12364	0.12
V3	12318	12340	0.18
Node 3			
V1	2249	2260.4	0.51
V2	2263	2269.7	0.30
V3	2259	2267.5	0.38
Node 4			
V1	1920	1977.2	2.98
V2	2054	2077.2	1.13
V3	1986	2029.0	2.17

Table 4.10: Current Validation Results of OpenDSS Step-down 4-bus Delta-Ground Wye Balanced with IEEE Test

Connection	IEEE Test Results (A)	OpenDSS Results (A)	Percentage of Error (%)
Current 1-2			
I_a	335.0	328.62	1.90
I_b	331.8	326.10	1.72
I_c	341.6	332.70	2.61
Current 3-4			
I_a	1041.9	1011.37	2.93
I_b	973.7	962.96	1.10
I_c	1007.0	985.58	2.13

Refer to Table 4.9 and Table 4.10, the percentages of error between OpenDSS simulation results of voltages and currents are not high too. The highest percentage of error is 2.98% which is at node 4. The percentages of error are considered low.

4.1.6 Step-up 4-Bus Ground Wye- Ground Wye Balanced Load

```
Set datapath=C:\OpenDSSAliahsWorks\4bYYbalSU
!set Datapath
New Circuit.4BusYYbalSU basekV=12.47 phases=3 mvasc3=200000 200000
!define Source
New wiredata.conductor Runits=mi Rac=0.306 GMRunits=ft GMRac=0.0244 Radunits=in Diam=0.721
!define Wire Data
New wiredata.neutral Runits=mi Rac=0.592 GMRunits=ft GMRac=0.00814 Radunits=in Diam=0.563
!define Wire Data
New LineGeometry.4wire nconds=4 nphases=3 reduce=yes
~ cond=1 wire=conductor units=ft x=-4 h=28
~ cond=2 wire=conductor units=ft x=-1.5 h=28
~ cond=3 wire=conductor units=ft x=3 h=28
~ cond=4 wire=neutral units=ft x=0 h=24
!define Line Geometry
New line.line1 geometry=4wire length=2000 units=ft bus1=sourcebus bus2=bus2
!define Overhead and Underground Lines
New transformer.T1 xhl=6
~ wdg=1 bus=bus2.1.2.3.0 conn=wye kV=12.47 kVA=6000 %r=0.5
~ wdg=2 bus=bus3 conn=wye kV=24.9 kVA=6000 %r=0.5
!define Transformer No.1
New line.line2 geometry=4wire length=2500 units=ft bus1=bus3 bus2=bus4
!define Overhead and Underground Lines
New load.load1 phases=3 bus1=bus4 conn=wye kV=24.9 kW=5400 pf=0.9 model=1 vminpu=0.75
!define Load at bus 4
New energymeter.busbar element=line.line2 terminal=1
Set voltagebases=[12.47, 24.9]
calcvoltagebases
solve
show voltages LN node
Export currents
```


Figure 4.6: Script Command of Step-up 4-Bus Ground Wye- Ground Wye Balanced

Table 4.11: Voltage Validation Results of OpenDSS Step-up 4-bus Ground Wye-Ground Wye Balanced with IEEE Test

Connection	IEEE Test Results (V)	OpenDSS Results (V)	Percentage of Error (%)
Node 2			
V1	7126	7134.0	0.11
V2	7145	7149.5	0.06
V3	7137	7143.2	0.09
Node 3			
V1	13675	13692	0.12
V2	13715	13725	0.07
V3	13698	13711	0.09
Node 4			
V1	13631	13653	0.16
V2	13682	13695	0.10
V3	13661	13678	0.12

Table 4.12: Current Validation Results of OpenDSS Step-up 4-bus Ground Wye-Ground Wye Balanced with IEEE Test

Connection	IEEE Test Results (A)	OpenDSS Results (A)	Percentage of Error (%)
Current 1-2			
I_a	293.0	292.44	0.19
I_b	291.9	291.55	0.12
I_c	292.3	291.92	0.13
Current 3-4			
I_a	146.7	146.46	0.16
I_b	146.2	146.01	0.13
I_c	146.4	146.20	0.14

The highest percentage of error between Table 4.11 and Table 4.12 is 0.19% which is lowest among others percentage of error. In conclusion, simulation results of three-phase step-down transformer models or three-phase step-up transformer models with balanced load are valid when compared to IEEE test results as the highest percentage of error is 3.02% at Table 4.1 where it is at low. Therefore, OpenDSS program is valid to use in execution of power flow of Malaysia distribution system.

4.2 Validation Results of IEEE European Low Voltage Test Feeders

As this project is to study the impact or effects of different penetration of power distributed from grid-connected PV system on the Malaysia residential area distribution networks, the European system or network need to be used in the simulation using Open Distribution System Simulator (OpenDSS) as Malaysia distribution network follow the European system. Therefore, new validation needs to be done.

Since time-series simulation results over a one-day period and static power flow calculation results at some key moments are provided by the test feeders working group of the IEEE Distribution System Analysis Subcommittee, the validation is on load 1 at bus 34, load 32 at bus 614 and load 53 at bus 899. The validation is done used the current values from both OpenDSS simulation and IEEE test results where the current pattern is compared as shown in Figure 4.7, Figure 4.8 and Figure 4.9.

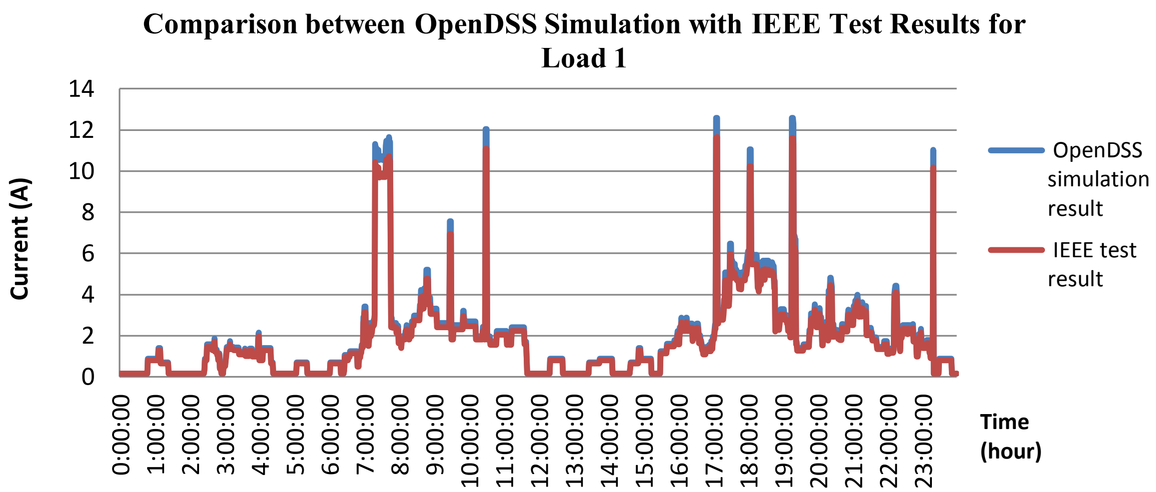

Figure 4.7: Comparison between OpenDSS Simulation with IEEE Test Results for Load 1

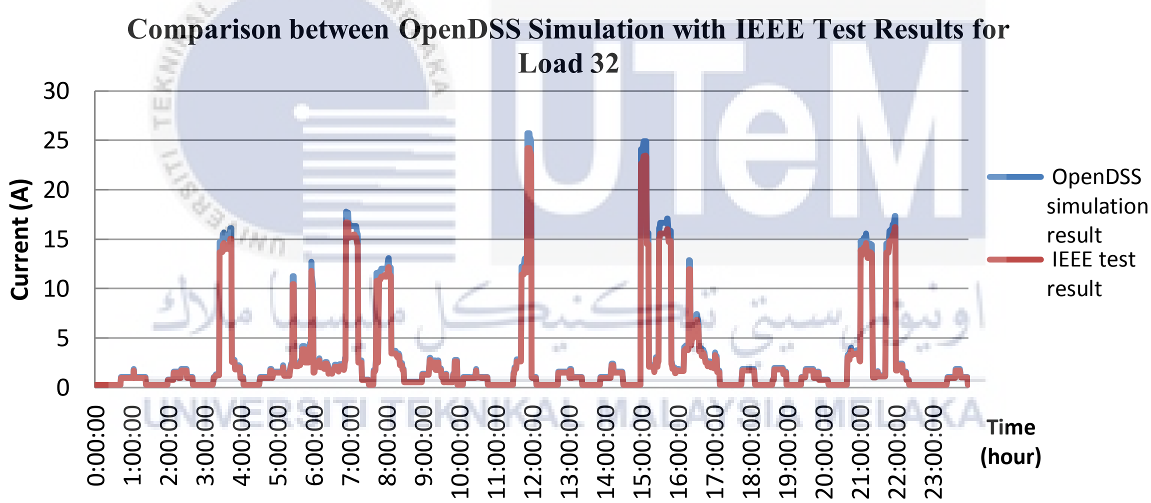

Figure 4.8: Comparison between OpenDSS Simulation with IEEE Test Results for Load 32

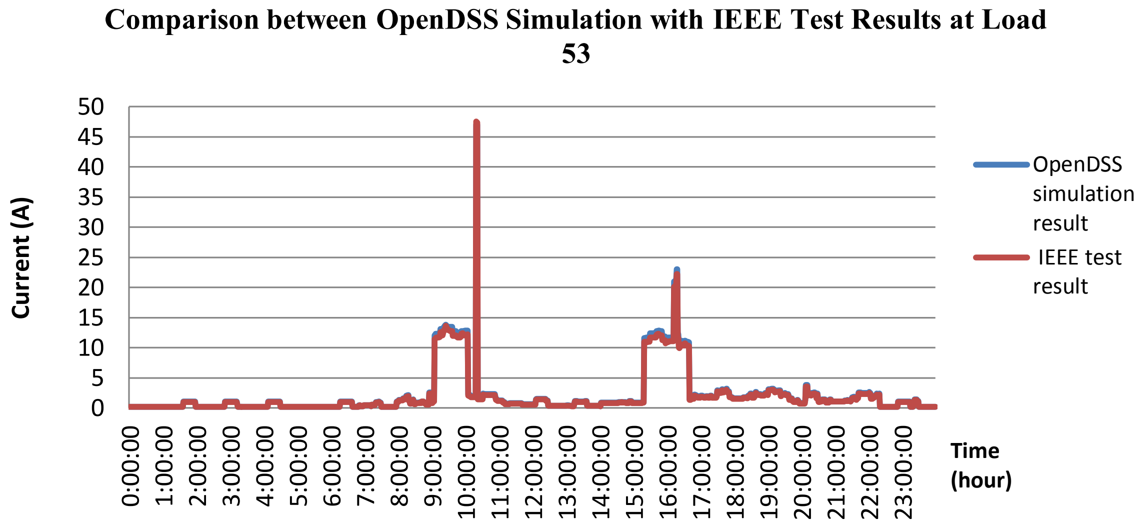

Figure 4.9: Comparison between OpenDSS Simulation with IEEE Test Results at Load 53

Figure 4.7, Figure 4.8 and Figure 4.9 show that there are slightly different between OpenDSS simulation results and IEEE test results. To be more accurate, the results are compared by calculate the percentage of error by using the current values shown in Figure 33, 34 and 35. Table 4.13 shows the percentage error between OpenDSS simulation results and IEEE test results.

Table 4.13: Percentage Error between OpenDSS Simulation and IEEE Test Results

Types of load	Average Value of OpenDSS Simulation Results	Average Value of IEEE Test Results	Percentage Error (%)
Load 1	1.93	1.78	8.43
Load 32	2.83	2.63	7.60
Load 53	2.24	2.12	5.66

The highest percentage error is 8.43% at Load 1 where it is below 10% of percentage error. Although error of percentage is quite high, but then the current shape shows in Figure 4.7, Figure 4.8 and Figure 4.9 compared between OpenDSS simulation results and IEEE test results are the same. Therefore, OpenDSS program is valid to be use in execution of power flow of Malaysia distribution system by using the IEEE European Low Voltage Test Feeders.

4.3 Simulation Results

4.3.1 Introduction

In this section, the results of the research are presented and discussed follow the sequence of cases that have been set which are 0% penetration of PV power and 100% penetration of PV power on the distribution network built by using OpenDSS. At the loads side, the results are measured on the line to see more significant changes. The impacts of PV power penetration on the low voltage side of distribution network in term of voltage characteristics are stated in this chapter at both six selected line loads and at upstream at low voltage side of transformer when two different types of PV power irradiance profile are used in this project.

In this project, to analyze the impact of photovoltaic (PV) power penetration on the selected buses in small scale residential distribution system, there are 55 different actual data of loads provided by IEEE Distribution System Analysis Subcommittee connected in the distribution network built in the simulation where several of the load profile is shown in Appendix B. But, the analysis is done on six chosen loads because of their unique behavior. The six chosen loads are at different buses with different load profile as shown in Figure 4.10 until Figure 4.15.

. Load profile 1 shown in Figure 4.10 shows the normal pattern of energy usage where the used of power is at high in the morning and at night as basically the residents are at home and use electrical equipments. At noon, the uses of power at low as the locals have done most of their house course and the use of electrical equipments not much. Furthermore, some of the residents go to work. As the power set in the simulation for the load is 1 kW and the highest multiplier is 2.771. Therefore, the total power usage read by the OpenDSS is 2.771 kW, the multiplication of 2.771 x 1 kW. The load 1 is connected in single-phase, at phase A and at bus 34.

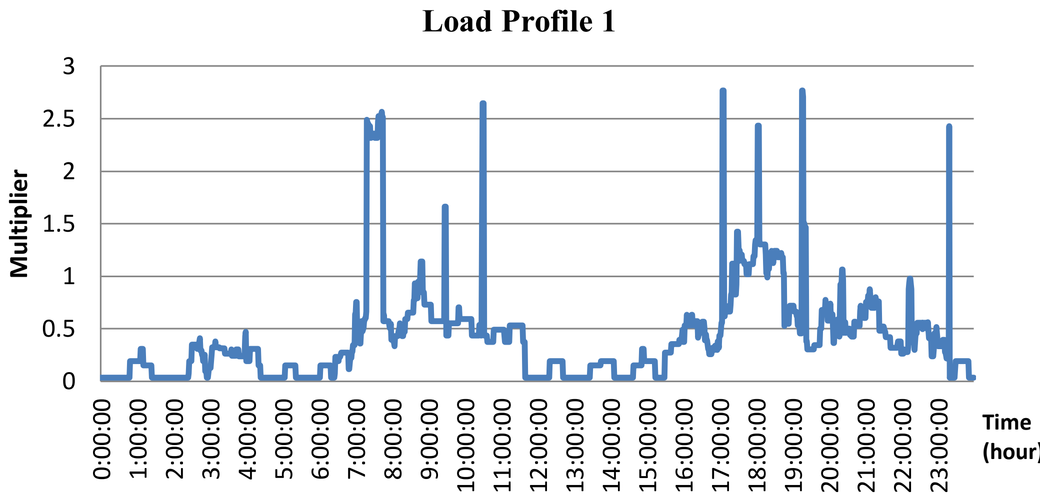

Figure 4.10: Load Profile 1 at bus 34

Load profile 4.11 is very unique to be discuss as the used of energy is at low level where the highest is at 3 kW at certain time noon to night but suddenly at 11.00 p.m. the use of energy is very high which is 15 kW. While the use of energy is lower than 1 kW in the morning. Load profile 7 is connected single-phase, at phase B and at bus 178 in the network.

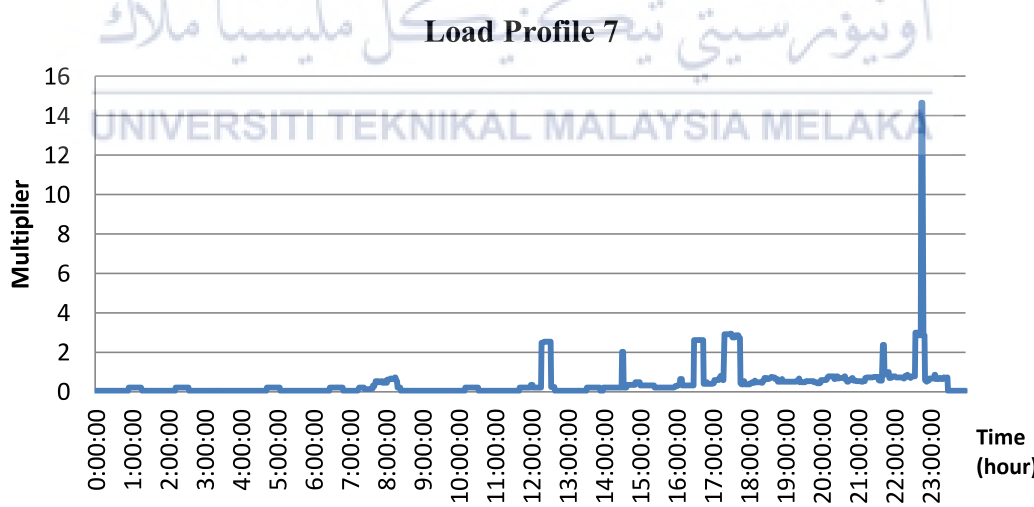

Figure 4.11: Load Profile 7 at bus 178

Load profile 12 shown in Figure 4.12 shows that, power usage increase drastically at 12.00 a.m. with 2.23 kW and starts to drop and remain low until 9.00 p.m. at power range of less than 1 kW. This is probably because many residents in the area were not at home. Then the uses of power start to increase and stay at high level until late night as it is might be because this is the time where the most of the residents were at home and used their electric equipments. The load profile 12 is connected single-phase, phase C at bus 264.

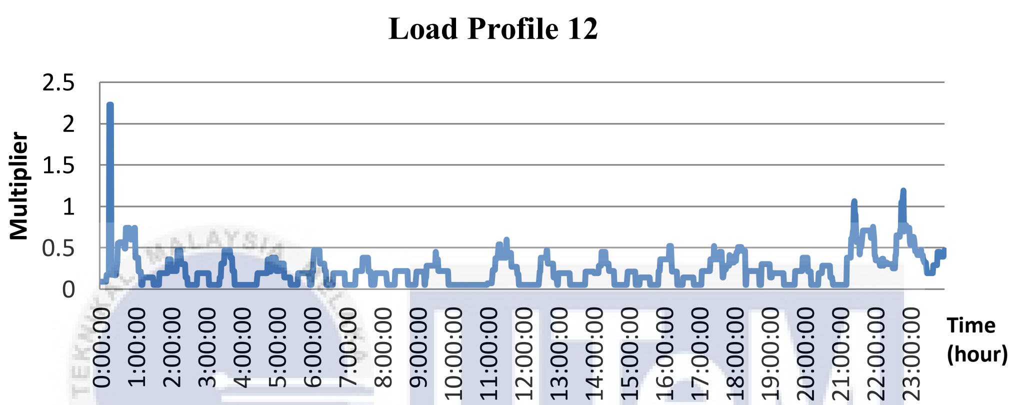

Figure 4.12: Load Profile 12 at bus 264

Load profile 23 shown in Figure 4.13 shows that, electricity consumption is too low at early in morning and the usage started to rise at 12.00 p.m. until 12.00 a.m. But then, the usage of electricity fluctuate high and low at certain time where the used of electricity by the locals not uniformly. The maximum power is at 4.30 p.m. where the maximum level of the power is 9.5 kW. In the network, the load profile 23 is connected single-phase, phase B at bus 406.

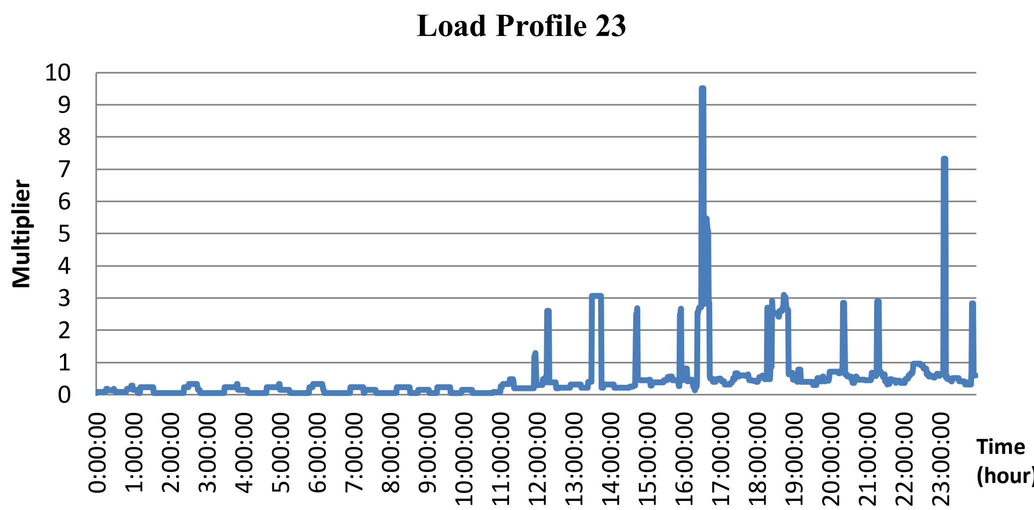

Figure 4.13: Load Profile 23 at bus 406

Load profile 50 shown in Figure 4.14 shows that in the morning the locals used the power at low level until around 1.30 p.m. and the used of power start high at 2.00 p.m. until 11.00 p.m. The used of power drop drastically around 11.00 p.m. as local residents began to go sleep. But then, as the power used at high level by the locals, the power is increase and decrease at certain time. From the analysis, the power is used at high level in short time than remain low level for 1 to 2 hours. The pattern is continuously fluctuating in the same behavior for both in morning till night. The load profile 50 is connected single-phase, phase B at bus 886.

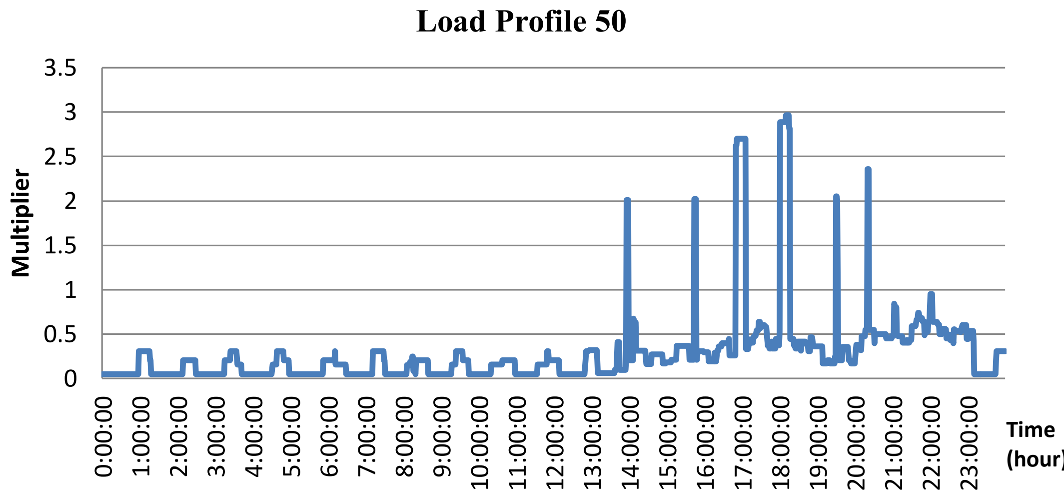

Figure 4.14: Load Profile 50 at bus 886

Load profiles 53 as shown in Figure 4.15 are unique as the graph shows that the used of power is at high level at 9.00 a.m. until 10.00 a.m. and suddenly start decrease drastically for a few minutes and ascending to the maximum power of 11 kW at 10.20 a.m. Then, the power consumption starts to increase again at high level with the value of 5 kW around 3.20 p.m. until 4.40 p.m. Other than the stated time, the power is at very low level. The load profile 53 is connected single-phase, phase B at bus 899 in the network.

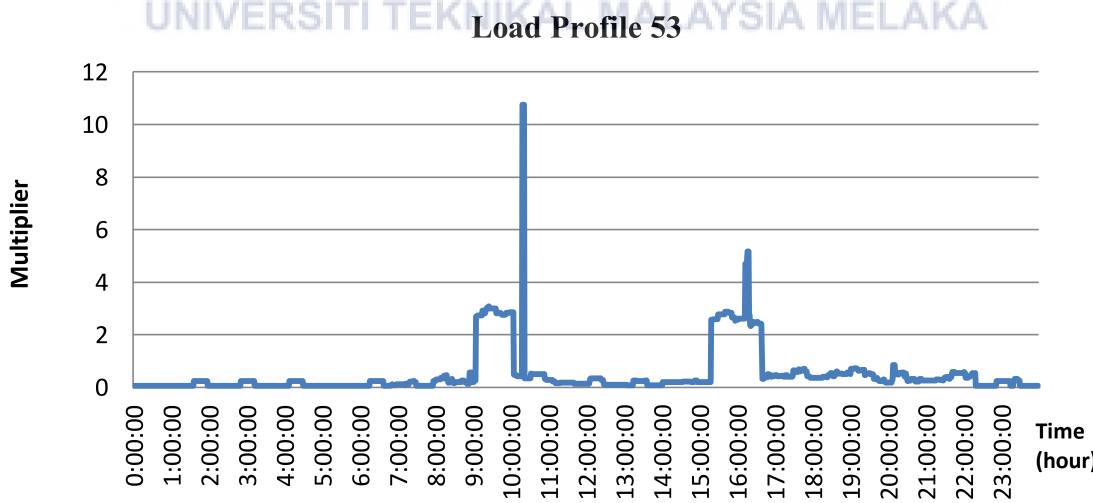

Figure 4.15: Load Profile 53 at bus 899

4.3.2 Simulation Results without PV Penetration

When there is 0% power penetration of PV at the distribution network, voltage at load 1 as shown in Figure 4.16 has no sign of voltage rise occur as Figure 4.17 shows that the voltage of load 1 is fluctuate within 0.95 pu to 1.05 pu proved that there is no voltage rise issue occurred when there is no power penetration at the low voltage side of distribution network.

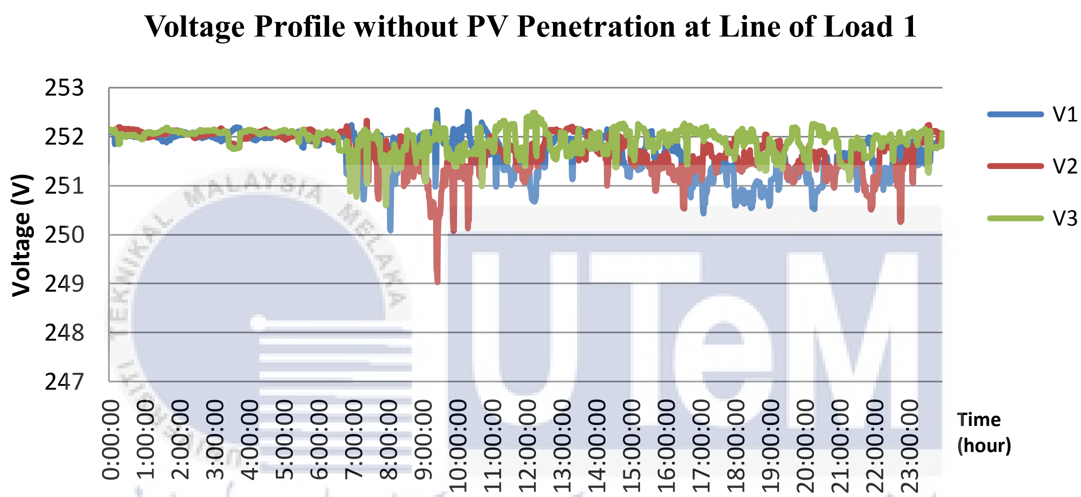

Figure 4.16: Voltage Profile without PV Penetration of Load 1

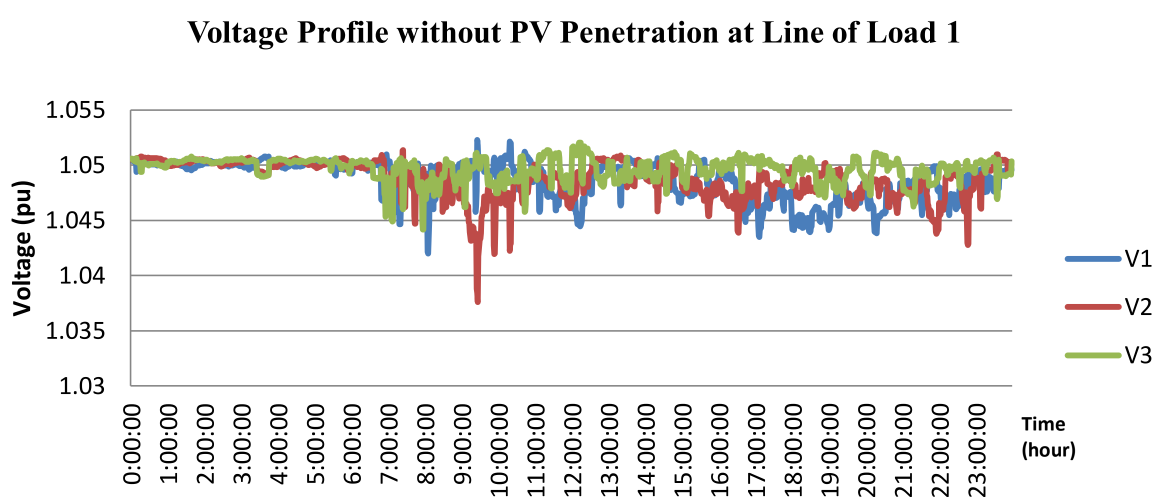

Figure 4.17: Voltage Profile without PV Penetration of Load 1 in Per Unit

Figure 4.18 shows that the measured current of load 1 is exactly the same as the actual load profile connects to it before the simulation is run. Besides that, during 0% penetration of PV power, the behavior of power at upstream of distribution network is measured at the low voltage side of transformer.

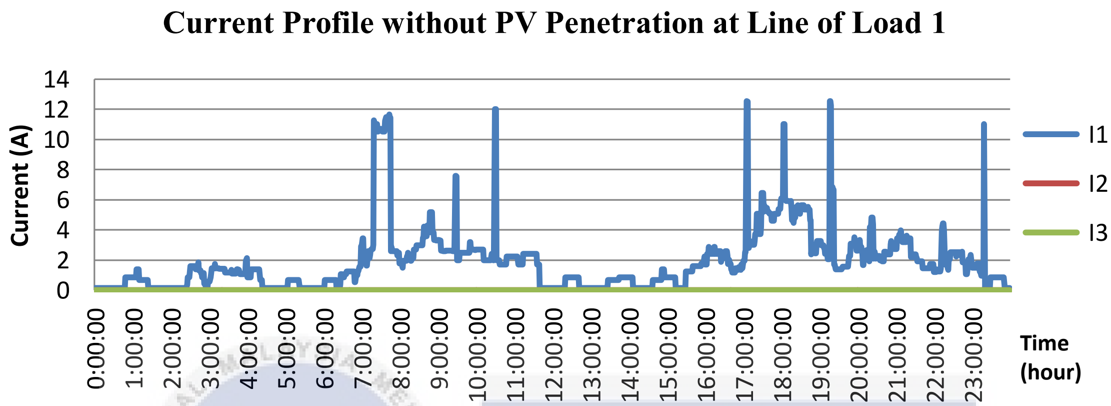

Figure 4.18: Current Profile without PV Penetration of Load 1

Figures 4.19 and show that the voltage at the low voltage side of transformer does not show any voltage rise occurred and Figure 4.20 shows that the voltage at the upstream is fluctuated within the range of Standard IEEE which is 0.95 to 1.05 pu. Therefore, there is also no voltage rise issue at the upstream.

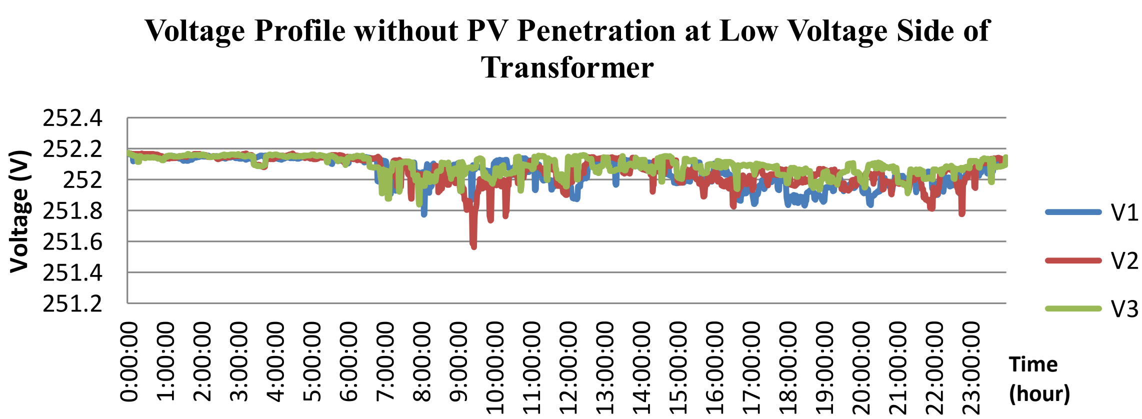

Figure 4.19: Voltage Profile without PV Penetration at Transformer

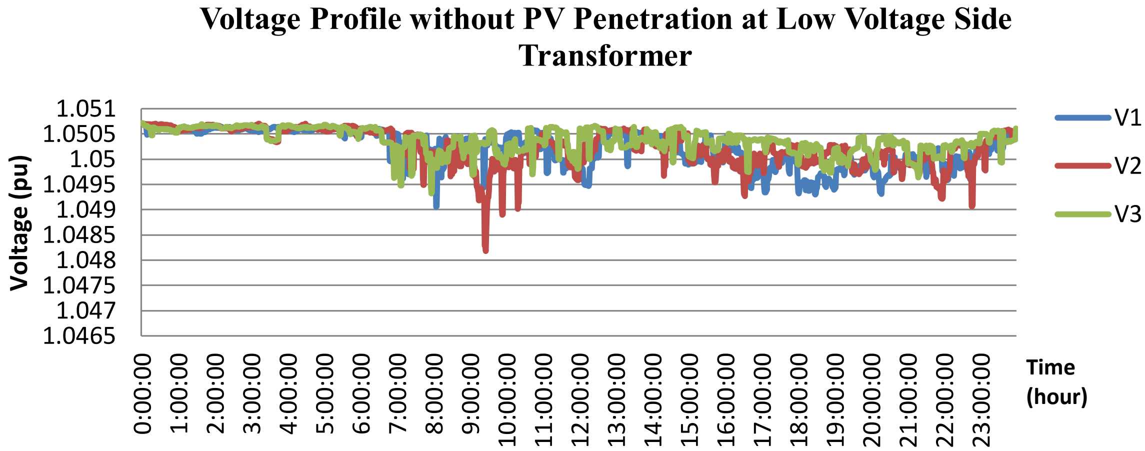

Figure 4.20: Voltage Profile without PV Penetration at Transformer in Per Unit

In addition, Figure 4.21 show that the variation of current is in positive value where it is indicates that there is no generation of power in the system. Therefore, there is no reverse power flow at the upstream as shown in Figure 4.22.

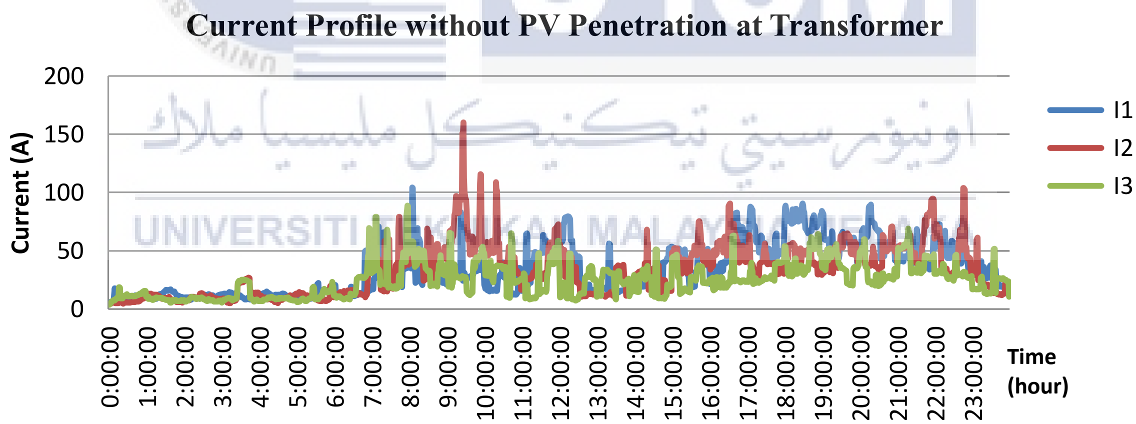

Figure 4.21: Current Profile without PV Penetration at Transformer

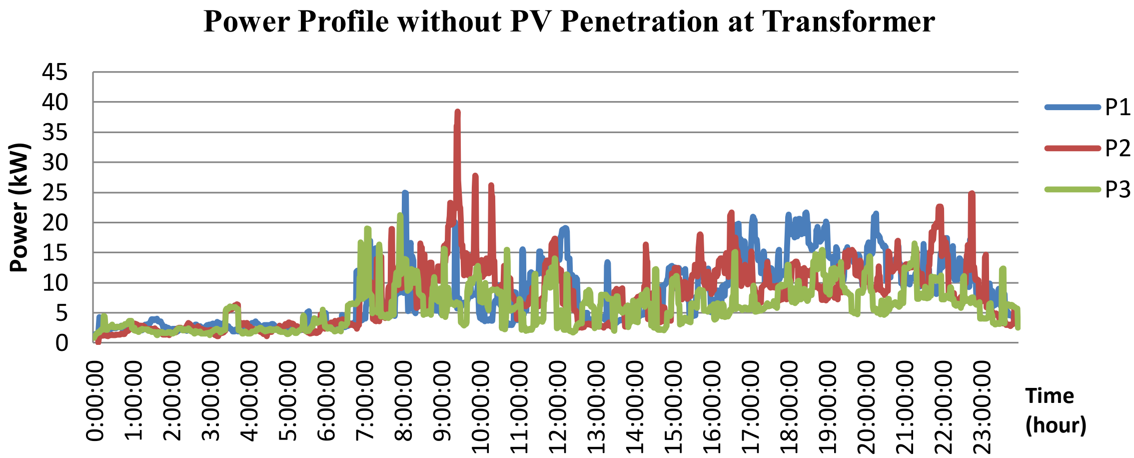

Figure 4.22: Power Profile without PV Penetration at Transformer

As the design of three phase distribution network in this study is in unbalanced, the voltage, current and power profiles is in unbalanced behavior. The analysis in this section is same for load 7, 12, 23, 50 and 53.

4.3.3 Simulation Results with PV Penetration

4.3.3.1 Voltage Unbalance

Simulation results show that, voltage unbalance occurred due to PV power penetration on each of the phases is distributed unequally. In this project, PV is distributed unevenly within each phase where phase-A is connected with 21 photovoltaic, phase-B is connected with 19 photovoltaic while phase-C is connected with 15 photovoltaic and it is 100% PV with 4 kW power penetration in the network. Therefore, voltage magnitude is dissimilar in each phase. As phase-A is connected with more photovoltaic compare to phase-B and phase-C, voltage is higher at phase-A than other phases as shown in Figure 4.23 and Figure 4.24 where this scenario is apply in both, clear sky irradiance of PV and high variability irradiance of PV. This situation creates uneven or unbalanced voltage rise at the loads side.

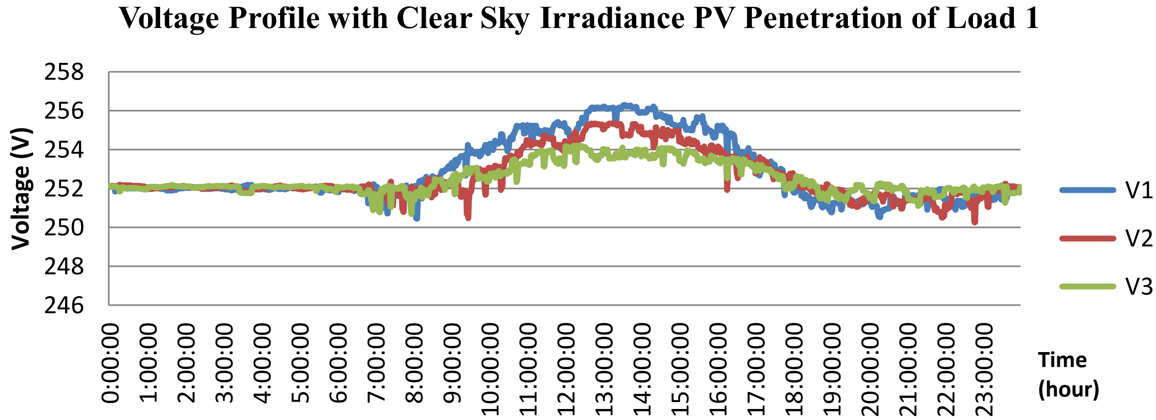

Figure 4.23: Voltage Profile with Clear Sky Irradiance PV Penetration of Load 1

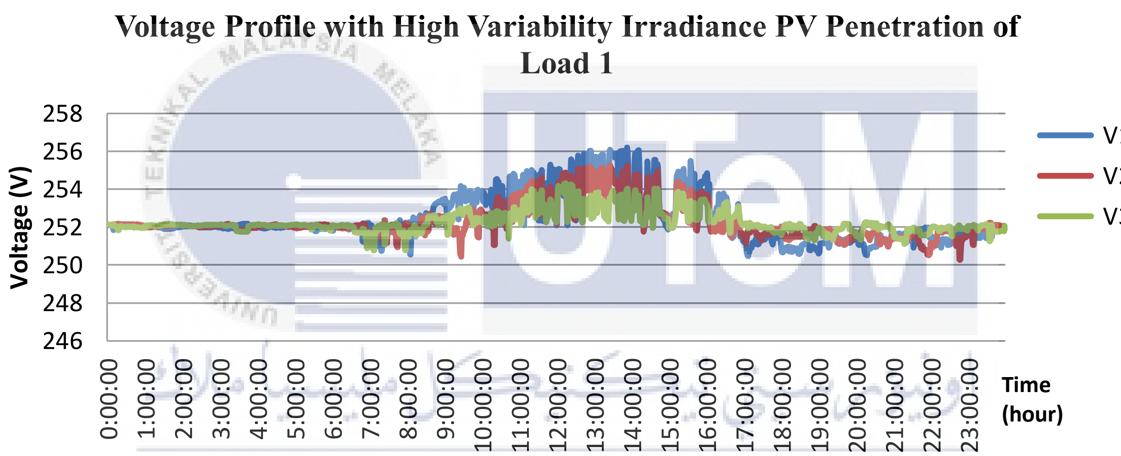

Figure 4.24: Voltage Profile with High Variability Irradiance PV Penetration of Load 1

According to researcher in [7] and [8], the unbalanced voltage in the network disrupts the stability of the grid and uneven voltage rise at the distribution level creates even worst condition on grid stability. Therefore, the installation of integration PV on grid on each phase at distribution network should be control where the PVs need to be install equally, according to [9], the unbalanced voltage at the phases can be reduced by distribute PV power in each of the phases equally.

Load 7, 12, 23, 50 and 53 simulation results show the same behavior of voltage magnitude, where the three phase magnitude voltage is dissimilar and magnitude voltage at phase-A is higher than phase-B and phase-C whether with clear sky irradiance profile or high variability irradiance profile of PV. These two conditions lead to voltage unbalance and develop voltage rise which create a worst case to stability of distribution network. Simulation results of load 7, 12, 23, 50 and 53 are shown in Appendix C.

Unbalance voltage is also occurred at the upstream as shown in Figure 4.25 and Figure 4.26 where the magnitude of voltage is dissimilar for each phase for both clear sky irradiance and high variability irradiance of PV. Through the analysis, found that any impacts at load side do affect the upstream of distribution level.

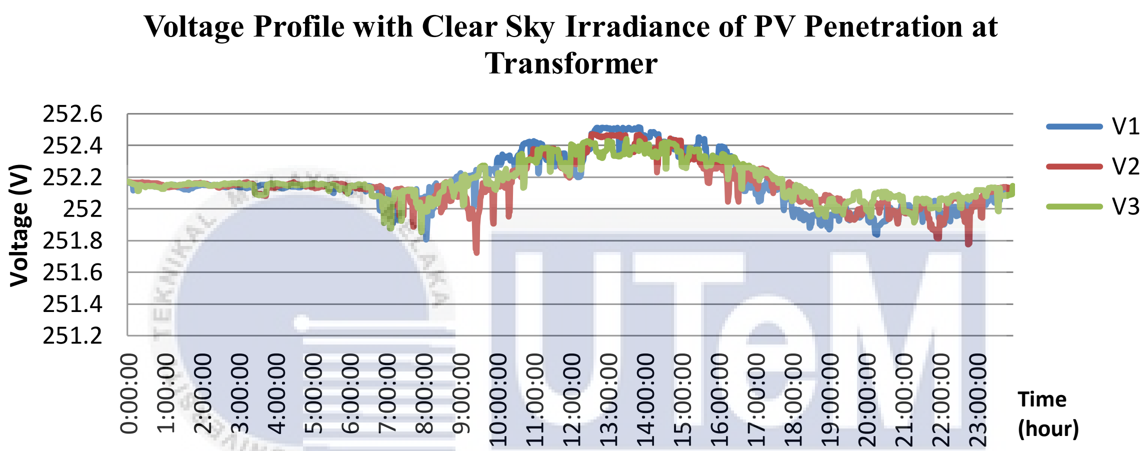

Figure 4.25: Voltage Profile with Clear Sky Irradiance PV Penetration at Transformer

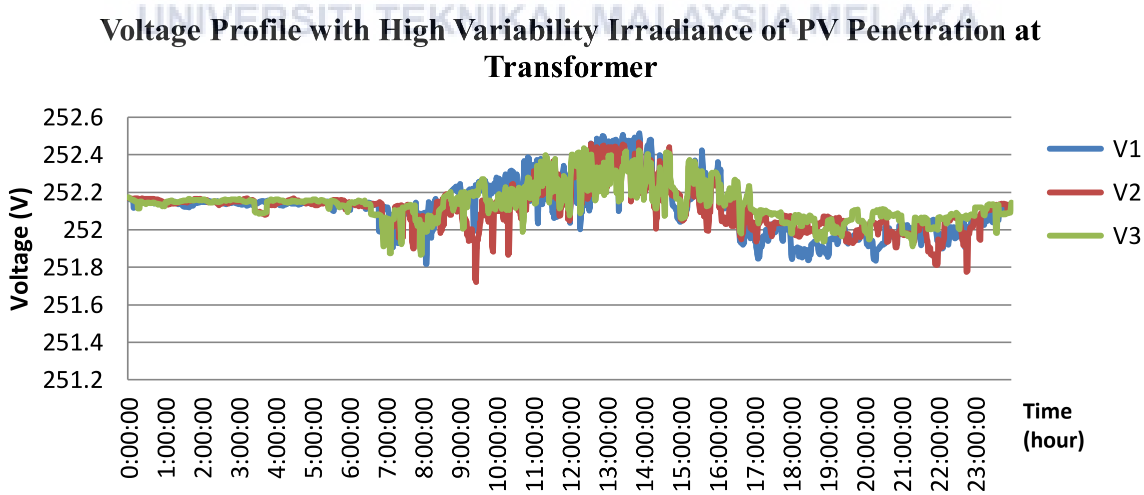

Figure 4.26: Voltage Profile with High Variability Irradiance PV Penetration at Transformer

4.3.3.2 Voltage Rise

The simulation results show that voltage rise do occurred at the distribution level when there is PV power penetration at the load side. Figure 4.27 and Figure 4.28 show that the fluctuation of voltage at load side has exceeded the range of normal voltage fluctuation in the traditional distribution network which is within 0.95 pu to 1.05 pu.

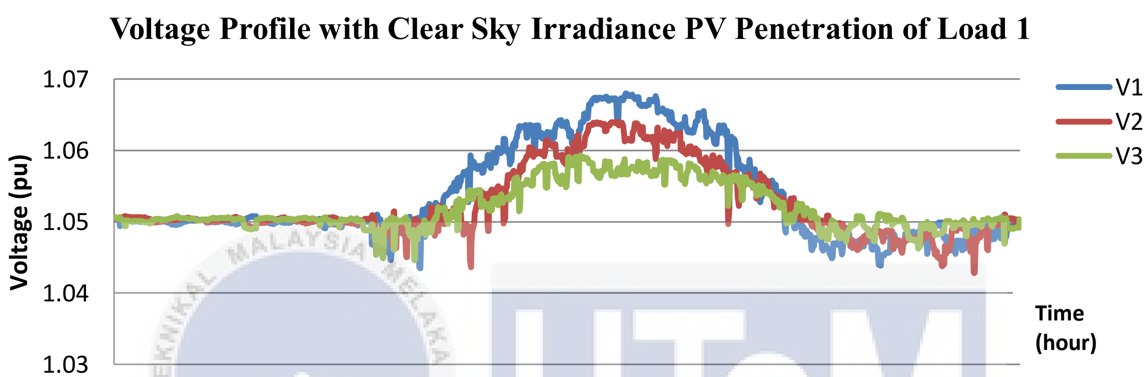

Figure 4.27: Voltage Profile with Clear Sky Irradiance PV Penetration of Load 1 (pu)

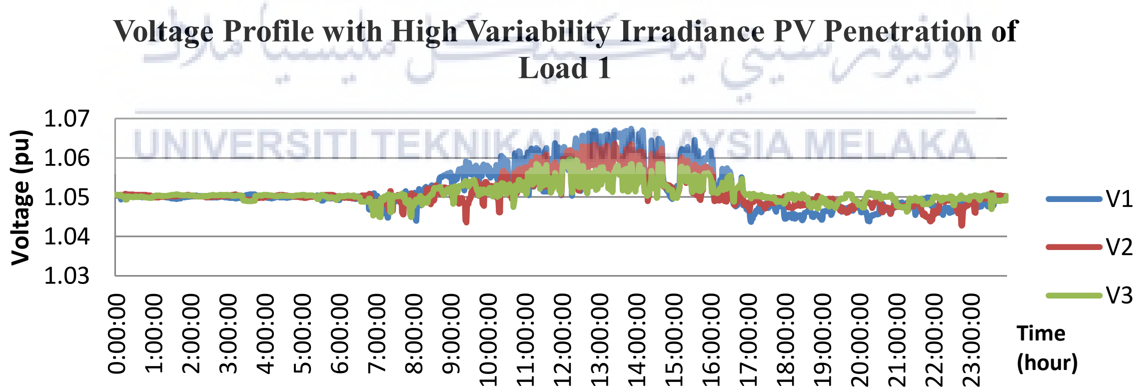

Figure 4.28: Voltage Profile with High Variability Irradiance PV Penetration of Load 1 (pu)

Voltage rise is also occurred at the upstream as shown in Figure 4.29 and Figure 4.30 when there is penetration of PV power. At both, downstream and upstream, the three phases voltages critically rise where the voltage magnitude is exceed 1.05 pu. But then, the voltage rise at the upstream at low voltage side of the transformer is not high as at the load side.

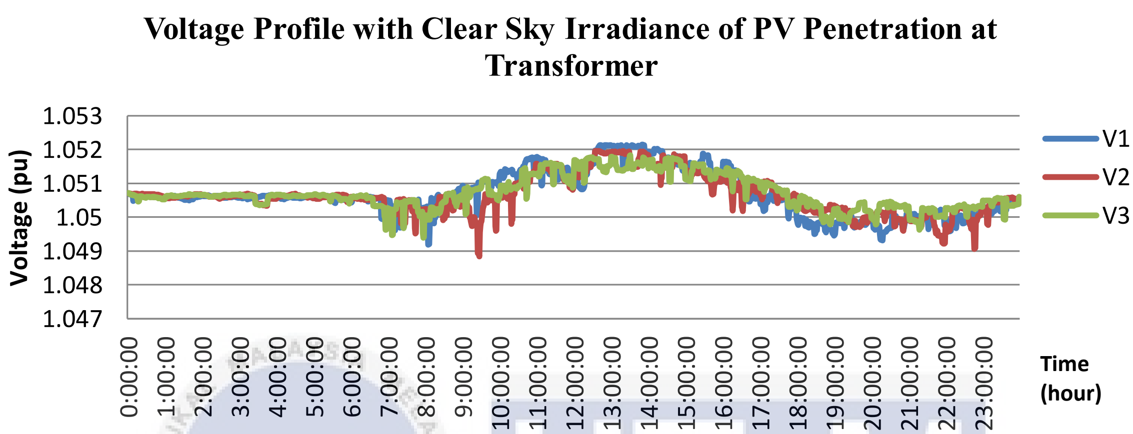

Figure 4.29: Voltage Profile with Clear Sky Irradiance PV Penetration at Transformer (pu)

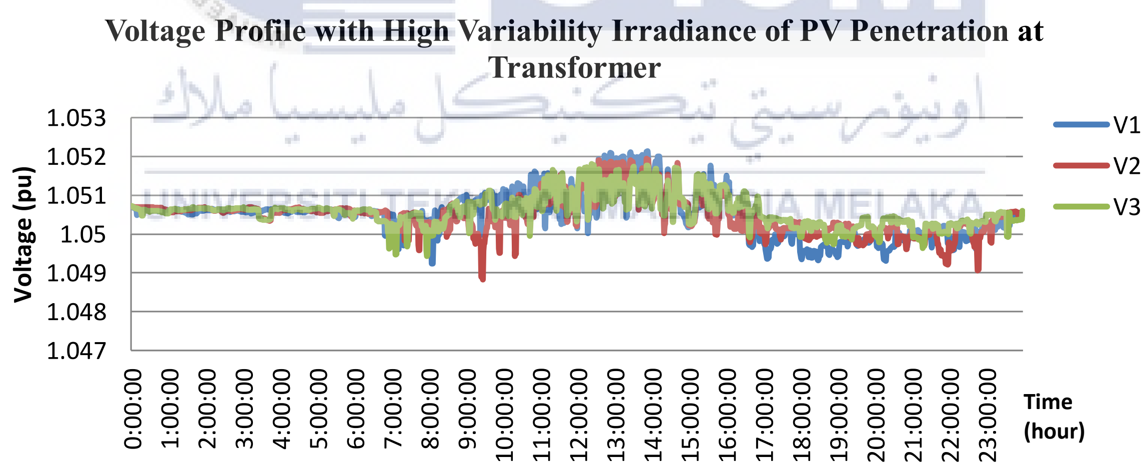

Figure 4.30: Voltage Profile with High Variability Irradiance PV Penetration at Transformer in Per Unit

The results of the simulation proved that for an unbalanced network, each phases react differently to the change of PV power output. Therefore, each of the phases can have a voltage rise that exceeds the critical value. This cannot be seen in balanced network where PV is installed equally within the three phases in the network. Besides that, through the analysis, the rise of voltage magnitude follows the pattern of irradiance profile of PV. Therefore, the voltage rise issue is raised when the penetration of PV power generation connected to the load is suddenly goes high in the short period of time especially during noon.

Through the actual data of sun irradiance in Malaysia, the penetration of PV power is fluctuate high from 8.00 a.m. to 2.00 p.m. Therefore, voltage rises critically within that period of time with 100% of PV power penetration in the network. In conclusion, PV power fluctuation depends on weather conditions and affects the voltage fluctuation in distribution networks. Therefore, voltage rise occurs due to fluctuation of voltage on grid. Same goes to load 7, 12, 23, 50 and 53, where the simulation results show the same behavior. The simulation results are shown in Appendix D.

3.3.3.3 Reverse Power Flow

Reverse power flow is occurred when the power generates on grid by PV is higher and during that time the load demand is low. This situation is shown in Figure 4.31 where the red line show the power generates on grid by PV while blue line in the figure shows the load demand profile. As a result, the current is inverted during power generates by PV is higher than the load demand as shown in Figure 4.32. According to [10], the grid operation at the distribution side becomes most challenging at this condition. Furthermore, during the PV power penetration higher than load demand, household can damage because voltage is more than necessary.

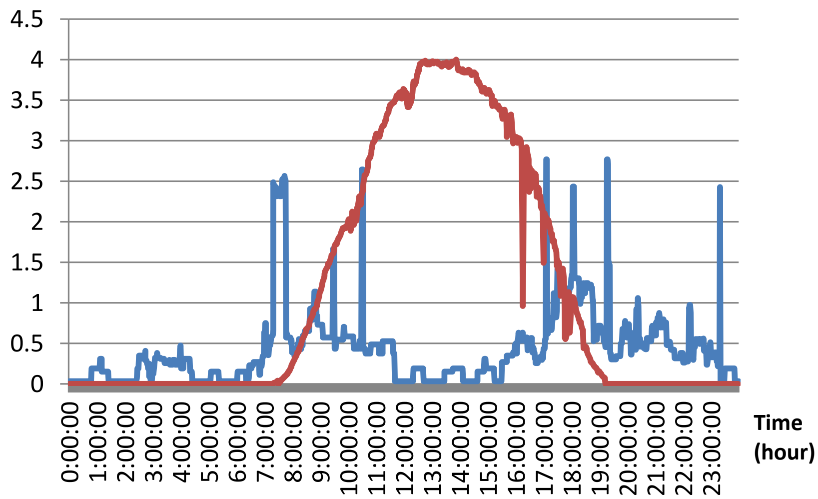

Figure 4.31: Graph of Penetration of Photovoltaic Higher Than Load Demand

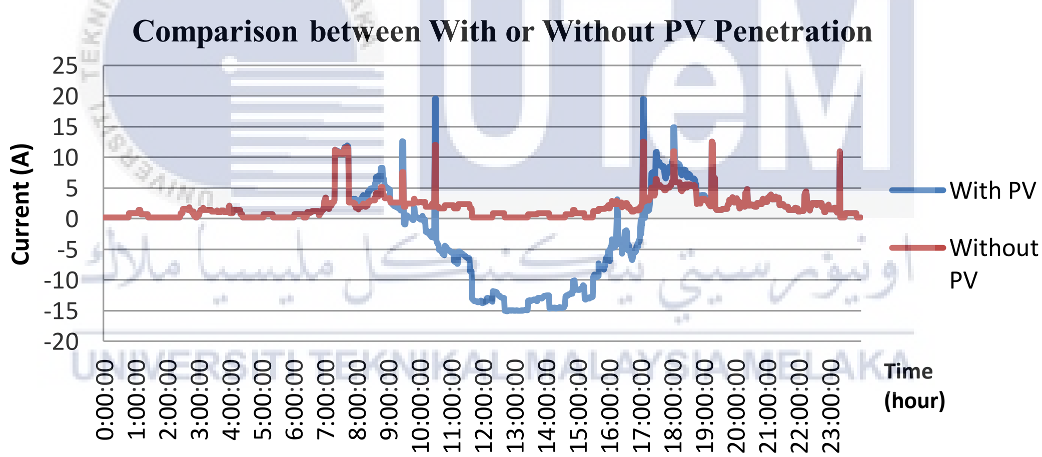

Figure 4.32: Comparison of Current Profile between With and Without PV Penetration at Load 1

Figure 4.33 and Figure 4.34 show the behavior of current at load 1 for both two types of sun irradiance profile that are used in this project. The inverted current shows that the generation power of photovoltaic behave as negative load. Simulation results for load 7, 12, 23, 50 and 53 are shown in Appendix E.

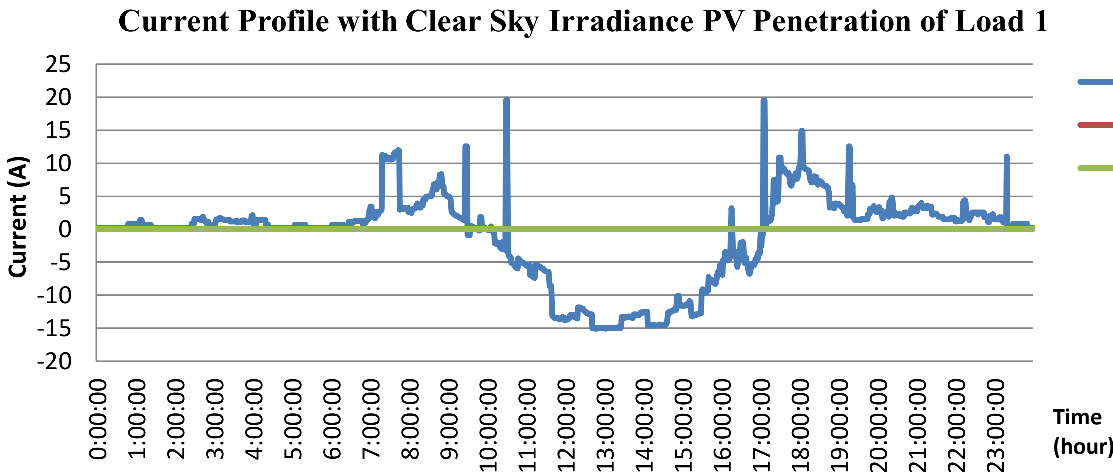

Figure 4.33: Current Profile with Clear Sky Irradiance PV Penetration of Load 1

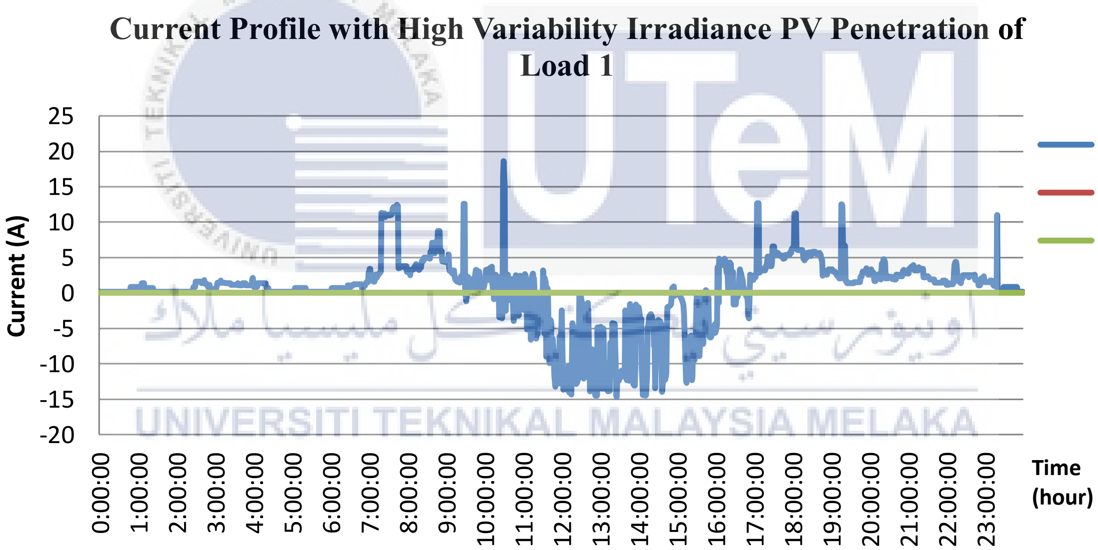

Figure 4.34: Current Profile with High Variability Irradiance PV Penetration of Load 1

Figure 4.35 and Figure 4.36 show that the inverse power flow also occurred at upstream. The normal flow of power in the distribution system is the generated power distribute in one direction which is from feeder to load where voltage at the feeder is higher than the connection point at the customer side which is at the load side. But, during the period of high penetration of PV power on grid which is within 8.00 a.m. to 2.00 p.m. shown in Figure 4.31 the sun irradiation is the highest, PV generate an excessive power which is more than consumer needed or more than load demand.

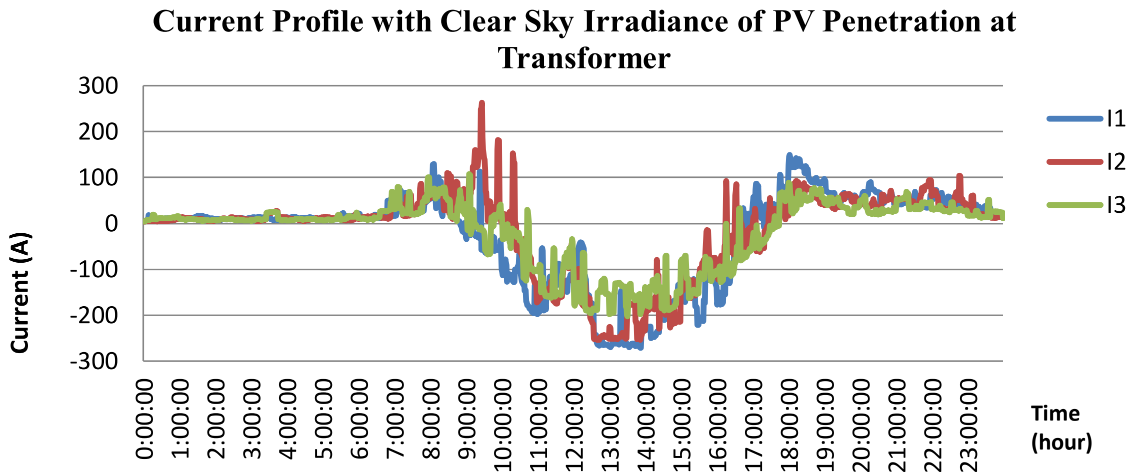

Figure 4.35: Current Profile with Clear Sky Irradiance PV Penetration at Transformer

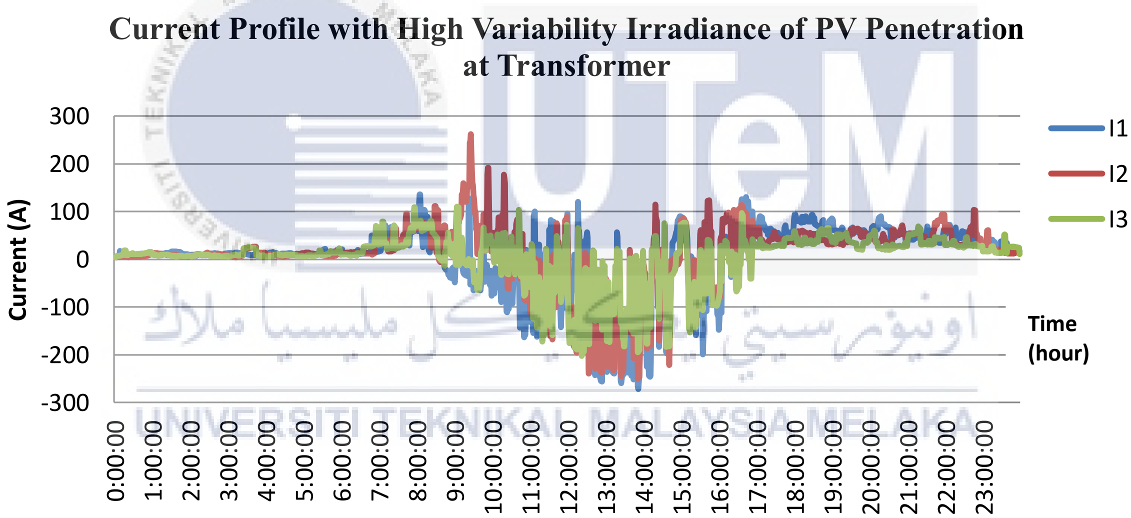

Figure 4.36: Current Profile with High Variability Irradiance PV Penetration at Transformer

As a result, direction of power flow is reversed as shown in Figure 4.37 and Figure 4.38 where most of the times the grid-connected PV system will send the extra electrical power back to the normal mains electrical grid. Now power flows from the connection point at the load side to the feeder. The impact of reverse power flow is it caused voltage rise as simulation results shown that the voltage issue does occur at both downstream and upstream.

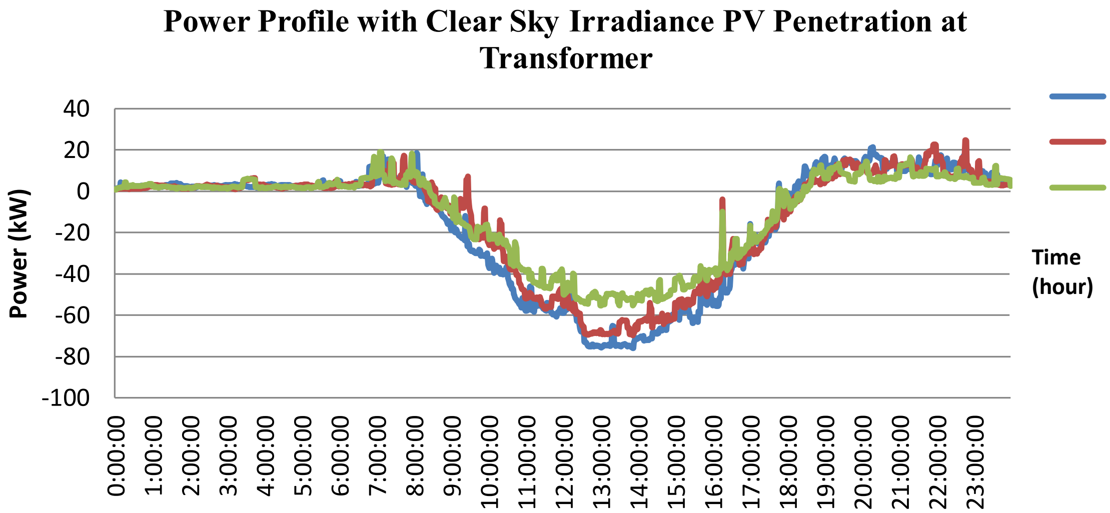

Figure 4.37: Power Profile with Clear Sky Irradiance PV Penetration at Transformer

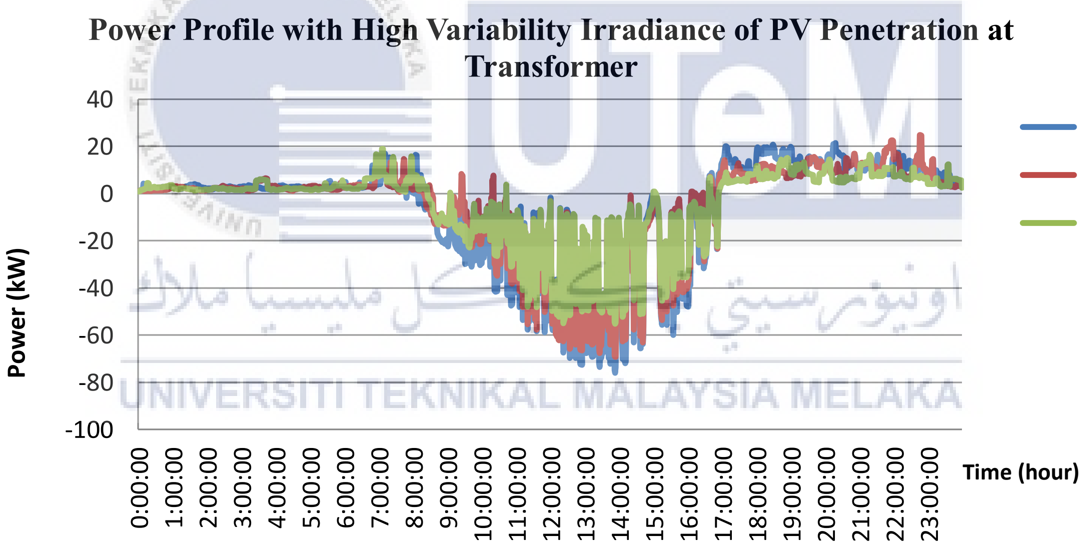

Figure 4.38: Power Profile with High Variability Irradiance PV Penetration at Transformer

Besides that, by comparing Figure 4.37 and Figure 4.38, high variability irradiance profile has more impact towards the distribution system than clear sky irradiance profile. This is because, high variability profile fluctuate more frequent compared to clear sky irradiance profile, where this behavior of PV power penetration can caused protection equipment started to lose the direction in determining the time of trip amongst them. In addition, generation of PV at consumption side will reduce the total power flow from transformer side which means kWh reduction from transformer point of view. Lastly, power reduction or inverted behavior of power when there is PV power penetration does impact on voltage profile which voltage profile increase.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

In conclusion, a small scale Malaysian residential distribution network follow the standard of European system with base frequency of 50Hz, three-phase step-down transformer at substation rated MVA of 0.8 with rated voltages of 11/0.416 kV, and a Delta/grounded-Wye connection, the resistance and reactance of the windings are 0.4% and 4% (use the kVA and kV base of the high-voltage winding), respectively and 205 lines, 906 buses, 55 loads connected in single phase with 0.23 kV, 0.95 power factor in Wye-connection is simulated using OpenDSS.

Besides that, small scale distribution system with penetration of photovoltaic power is simulated using OpenDSS software with two types of PV power penetration which is clear sky irradiance profile and high variability irradiance profile. In this project the penetration of PV power is distributed unequally among three phases creates the unbalanced small scale three phase distribution network environmental study. The power generation of PV is penetrated with maximum 100% penetration where each of the PV generator power is set 4 kW to study the impact of PV system in a residential area.

Lastly, the impact of distributed photovoltaic power to the distribution network on voltage and current characteristics is evaluated. The impacts of PV penetration on the distribution network are voltage unbalanced, voltage rise and reverse power flow. The significant findings of this project are voltage rise exceed the standard of 1.05 pu during noon where the voltage rise occurred at load side is higher than at the low voltage side of the transformer. Besides that, the high variability irradiance has more impact than clear sky irradiance during reverse power flow as the fluctuation of high variability irradiance is fluctuate more often compared to clear sky irradiance. Furthermore, the change in voltage and current behavior at the load sides affects the upstream at low voltage side of the transformer in distribution system. Therefore, the objectives are achieved.

5.2 Recommendations for Future Work

For future study, as this project used 100% PV power penetration, it is highly recommended to use different level of PV to study the impact of distributed photovoltaic (PV) power penetration to the distribution network. Besides that, it is suggested to use larger model of distribution network to study the impact of distributed photovoltaic (PV) power penetration on the low voltage side of distribution network. Lastly, to study the impact of PV power penetration on the distribution system in more detail, the interfacing process between OpenDSS and Matlab can be use especially when tap change of transformer is use in the study.

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APPENDICES

APPENDIX A – IEEE 4 NODE TEST FEEDER

Both the primary line (Node1-Node 2) and the secondary line (Node 3-node4) will be constructed using the pole configuration shown in Figure 2.

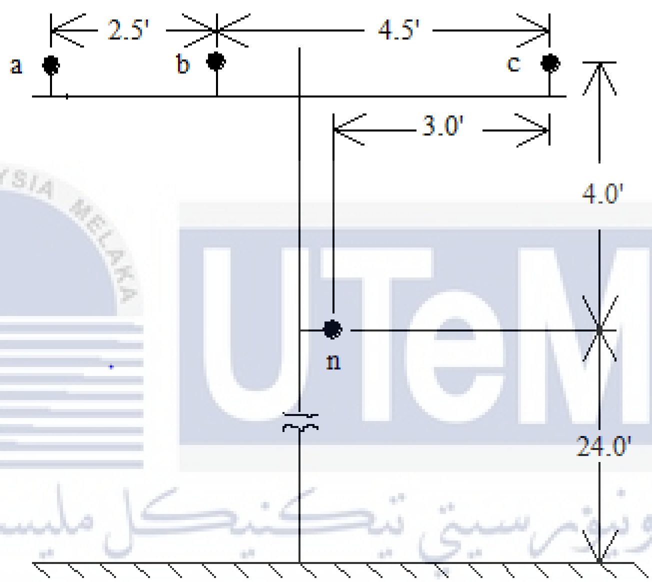


Figure 2 – Pole Configuration

Phase Conductor: 336,400 26/7
GMR = 0.0244 ft., Resistance = 0.306 Ω/mile, Diameter = 0.721 inch

Neutral Conductor: 4/0 6/1 ACSR
GMR = 0.00814 ft., Resistance = 0.592 Ω/mile, Diameter = 0.563 inch

The source is a 12.47 kV line-to-line infinite bus.

Three-Phase Transformer Data:

Connection	kVA	kVLL-high	kVLL-low	R - %	X - %
Step-Down	6,000	12.47	4.16	1.0	6.0
Step-Up	6,000	12.47	24.9	1.0	6.0

Open Wye – Open Delta:
(Two Single Phase Transformers Each Rated)

Connection	kVA	kV-high	kV-low	R - %	X - %
Step-Down	2000	7.2	4.16	1.0	6.0
Step-Up	2000	7.2	24.9	1.0	6.0

Closed Connections Load Data:

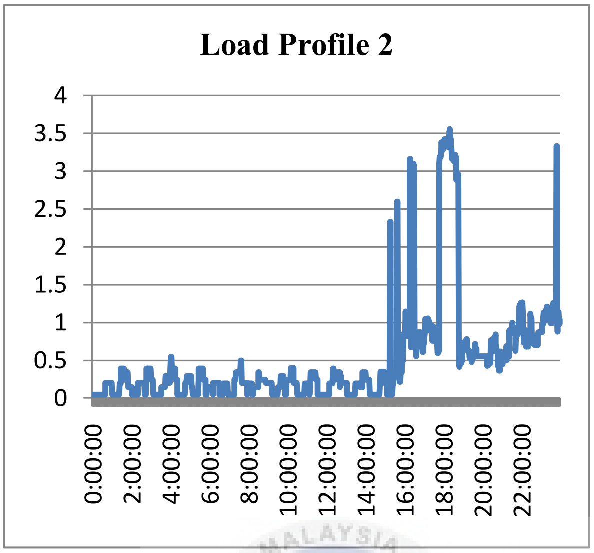
	Balanced	Unbalanced
Phase-1		
kW	1800	1275
Power Factor	0.9 lag	0.85 lag
Phase-2		
kW	1800	1800
Power Factor	0.9 lag	0.9 lag
Phase-3		
kW	1800	2375
Power Factor	0.9 lag	0.95 lag

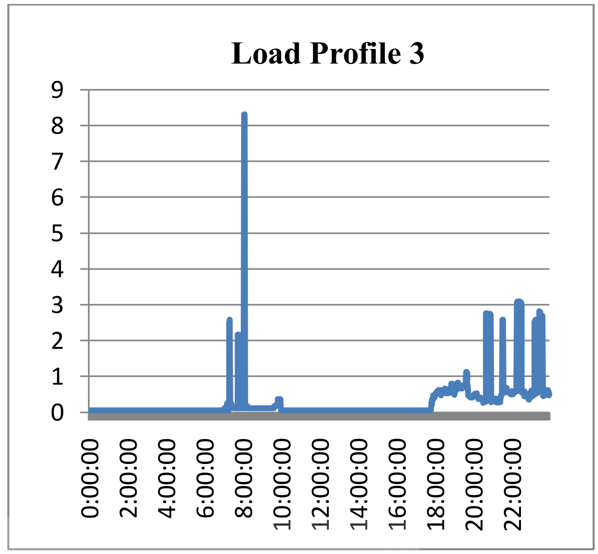
Open Connection Load Data:

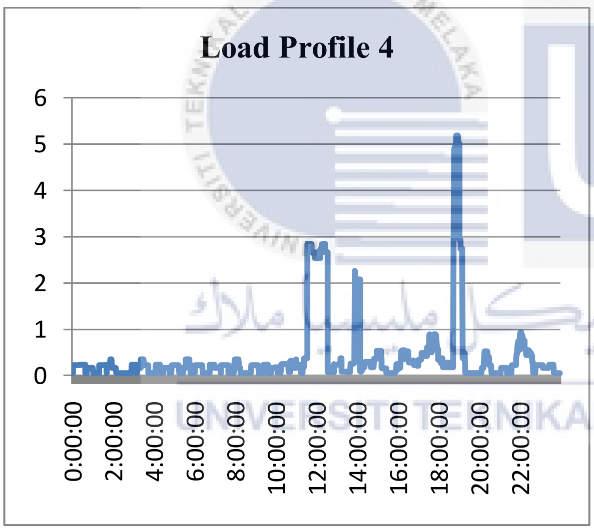
	Balanced	Unbalanced
Phase-1		
kW	1200	850
Power Factor	0.9 lag	0.85 lag
Phase-2		
kW	1200	1200
Power Factor	0.9 lag	0.9 lag
Phase-3		
kW	1200	1583.33
Power Factor	0.9 lag	0.95 lag

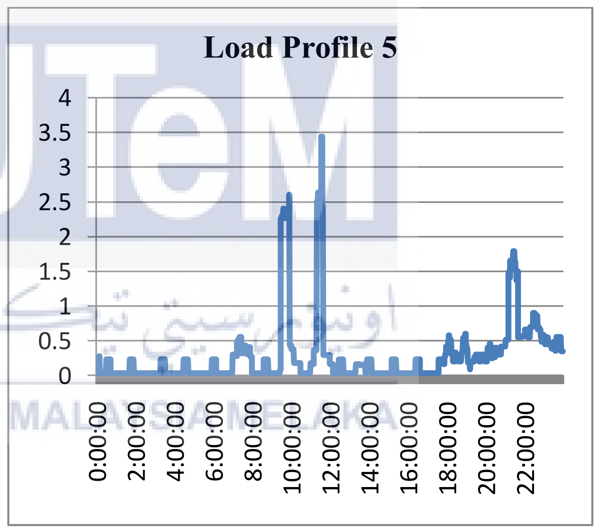
Loads are connected in grounded wye for four wire line configurations and connected in closed delta for three wire line configurations.

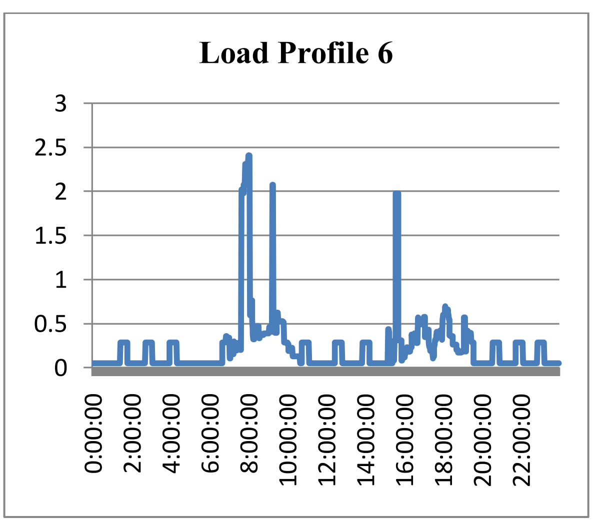
APPENDIX B- LOAD PROFILE

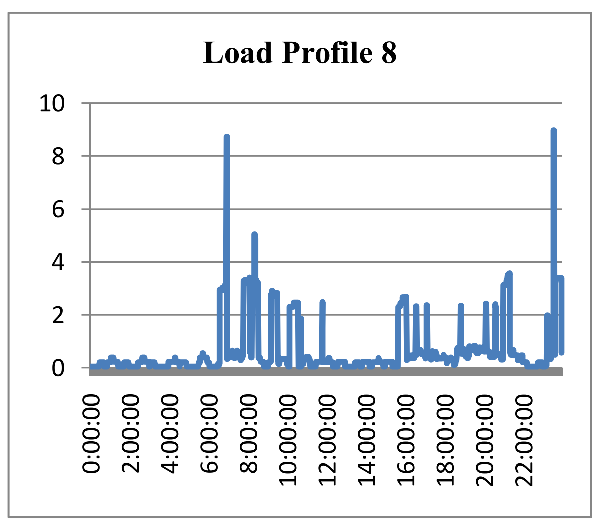


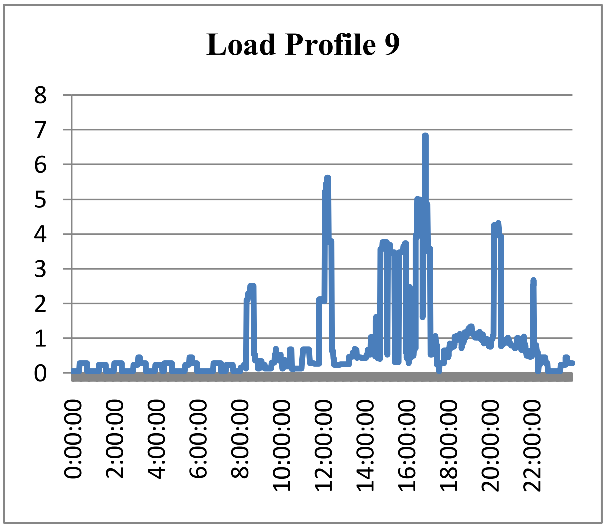








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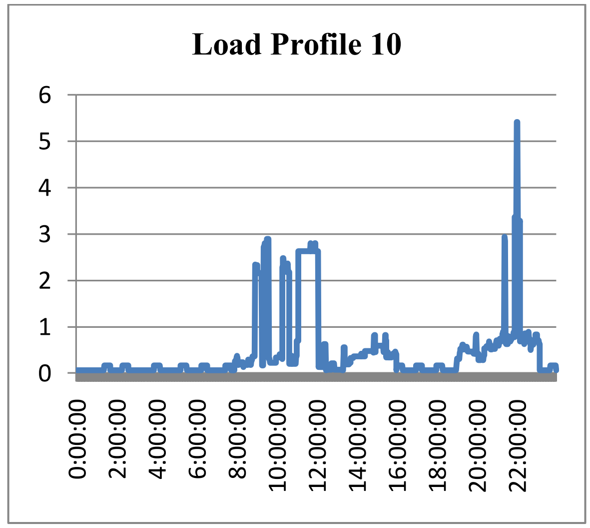
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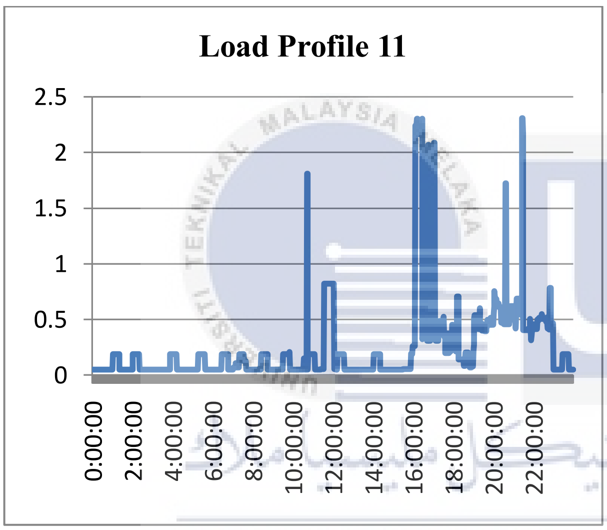
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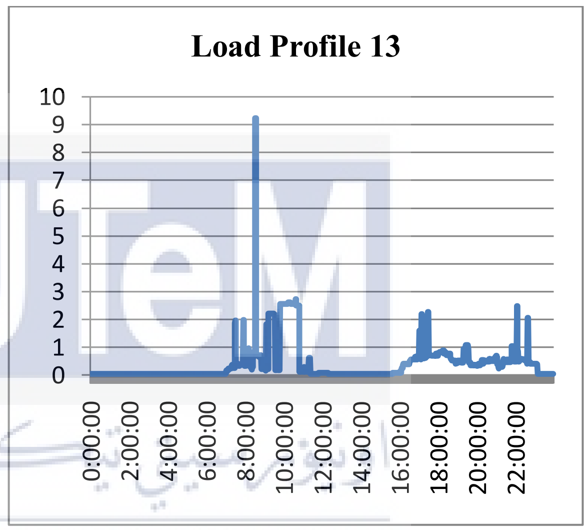
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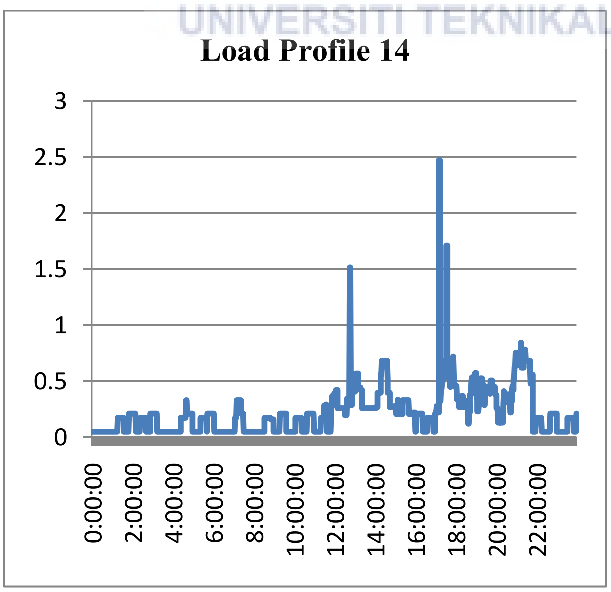
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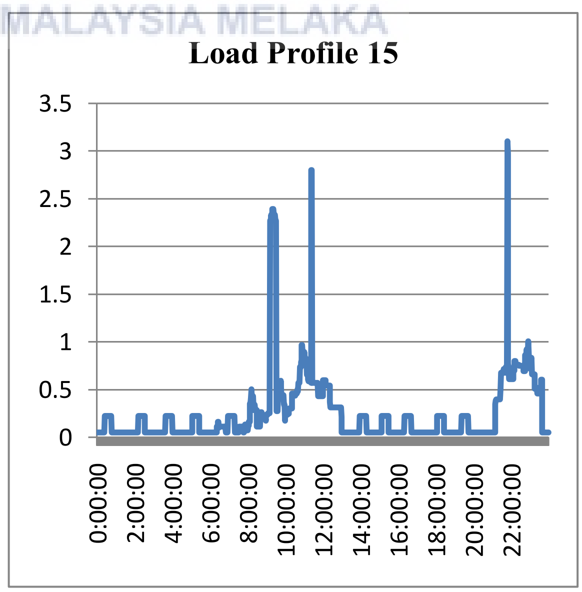
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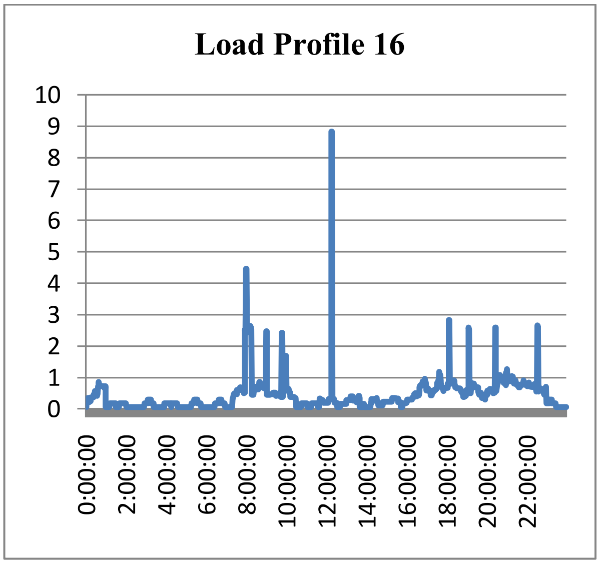
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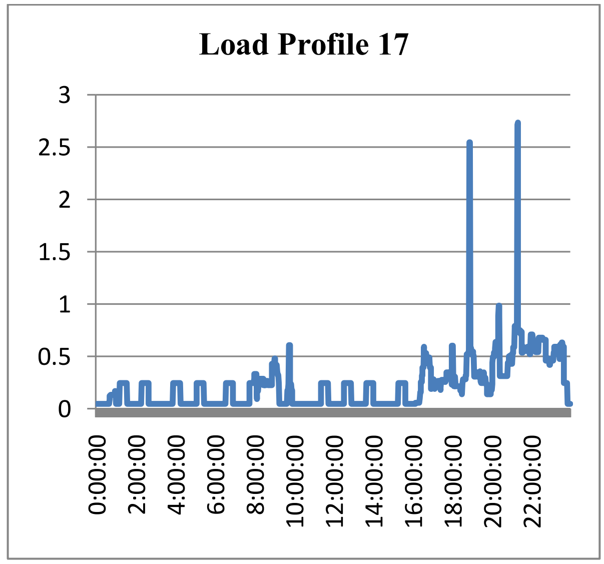
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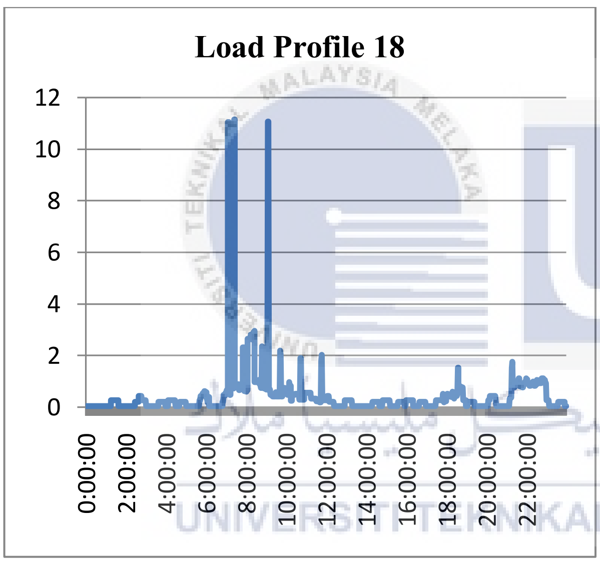
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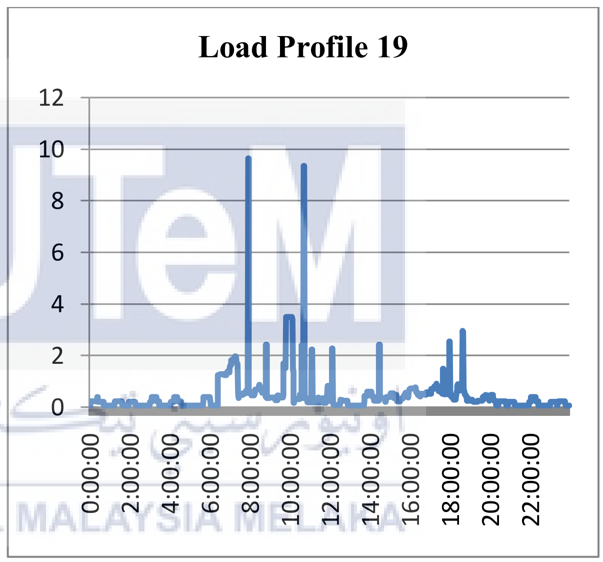
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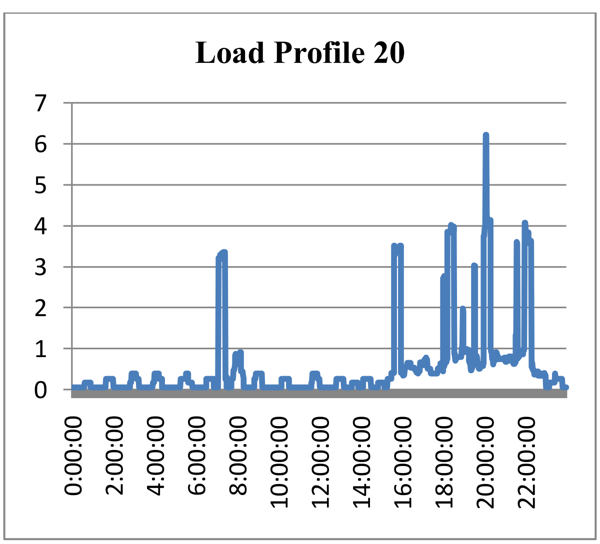
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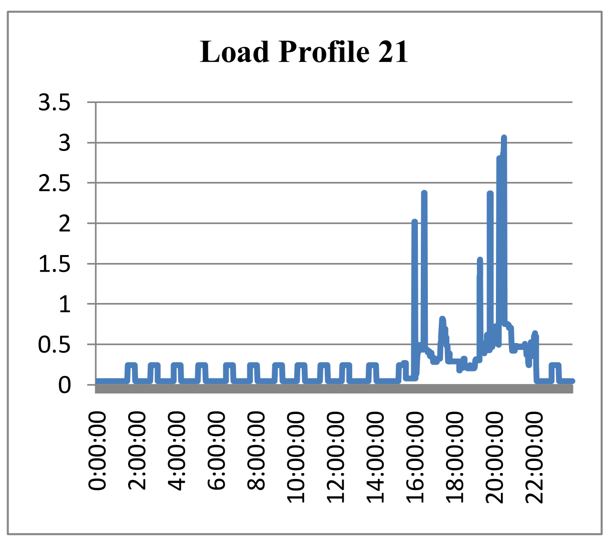
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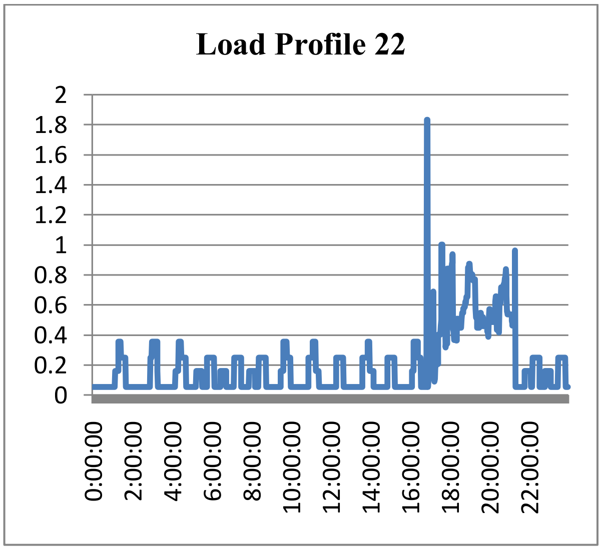
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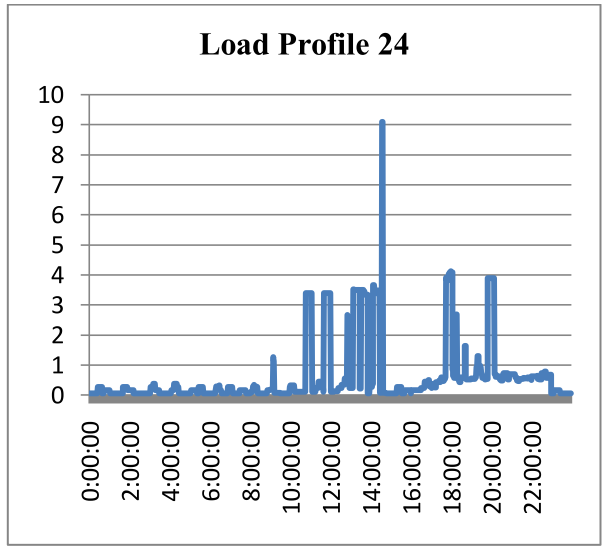
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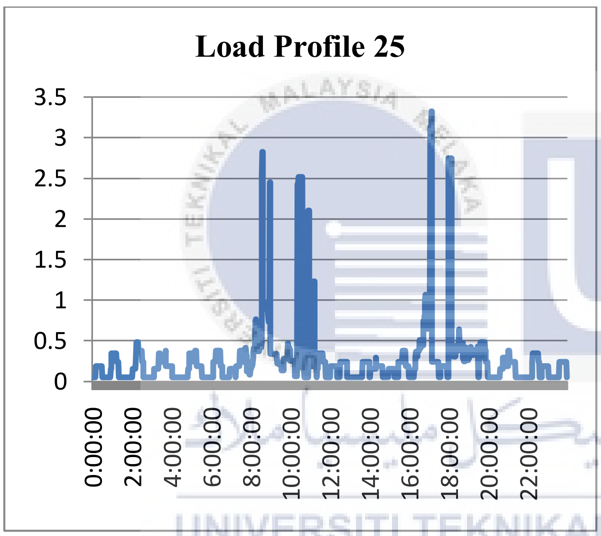
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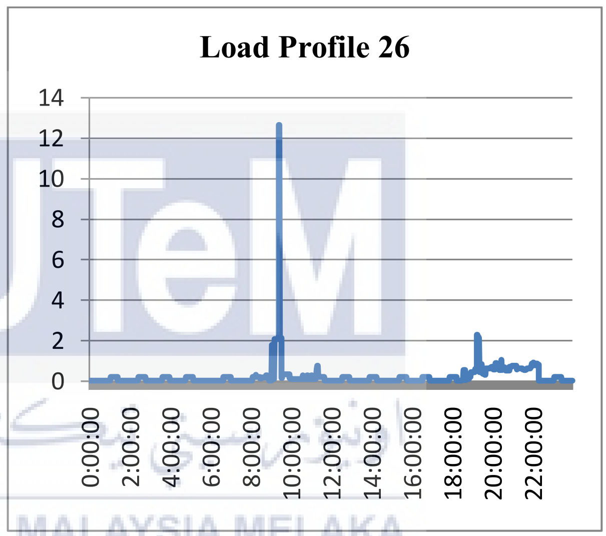
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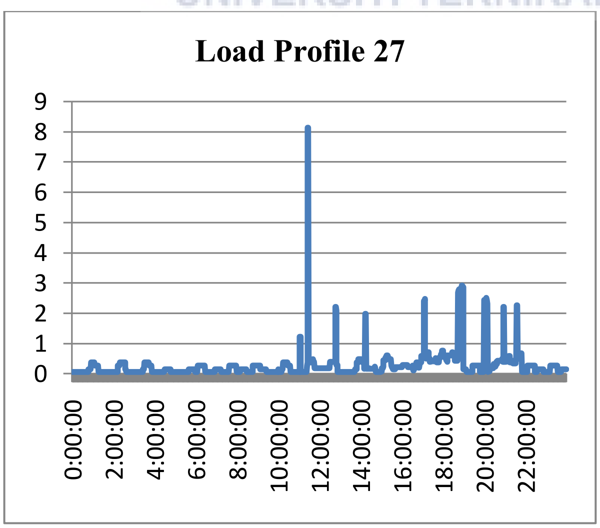
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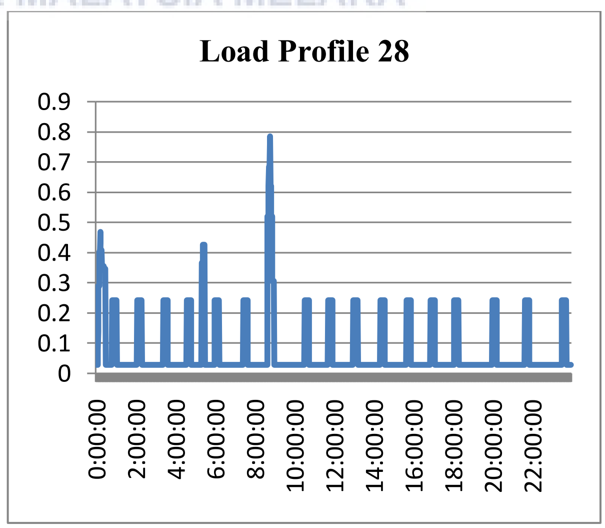
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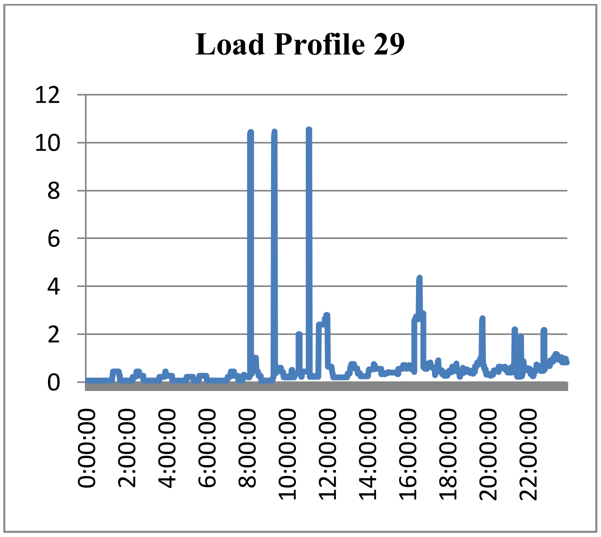
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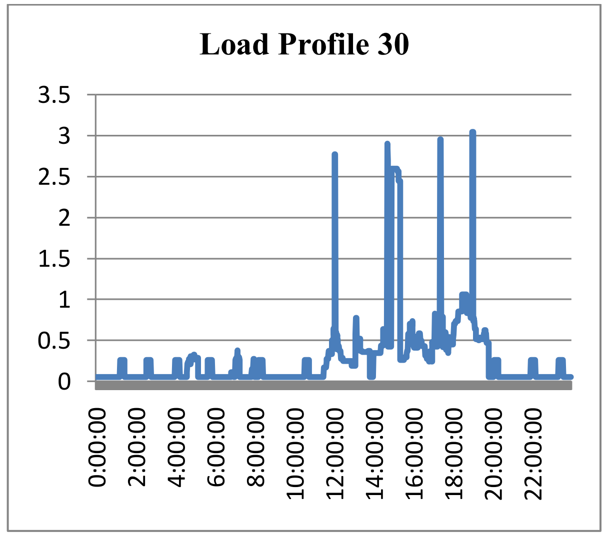
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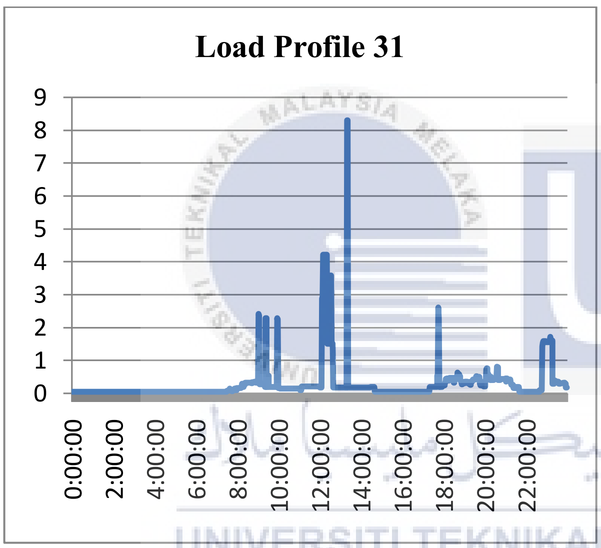
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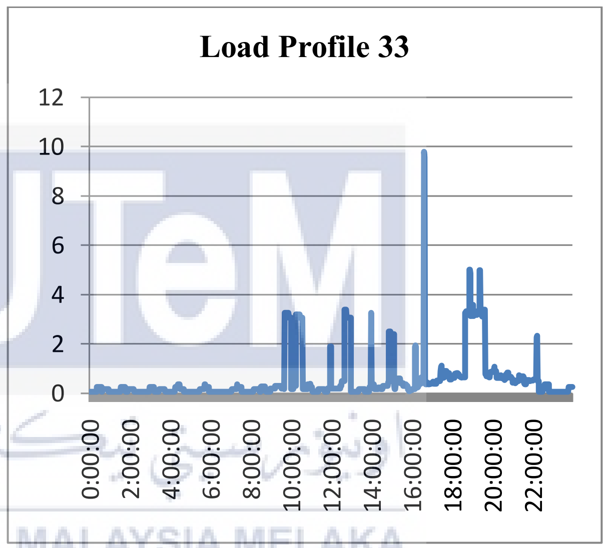
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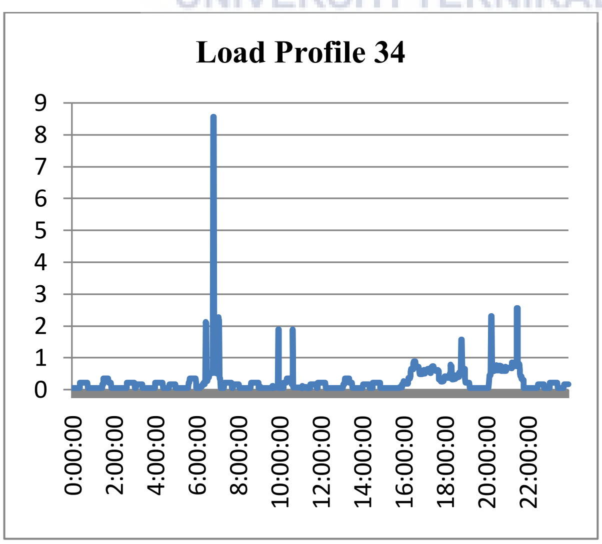
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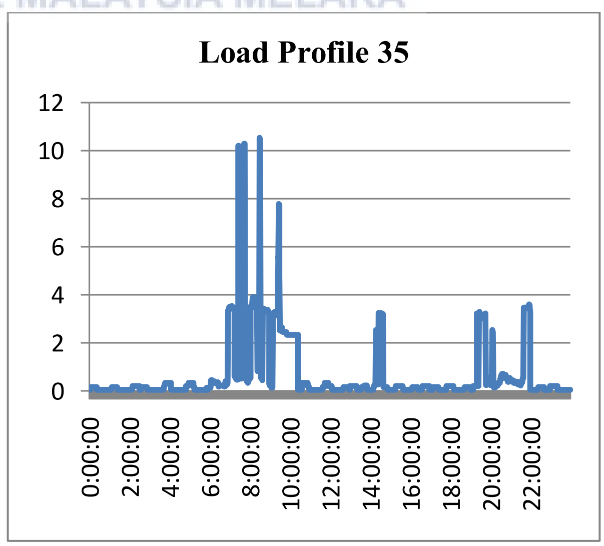
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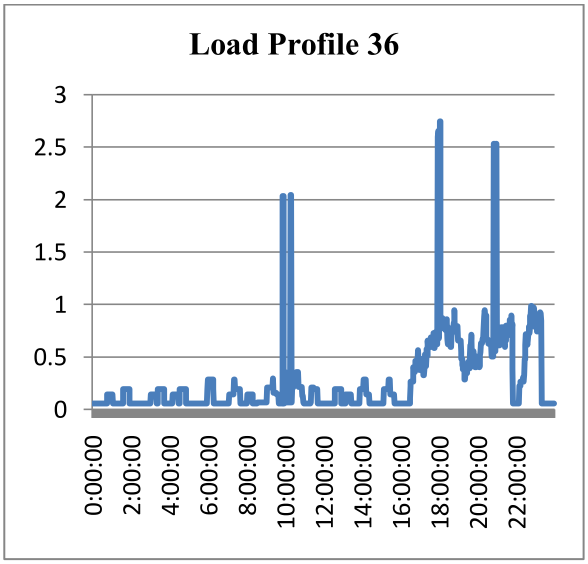
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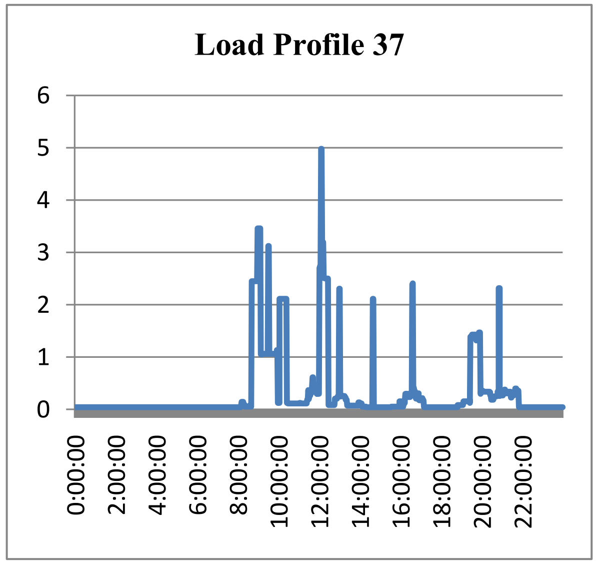
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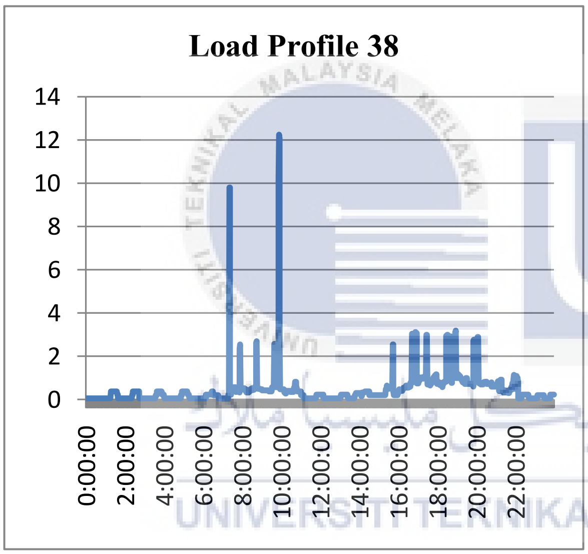
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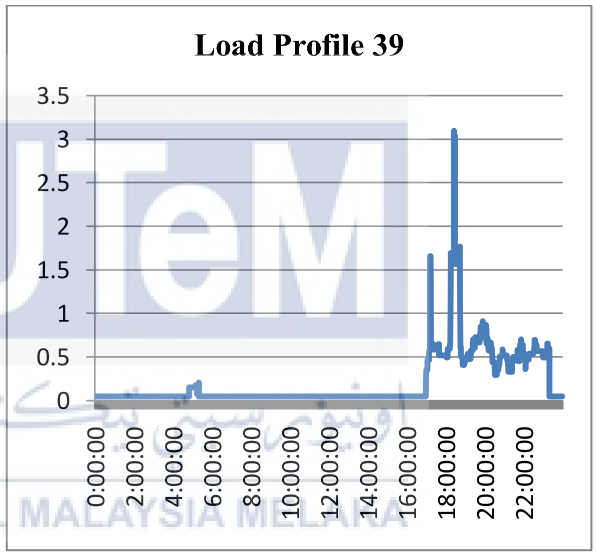
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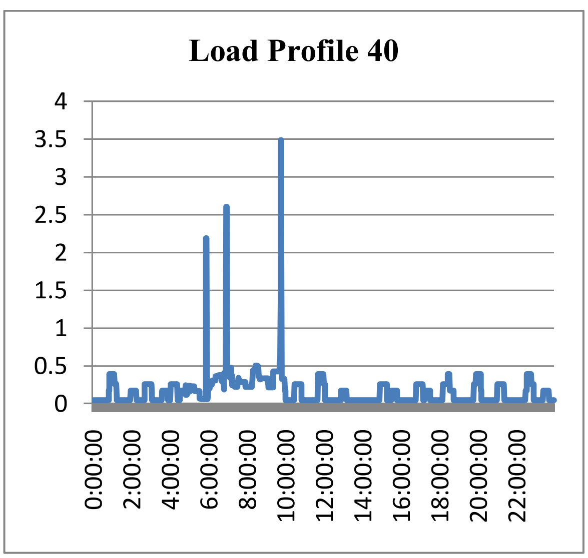
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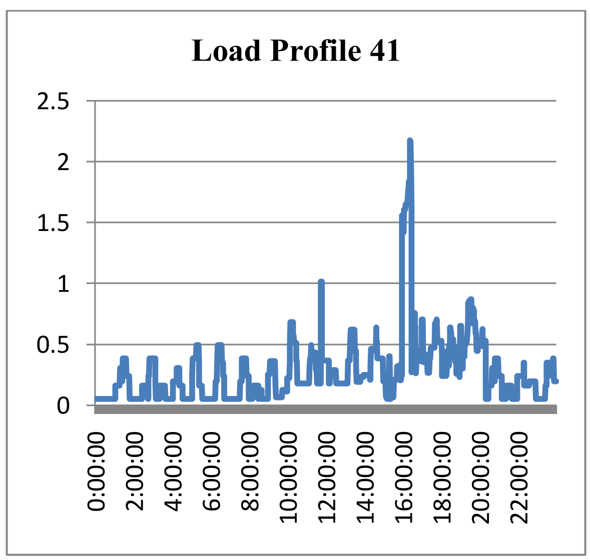
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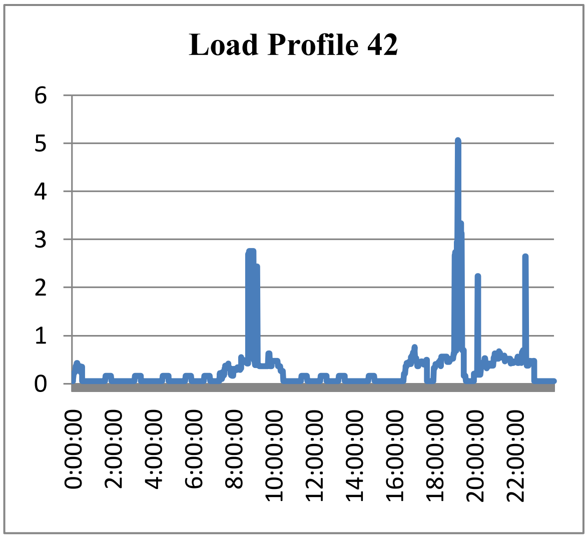
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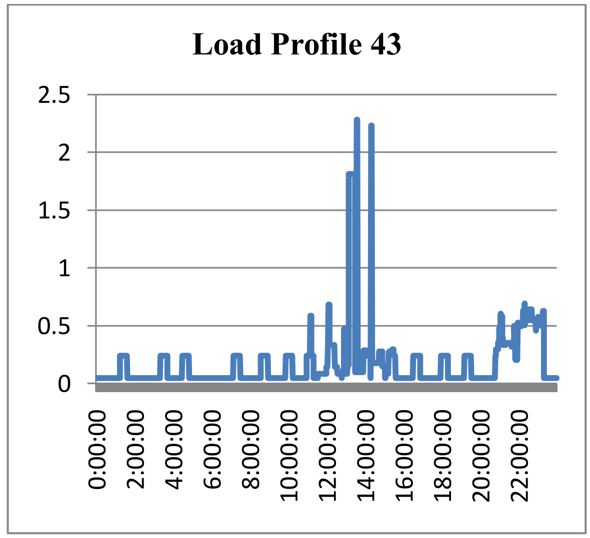
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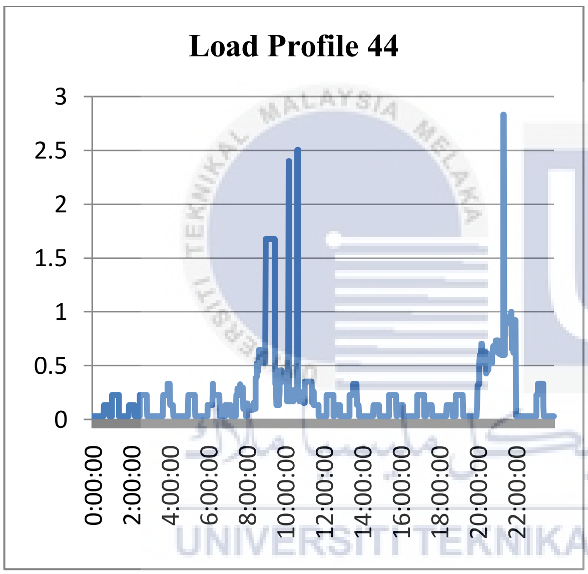
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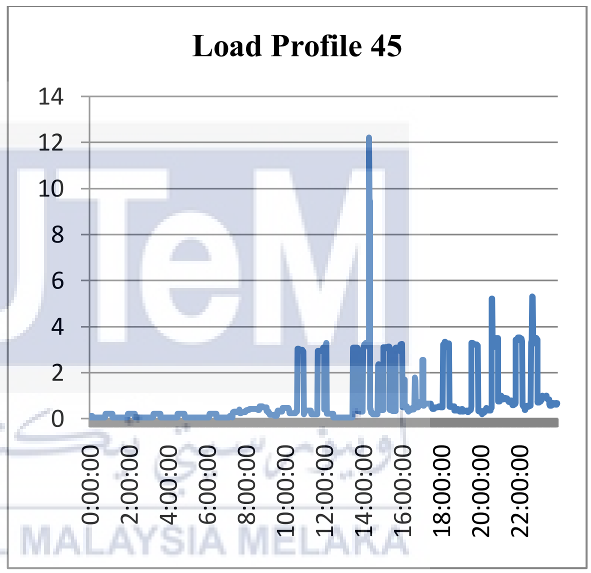
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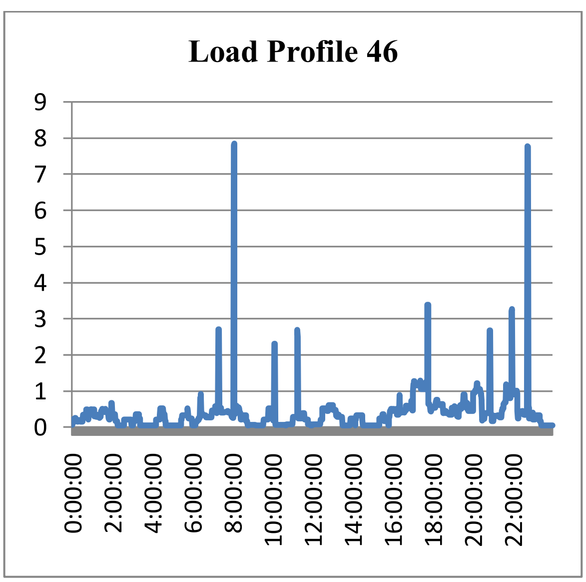
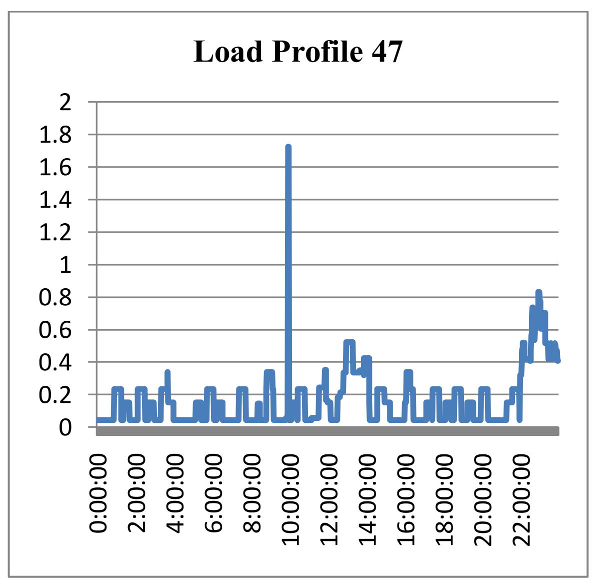
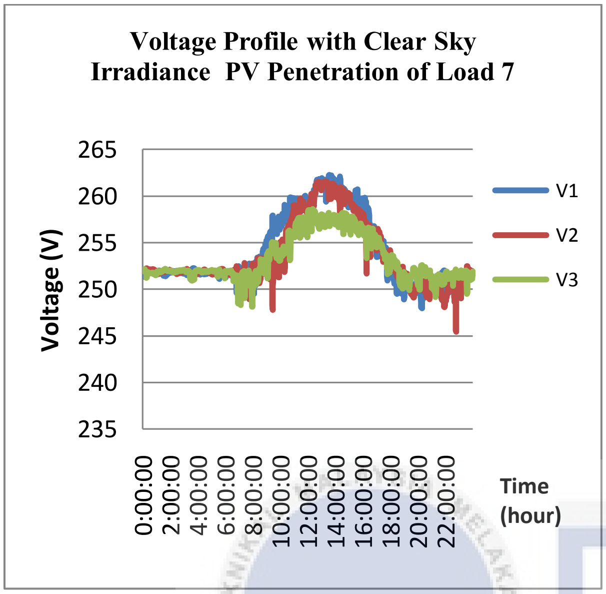
22:00:00

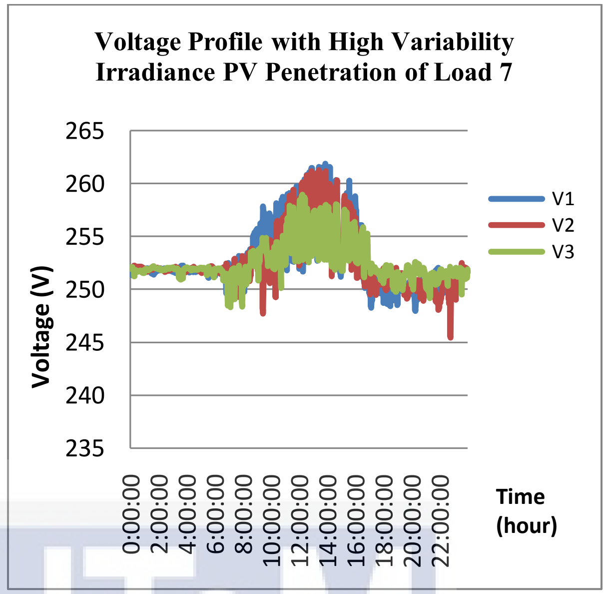

Load Profile 46
0
1
2
3
4
5
6
7
8
9
0:00:00
2:00:00
4:00:00
6:00:00
8:00:00
10:00:00
12:00:00
14:00:00
16:00:00
18:00:00
20:00:00
22:00:00

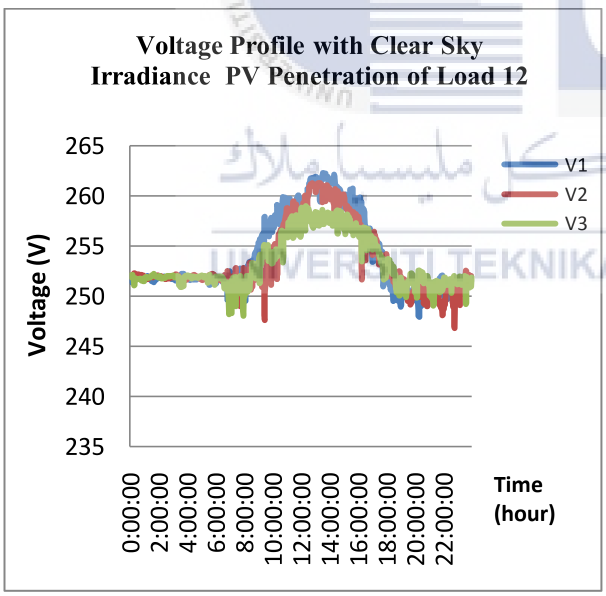

Load Profile 47
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
0:00:00
2:00:00
4:00:00
6:00:00
8:00:00
10:00:00
12:00:00
14:00:00
16:00:00
18:00:00
20:00:00
22:00:00

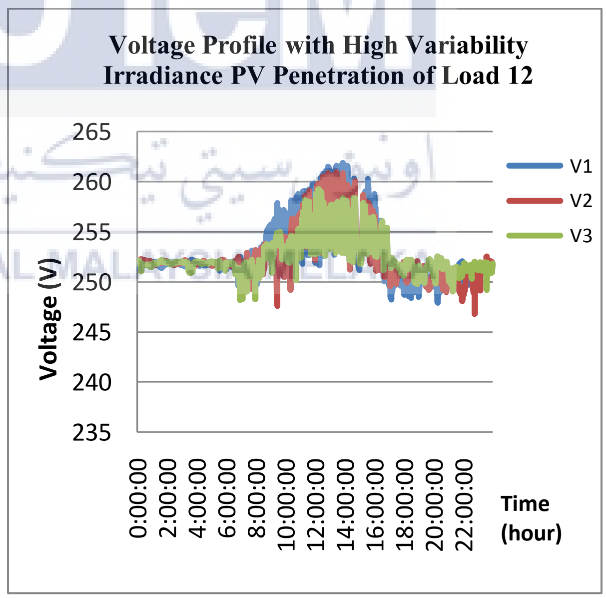
APPENDIX C: SIMULATION RESULTS WITH PV PENETRATION

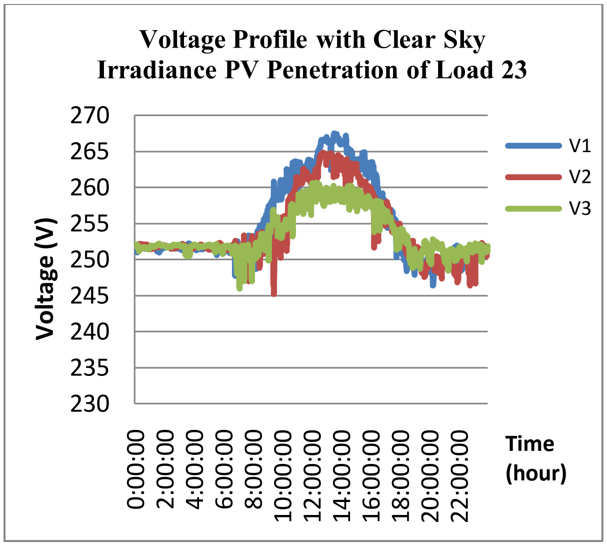
VOLTAGE UNBALANCE

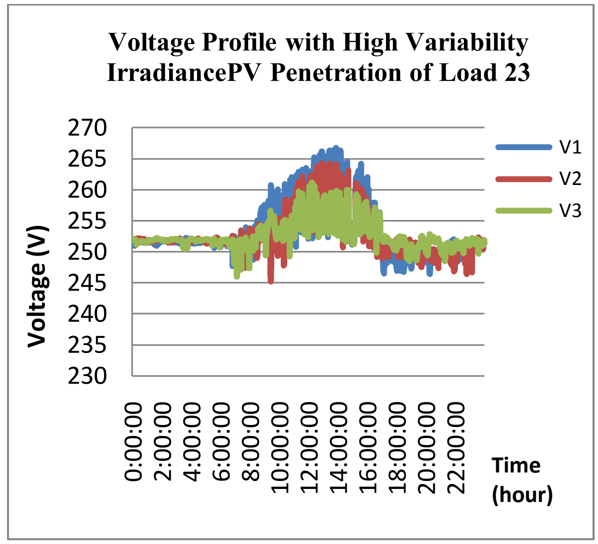


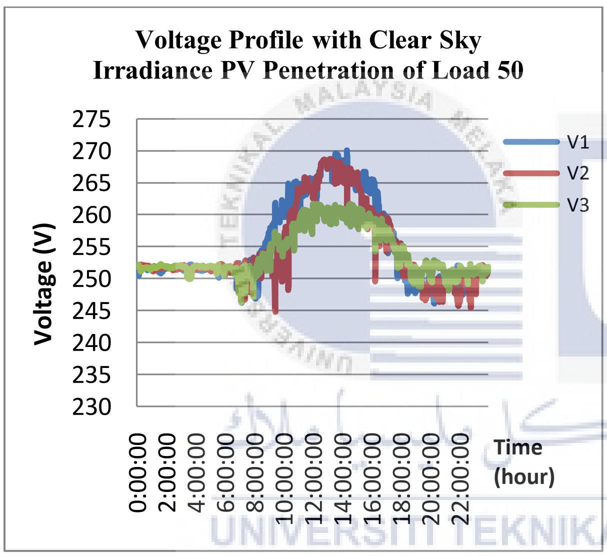


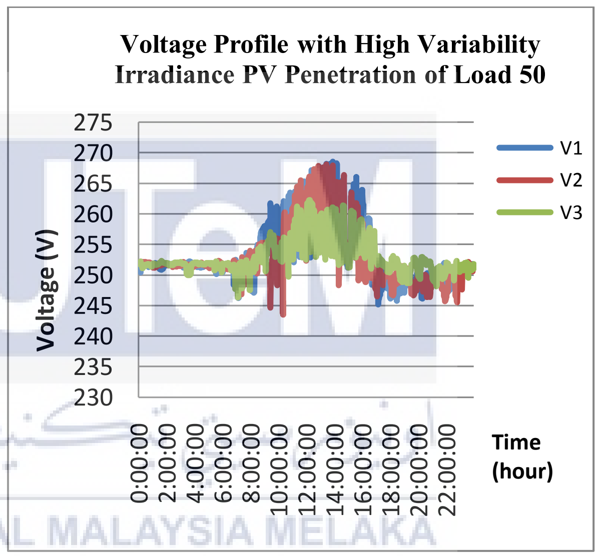


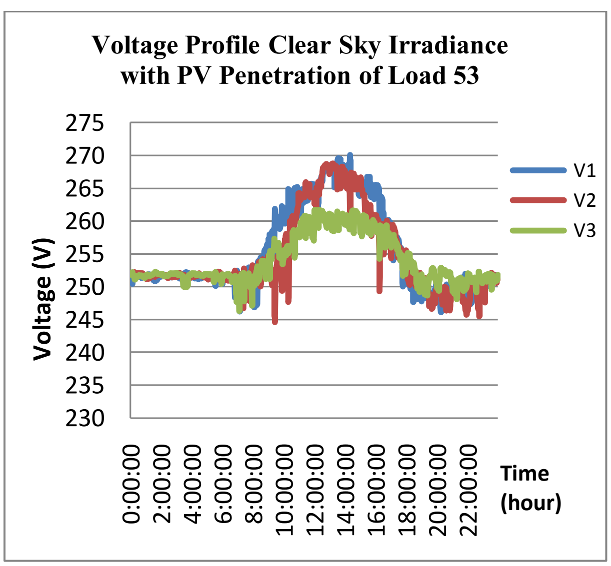


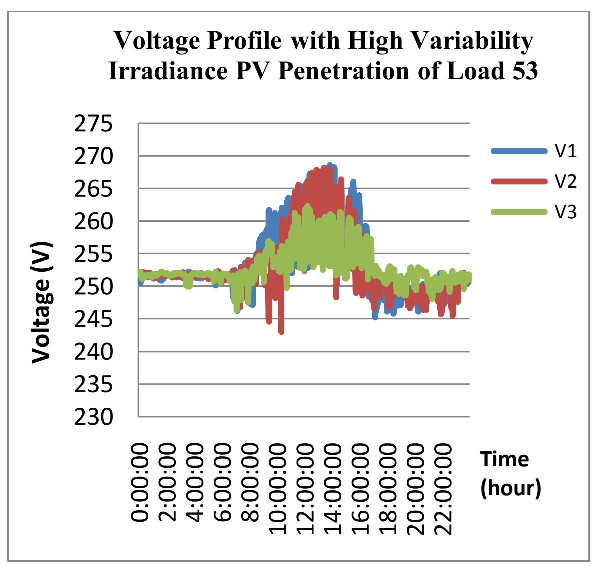

Voltage Profile with Clear Sky Irradiance PV Penetration of Load 23
Voltage (V)
Time (hour)
V1
V2
V3


Voltage Profile with High Variability IrradiancePV Penetration of Load 23
Voltage (V)
Time (hour)
V1
V2
V3


Voltage Profile with Clear Sky Irradiance PV Penetration of Load 50
Voltage (V)
Time (hour)
V1
V2
V3

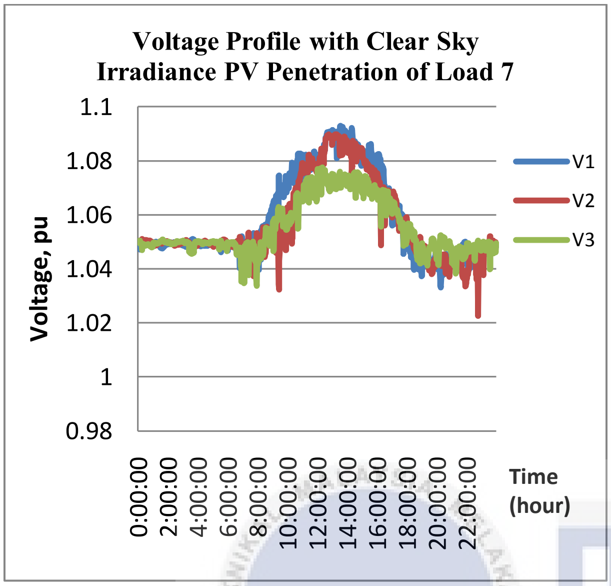

Voltage Profile with High Variability Irradiance PV Penetration of Load 50
Voltage (V)
Time (hour)
V1
V2
V3

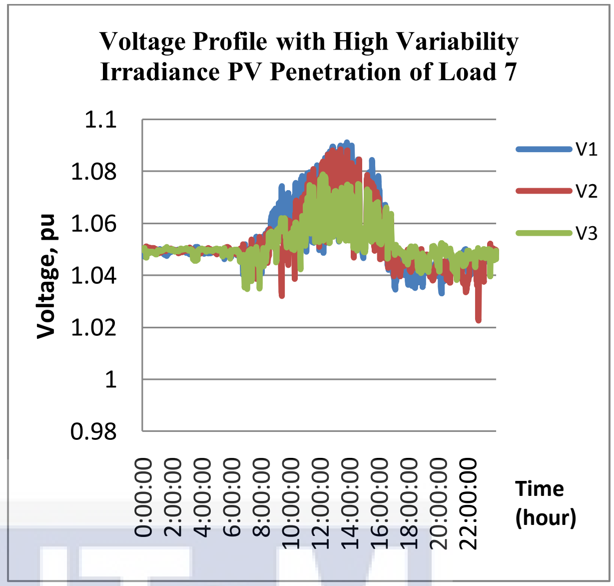

Voltage Profile Clear Sky Irradiance with PV Penetration of Load 53
Voltage (V)
Time (hour)
V1
V2
V3

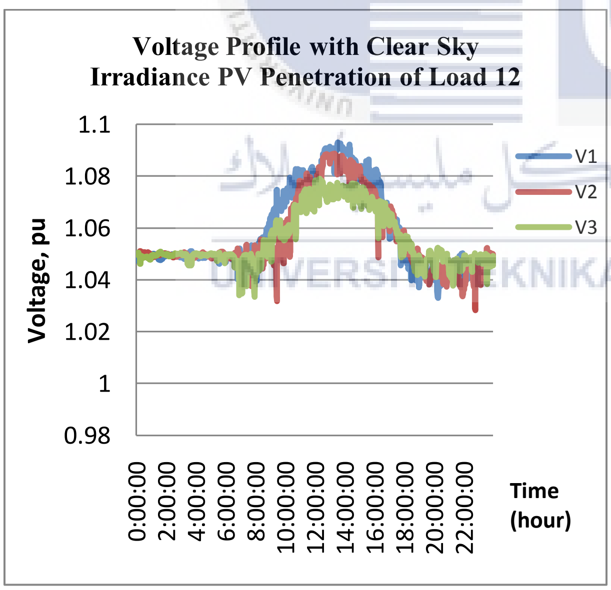

Voltage Profile with High Variability Irradiance PV Penetration of Load 53
Voltage (V)
Time (hour)
V1
V2
V3

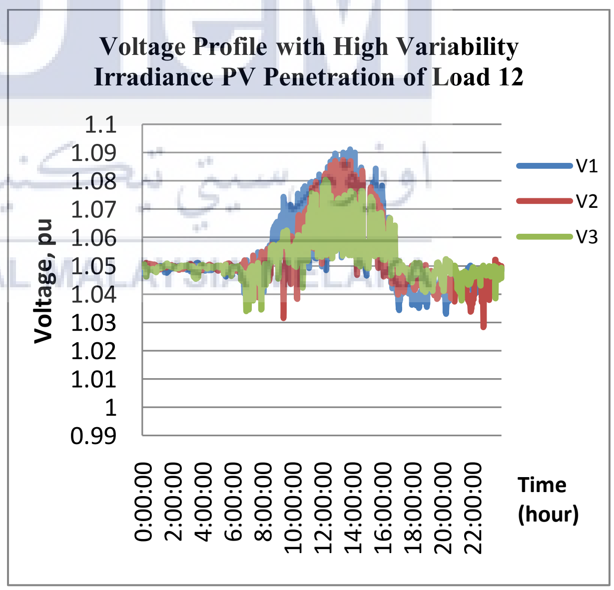
APPENDIX D: SIMULATION RESULTS WITH PV PENETRATION

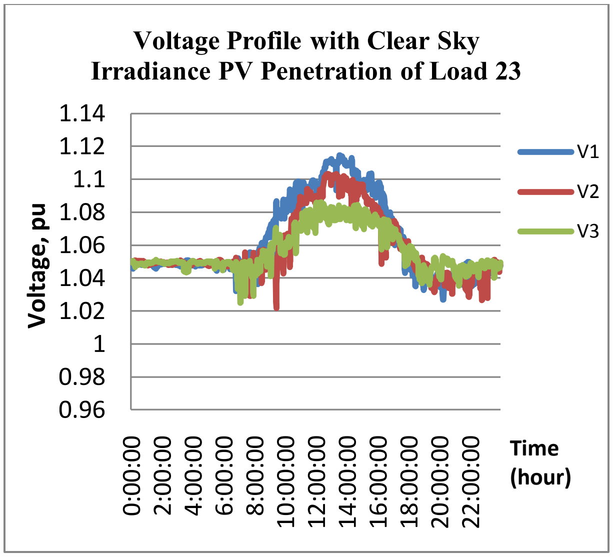
VOLTAGE RISE

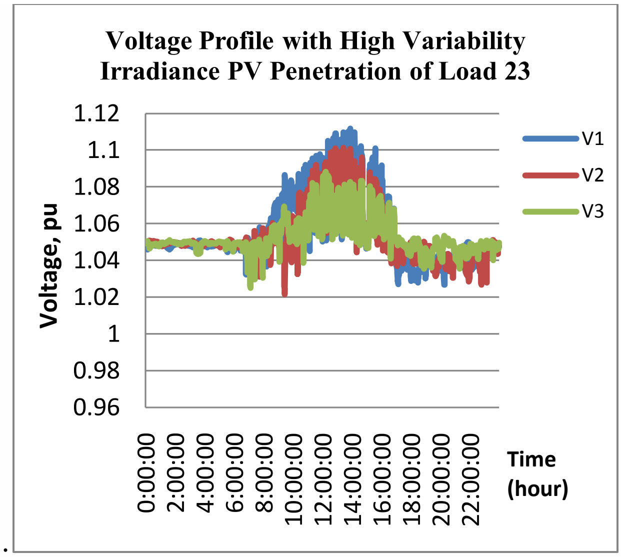


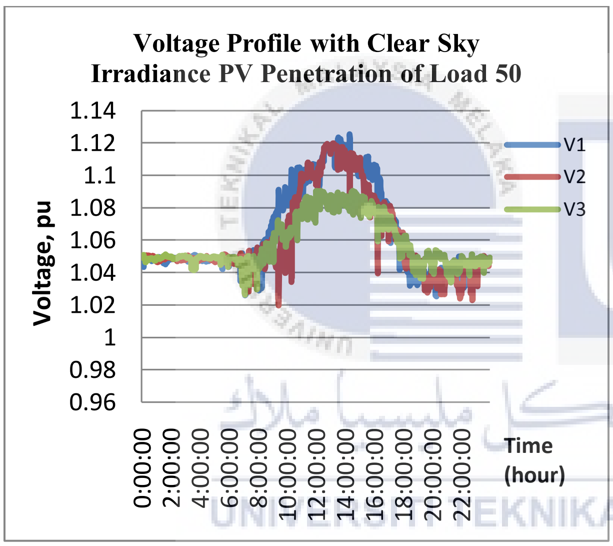


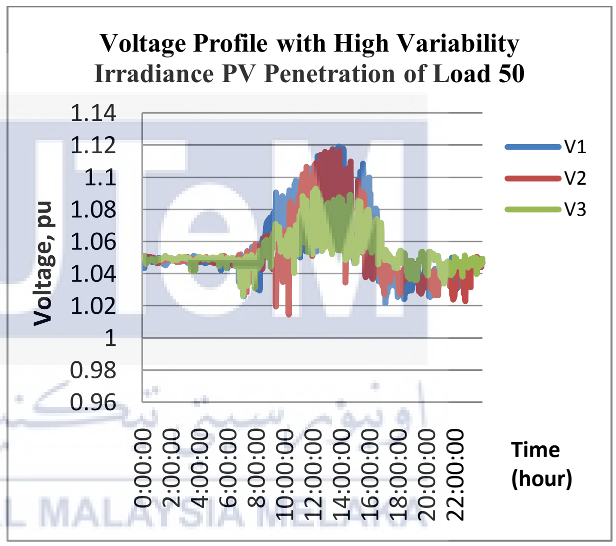


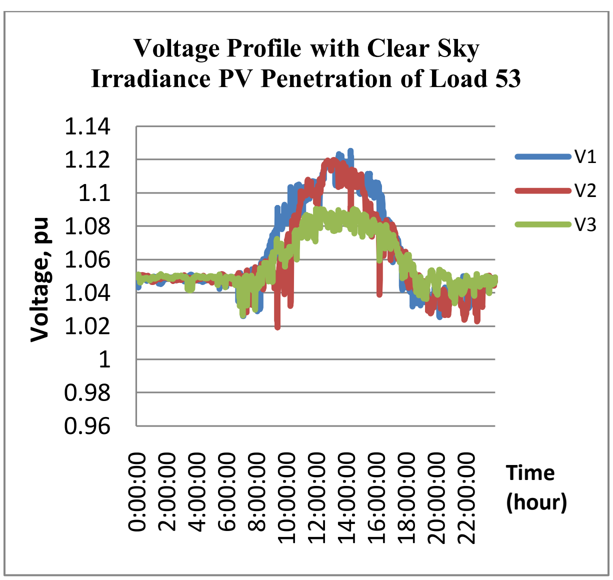


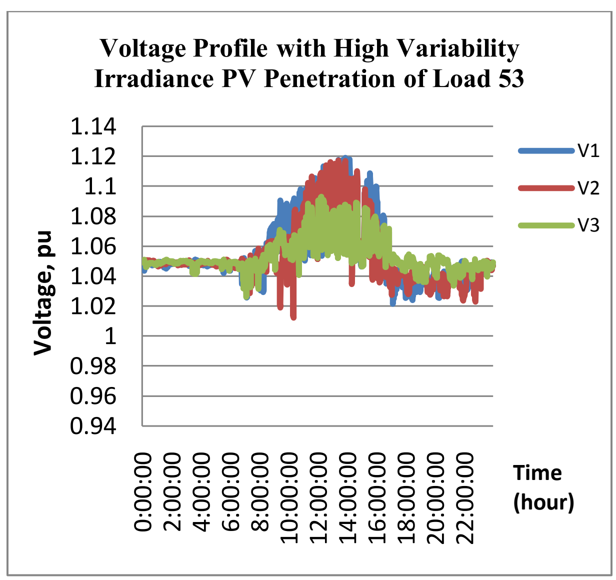

Voltage Profile with Clear Sky
Irradiance PV Penetration of Load 23
Voltage, pu
1.14
1.12
1.1
1.08
1.06
1.04
1.02
1
0.98
0.96
V1
V2
V3
0:00:00
2:00:00
4:00:00
6:00:00
8:00:00
10:00:00
12:00:00
14:00:00
16:00:00
18:00:00
20:00:00
22:00:00
Time
(hour)


Voltage Profile with High Variability
Irradiance PV Penetration of Load 23
Voltage, pu
1.12
1.1
1.08
1.06
1.04
1.02
1
0.98
0.96
V1
V2
V3
0:00:00
2:00:00
4:00:00
6:00:00
8:00:00
10:00:00
12:00:00
14:00:00
16:00:00
18:00:00
20:00:00
22:00:00
Time
(hour)


Voltage Profile with Clear Sky
Irradiance PV Penetration of Load 50
Voltage, pu
1.14
1.12
1.1
1.08
1.06
1.04
1.02
1
0.98
0.96
V1
V2
V3
0:00:00
2:00:00
4:00:00
6:00:00
8:00:00
10:00:00
12:00:00
14:00:00
16:00:00
18:00:00
20:00:00
22:00:00
Time
(hour)

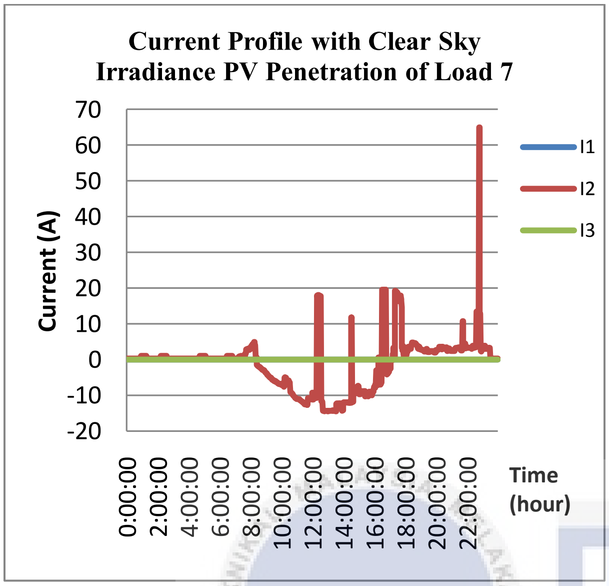

Voltage Profile with High Variability
Irradiance PV Penetration of Load 50
Voltage, pu
1.14
1.12
1.1
1.08
1.06
1.04
1.02
1
0.98
0.96
V1
V2
V3
0:00:00
2:00:00
4:00:00
6:00:00
8:00:00
10:00:00
12:00:00
14:00:00
16:00:00
18:00:00
20:00:00
22:00:00
Time
(hour)

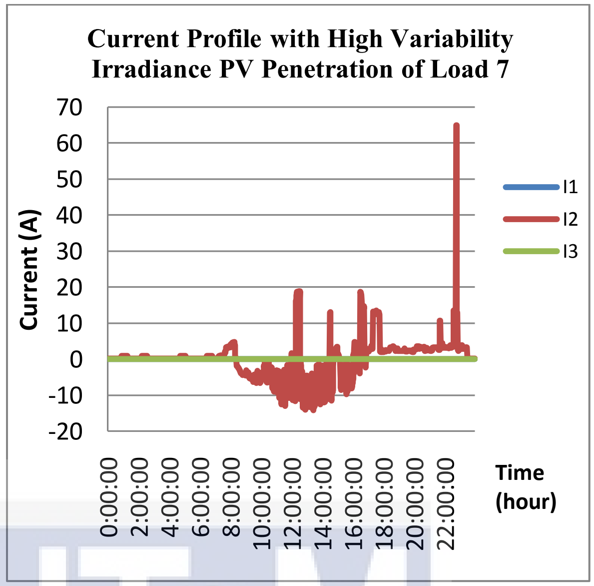

Voltage Profile with Clear Sky
Irradiance PV Penetration of Load 53
Voltage, pu
1.14
1.12
1.1
1.08
1.06
1.04
1.02
1
0.98
0.96
V1
V2
V3
0:00:00
2:00:00
4:00:00
6:00:00
8:00:00
10:00:00
12:00:00
14:00:00
16:00:00
18:00:00
20:00:00
22:00:00
Time
(hour)

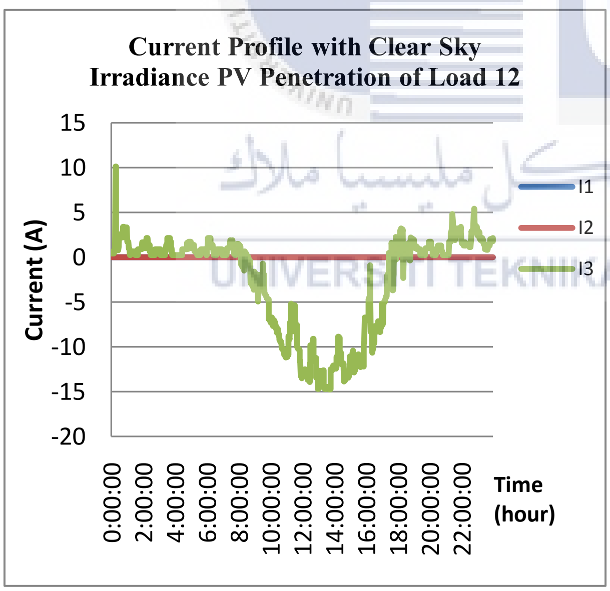

Voltage Profile with High Variability
Irradiance PV Penetration of Load 53
Voltage, pu
1.14
1.12
1.1
1.08
1.06
1.04
1.02
1
0.98
0.96
0.94
V1
V2
V3
0:00:00
2:00:00
4:00:00
6:00:00
8:00:00
10:00:00
12:00:00
14:00:00
16:00:00
18:00:00
20:00:00
22:00:00
Time
(hour)

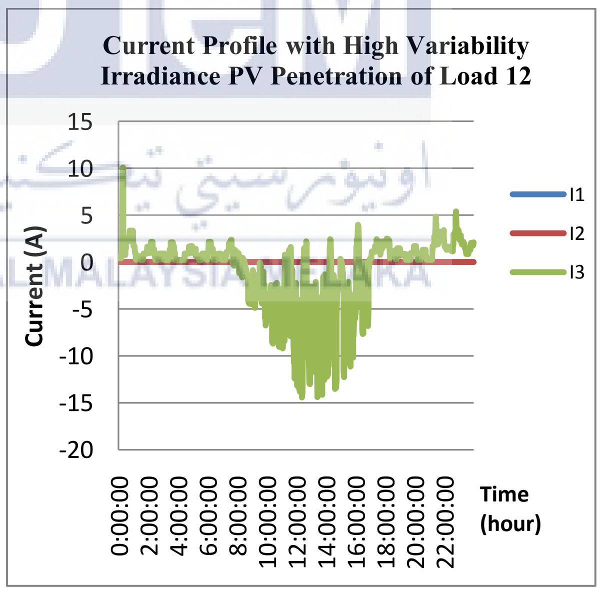
APPENDIX E: SIMULATION RESULTS WITH PV PENETRATION

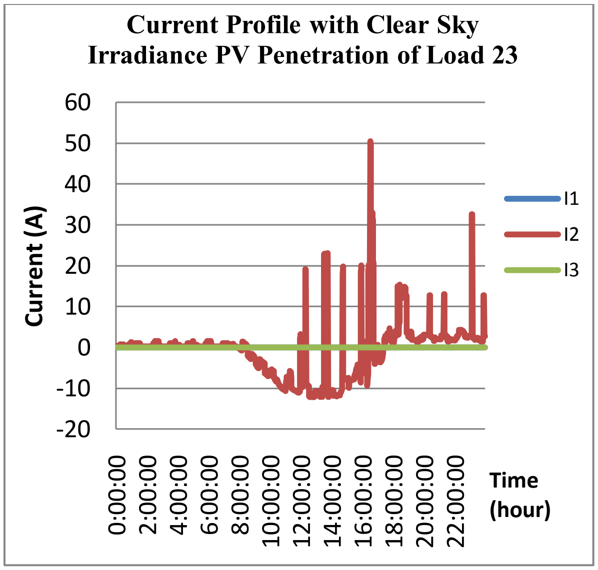
REVERSE POWER FLOW

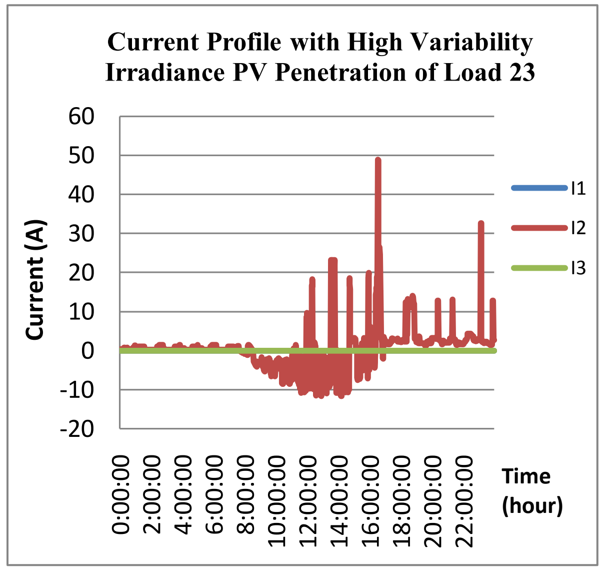


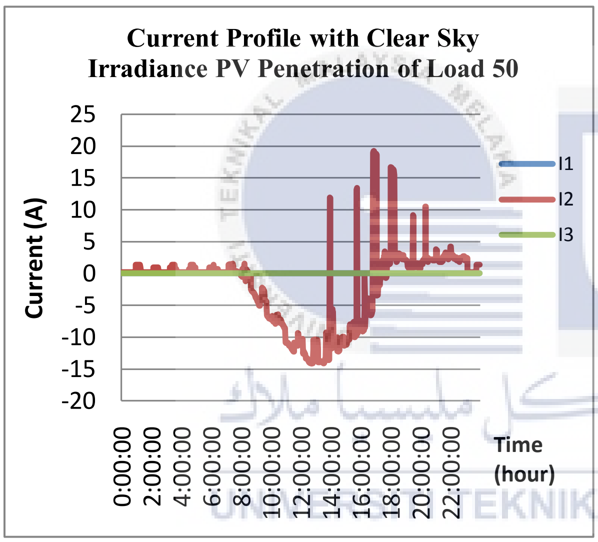


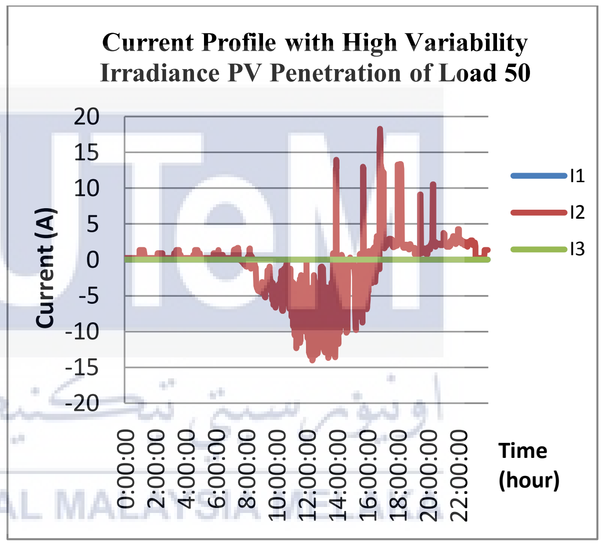


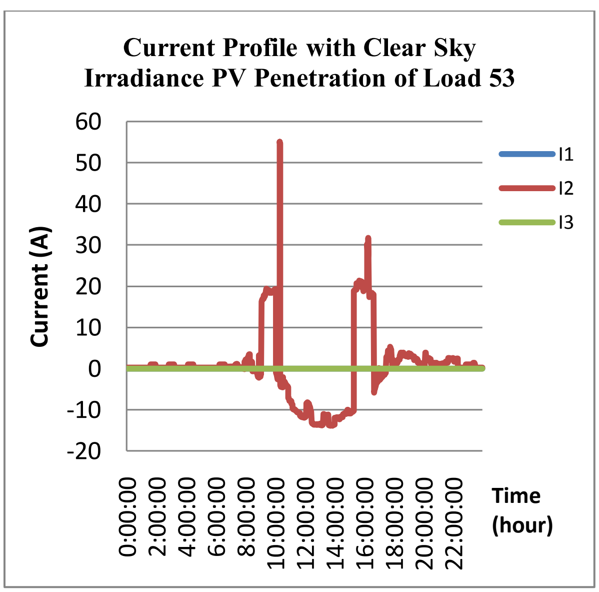


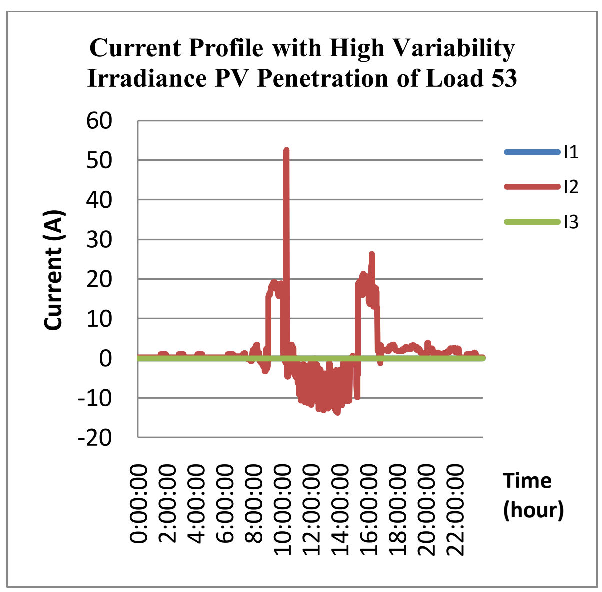

Current Profile with Clear Sky
Irradiance PV Penetration of Load 23
Current (A)
Time
(hour)
I1
I2
I3


Current Profile with High Variability
Irradiance PV Penetration of Load 23
Current (A)
Time
(hour)
I1
I2
I3


Current Profile with Clear Sky
Irradiance PV Penetration of Load 50
Current (A)
Time
(hour)
I1
I2
I3


Current Profile with High Variability
Irradiance PV Penetration of Load 50
Current (A)
Time
(hour)
I1
I2
I3


Current Profile with Clear Sky
Irradiance PV Penetration of Load 53
Current (A)
Time
(hour)
I1
I2
I3


Current Profile with High Variability
Irradiance PV Penetration of Load 53
Current (A)
Time
(hour)
I1
I2
I3