DESIGN AND MODELLING A THREE-PHASE GRID-CONNECTED PHOTOVOLTAIC AT LOW VOLTAGE NETWORK AND ITS PERFORMANCE USING PSCAD SOFTWARE

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

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“I hereby declare that I have read through this report entitle Design and Modelling a Three-Phase Grid-Connected Photovoltaic at Low Voltage Network and Its Performance Using PSCAD Software and found that it has comply the partial fulfilment for awarding the degree of Bachelor of Electrical Engineering (Industrial Power) with Honours”

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To my beloved father, mother, family, lecturer and friends for their loving, understanding, care and support in many aspects.

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ABSTRACT

Solar photovoltaic generation system is one of distributed generation (DG) that can generated electricity power to support load demand. Solar energy is the cleanest, sustainable and environmentally friendly renewable energy. Environment in Malaysia is more suitable for solar generation compared to wind generation since Malaysia receive sunlight for almost 10 hours a day besides wind speed in Malaysia is not enough to generate electricity. Since the output of the PV generation need to connect with grid network, there could a few issues occur. The issues that may occur including synchronization issue, overvoltage and undervoltage issue, and stability issue. The aim for this project is to analyze the impact of power generated by three-phase grid-connected photovoltaic system towards grid and load. Power System Computer Aided Design (PSCAD) software was used to model the three-phase grid-connected PV system. The flow of the three-phase grid-connected PV system was illustrated in block diagram to summarize the actual circuit. The performance of three-phase grid-connected photovoltaic system was analyzed based on several case studies which includes the import and export of active and reactive power at point of common coupling (PCC), impact of excessive power to support load demand without grid connection, effect of generated power from PV model toward voltage impact at distribution network including Microgrid and analysis of abnormal condition at PV model. From the case studies, it can be concluded that voltage across load was affected by the amount of power generated from PV model and capacity of the load. PV model also have a capability to export its generated power to grid and load. Besides that, generated power from PV model must equal with load demand to prevent undervoltage and overvoltage problem which can cause damage to equipment. In Microgrid model, it can be conclude that by connecting the PV model to the furthest load from utility grid can improves its voltage profile. Lastly, different types of fault give different amount of fault current. Three-phase fault will provide the highest fault current in the system and amount of generated power from PV model also can affect the amount of fault current in a system. As conclusion, three-phase grid-connected photovoltaic system that have been modelled able to be used in completing the case studies.

ABSTRAK

Sistem solar fotovolta (PV) merupakan salah satu sistem penjanaan kuasa teragih (KT) yang berupaya menjana kuasa elektrik bagi memenuhi permintaan pengguna. Tenaga solar merupakan satu tenaga yang boleh diperbaharui yang bersih, mampan dan mesra alam. Keadaan negara Malaysia lebih sesuai menggunakan tenaga solar untuk menjana tenaga elektrik berbanding tenaga angin kerana Malaysia menerima cahaya Matahari sekurang-kurang 10 jam dalam sehari. Hasil keluaran sistem penjanaan solar perlu disambungkan ke grid pembahagian dan ini mungkin akan menimbulkan beberapa masalah. Antara masalah yang mungkin timbul adalah masalah ketidakserasian antara sistem fotovolta dan grid, masalah lebihan dan kekurangan voltan pada beban dan juga masalah kestabilan sistem apabila berlakunya gangguan. Tujuan utama projek ini dilakukan adalah untuk menganalisis kesan penjanaan kuasa dari sistem solar fotovolta tiga fasa terhadap grid dan juga beban. Perisian PSCAD digunakan untuk membuat model sistem solar fotovolta tiga fasa. Beberapa kajian kes dijalankan untuk menganalisis keupayaan sistem iaitu import dan eksport kuasa di titik sambungan (TS) grid, sistem fotovolta, dan beban, kesan kuasa berlebihan untuk menampung beban tanpa penyambungan grid, kesan jumlah kuasa yang dijana oleh sistem fotovolta terhadap voltan dibeban termasuk dengan menggunakan model Microgrid dan yang terakhir adalah analisis terhadap gangguan yang berlaku pada sistem fotovolta. Berdasarkan kajian kes yang dijalankan, model fotovolta mampu mengeksport kuasa yang dihasilkan kepada grid dan juga beban. Selain itu, jumlah kuasa dari model fotovolta haruslah sama dengan jumlah beban bagi mengelak berlakunya masalah lebihan atau kekurangan voltan. Profil voltan dalam model Microgrid boleh diperbaiki dengan menyambungkan model fotovolta dengan beban yang paling jauh dari grid. Beban yang paling jauh mempunyai kejatuhan voltan yang paling tinggi. Akhir sekali, jenis gangguan yang berbeza menghasilkan jumlah arus gangguang yang berbeza. Gangguan tiga fasa menghasilkan arus yang paling tinggi dan jumlah kuasa dari model fotovolta juga mempengaruhi jumlah arus gangguan. Kesimpulannya, sistem solar fotovolta tiga fasa yang dimodel mampu berfungsi dengan baik untuk melengkapi kajian yang dijalankan.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Background

Electrical power network is a system that consist of several electrical component that are able to produce electrical power. There are three major sections in electrical power network which are generation, transmission, distribution and end users. Generation side will generates voltage from generating plant and the voltage is then step up and transmitted to distribution network. At distribution side, the voltage will be stepped down before distribute to end users. End users include large customer (factory), medium customer (business) and small customer (residential) [1].

Distributed Generation (DG) system also known as embedded system and it is a small scale electricity power generation technologies that produce electricity at site close to load or customers. Distributed generation can be a single structure or part of a Microgrid. DG can be classified as Microgrid when a smaller grid tied into the larger electricity delivery system. There are several DG that has been used for generation such as solar photovoltaic system, wind turbines, biomass combustion and combined heat and power (CHP) systems. DG was is one of alternative to produce electricity as it is convenient to avoid transmission and distribution losses. DG also requires lower cost to build the infrastructure as it is in small size. Besides that, DG technologies can produce near-zero or zero pollution [2].

Solar PV system is one of distributed system that was used to generate electricity. Compared to other renewable energy, solar energy is more suitable to be implemented in Malaysia since Malaysia receives direct sunlight approximately 10 hours a day. For solar irradiance between 800 W/m^2 and 1000 W/m^2, Malaysia receives approximately 6 hours a day. Besides that, solar energy system is more environmentally friendly as it does not produce any pollution during operation and require low maintenance. However, the installation of PV technologies requires higher cost as it is long lasting renewable energy technology [3]. Solar panels which is used to absorb solar energy can be mounted anywhere as long as it facing the sun and the angle of solar panel is important in order to receive 100% sunlight.

Photovoltaic arrays produce electricity once it is exposed to sunlight. Basically, solar energy that is collected by photovoltaic arrays is in DC form and will be converted into AC form using inverter. The electron that are freed by solar energy can be induced to travel through an electrical circuit, powering electrical devices or sending electricity to the grid [4]. Three-phase inverted was required to convert the DC electricity produced onto AC form before connect to grid. Switching mechanism that was use in the inverter is Insulated-Gate Bipolar Transistor (IGBT) because IGBT is a minority-carrier device with high input impedance and high current-carrying capability. Due to its bipolar output characteristics, IGBT also suitable to scale in current handling capability at higher voltage levels [5]. Each phase from solar PV system is 240V with $50H_Z$which will be connected to three-phase grid network.

1.2 Problem Statement

Distributed Generation (DG) system also known as embedded system and it is a small scale electricity power generation technologies that produce electricity at site close to load or customers. Solar PV system is one of distributed generation system that was used to generate electricity. PV generation system can be connected with grid network and this might lead to several issues such as synchronization issue, overvoltage and undervoltage issue, and stability issue. Synchronization issue occur when frequency, magnitude of voltage and phase angle from PV model are not same with grid network. The failure to follow this requirement could damage the equipment connected with the system. Besides that, overvoltage issue occur when voltage across load is higher than 5% allowable tolerance limit. This is due to the power generated by PV model that exceed the load demand. Insufficient power supply from grid can cause undervoltage problem as voltage across load is below 230V. This problem can occur especially at the load that was connected the furthest from grid network. Lastly, stability of the system can be affected by the occurrence of fault in the system. There are several types of fault that can occur in three-phase grid-connected photovoltaic system which are single line-to-ground (SLG) fault, double line-to-ground (DLG) fault and three-phase fault. Equipment can be damage if there is no protection in the system. Objectives for this project was developed in order to know the possible consequences from the following problem towards three-phase grid-connected photovoltaic system. In future development of PV model, suitable protection device can be choose based on the results from this project.

1.3 Objectives

This project should fulfil the following objectives:

- To design and model a three-phase grid-connected photovoltaic system and Microgrid model using PSCAD software.
- To examine the impact of power generated by three-phase grid-connected photovoltaic system towards grid and load using PSCAD software based on case studies which includes:
    i. Import and export of active and reactive power at point common of coupling (PCC).
    ii. Impact of excessive power to support load demand without grid connection.
    iii. Effect of generated power from PV model toward voltage impact at distribution network including Microgrid.
    iv. Stability of system – using single line-to-ground (SLG) fault, double line-to-ground (DLG) fault and three-phase fault.

1.4 Scope of Project

The scope of project are:

i. Designing and modelling of three-phase grid-connected photovoltaic system at low voltage network to reduce losses at load side using PSCAD software.
ii. The effect of injected power at point of common coupling (PCC).
iii. Abnormal condition occur at the photovoltaic model only.

CHAPTER 2

LITERATURE REVIEW

2.1 Three-Phase Grid-Connected Photovoltaic System

Solar energy is the cleanest, sustainable and environmentally friendly renewable energy. In generating electricity using solar energy, there are two different ways which is using solar collector and using photovoltaic system. Photovoltaic system can be use either as stand-alone or grid-connected system. Stand-alone PV generation system requires battery as energy storage while grid-connected PV system doesn't need battery since power is normally stored in the grid itself. Grid-connected PV system can reduce the dependencies on utility power and increase renewable energy production. Solar PV panel can be mounted anywhere as long as it can receive sunlight. Since PV system is classified as DG, it helps grid network to support active loads. If the PV system produced electricity more than demand, the excessive power will automatically flow to the grid. The main disadvantages of battery-less grid-connected PV system is the PV system will be affected by the failure occur at grid. When there is no power from grid, so does the PV system. So, consumers are not able to use output of PV system when grid is not operational [6].

Photovoltaic arrays are made of semiconductors that allow sunlight to be converted directly into electricity. The electron that was freed by solar energy can be induces to travel through an electrical circuit, powering electrical devices or sending electricity to the grid. The electricity produced by these arrays is in DC form. Since it will be connected with grid, an inverter is needed as power conversion in order to convert electricity from DC form into AC form. Besides that, power electronics inverter also function as interconnection and control optimization. In order to get proper grid synchronization, the output of the inverter which is voltage, frequency and phase angle must be properly sinusoidal [7].

Three-phase grid-connected PV system is able to support grid by supplying three-phase power to consumers. This distributed generation system also able to reduce losses in distribution network. This system requires three-phase PWM inverter that will convert the

DC power generated by PV panels into AC form. In order to obtain the desired performance and allow the system operates in stable condition, proper controller through inverter need to be implemented [8]. Three-phase PWM inverter will compare the reference wave of the system with triangular square wave. The amplitude of the output is determined by amplitude of the reference and carrier wave. Isolated transformer is used to isolate the output of inverter which is suitable for three-phase system [9]. Figure 2-1 shows the basic diagram for three-phase grid-connected PV system.

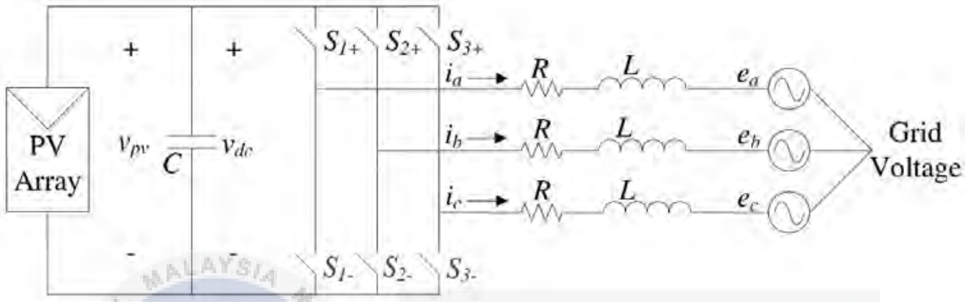

Figure 2-1: Basic Diagram for Three-Phase Grid-Connected PV System.

2.2 Components of Three-Phase PV System

2.2.1 PV Array

PV array is one of the most important part in photovoltaic system. In PV array, there are solar cells which is use to absorb the solar energy. Solar cell is made from semiconductor material and it comes in various sizes. Silicon is one of material that is use as solar cell. Solar cells have two different layer of silicon which is known as n-type and p-type. The silicon atoms will absorb some light and the lights energy knocks some electrons out of the atoms which is then flows between the two layers. The excess electrons from n-type region will diffuse with holes from p-type region and vice versa. The depletion region will be form as the movement of electrons to p-type region produce positive ion in the n-type region while movement of holes to n-type region produce negative ion in p-type region. This process will produce power in DC form. Only light with right wavelength will be absorbs by solar cells and transform into electricity power [4]. Figure 2-2 shows the structure of solar cell.

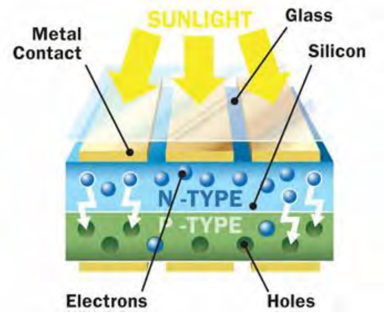

Figure 2-2: Structure of Solar Cell.

2.2.2 Three-Phase Inverter

Three-phase inverters are used for converting DC voltage and current into AC form. Since this system use PV solar, an inverter is needed in order to allow it connect with grid. There are three single-phase inverter switches each connected to one of the three load terminal in basic three-phase inverter. Operation of three switches is coordinated in basic control scheme $(S_1, S_4), (S_3, S_6), (S_5, S_2)$ which means one switch will operates at each 60 degree point of the fundamental output waveform [9]. Figure 2-3 shows the circuit for three-phase inverter.

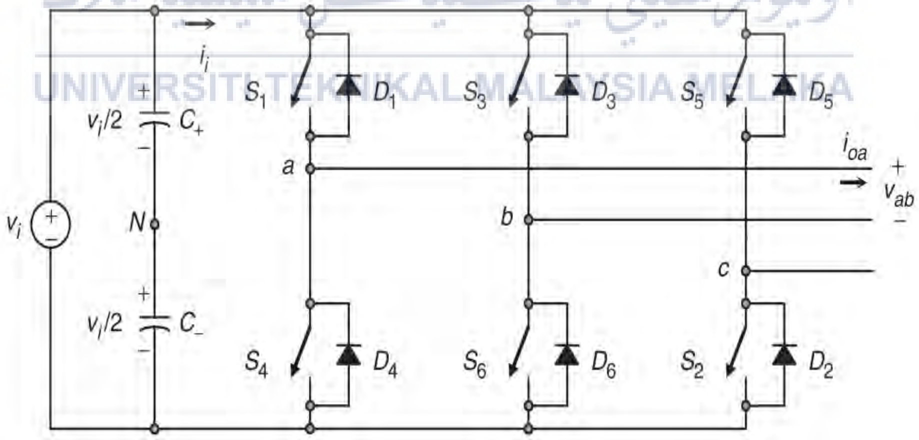

Figure 2-3: The Circuit for Three-Phase Inverter.

Each pair of switch must turned on at different time in order to allow the current flow through all phases. If both switch in each pair is turned on at the same time as short circuit will be occur in the system [9]. Figure 2-4 shows the switching sequence for three-phase inverter.

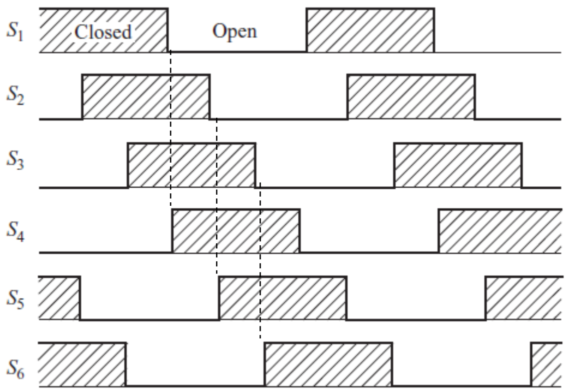

Figure 2-4: Switching Sequence for Three-Phase Inverter.

2.2.3 Insulated-Gate Bipolar Transistor (IGBT)

Insulated-Gate Bipolar Transistor (IGBT) is three-terminal semiconductor switch that was used as to control electrical energy in three-phase inverter. IGBT consists of three-terminal which is labelled as emitter ‘E’, collector ‘C’ and gate ‘G’. IGBT have combination properties from Metal-Oxide Semiconductor Field-Effect Transistor (MOSFET) and Bipolar Junction Transistor (BJT) [10]. Figure 2-5 shows the symbol of IGBT.

Figure 2-5: Symbol of IGBT.

IGBT is voltage-controlled device with maximum voltage rating equal to 3.5kV and 2kA maximum current rating. IGBT have high switching frequency which is up to 30 kHz compared to MOSFET and BJT. Since IGBT is a voltage-controlled device, small voltage on the gate is required to maintain the conduction through the device [11]. Table 2-1 shows the comparison between IGBT, MOSFET and BJT switching device.

Table 2-1: Comparison between IGBT, MOSFET and BJT.

Characteristics	IGBT	MOSFET	BJT
Control Variable	Voltage	Voltage	Current
Max. Voltage Rating	3.5kV	1kV	1.5kV
Max. Current Rating	2kA	150A	1kA
Switching Frequency	High (up to 30kHz)	Very High (up to 1MHz)	Medium (10kHz)

2.2.4 Pulse Width Modulation (PWM)

There will be disturbance in each electrical system which is also known as harmonics distortion. Using Pulse Width Modulation (PWM) and filter is one of the way to reduce the harmonic distortion. PWM can be divided into two types which are bipolar PWM and unipolar PWM [9]. In three-phase grid-connected PV system, PWM three-phase inverter can be used. Harmonics will be at higher frequencies than square wave for unfiltered PWM output. This will make filtering process easier. In PWM, modulating waveform can control the amplitude of output voltage. Modulating waveform which is in sinusoid is used to control the switches for PWM output while carrier wave which is in triangular wave is used to control the switching frequency [10]. Figure 2-6 shows the references and carrier signal for three-phase PWM inverter.

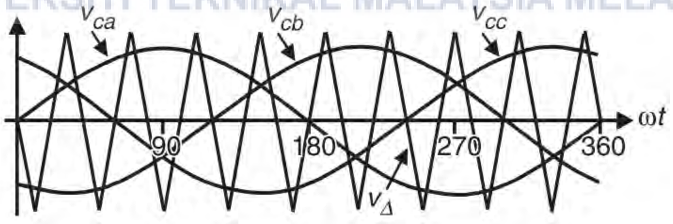

Figure 2-6: The References and Carrier Signal for Three-Phase PWM Inverter.

By using PWM in the three-phase inverter system can reduced the filter requirement and control the output of the voltage amplitude. But, PWM can make the control circuit for switches become more complex. Since it have six switching mechanisms which operate in pair. Each pair of switches require difference reference signal. For balanced three-phase output, the three reference signals are 120° apart. The condition of each switch in the inverter are as follow [10].

S_1 is on when $v_{ca} > v_\Delta$

S_4 is on when $vc_a < v_\Delta$

S_3 is on when $v_{cb} > v_\Delta$

S_6 is on when $v_{cb} < v_\Delta$

S_5 is on when $v_{cc} > v_\Delta$

S_2 is on when $v_{cc} < v_\Delta$

Pair of S_1, S_4 is used for phase A while S_2, S_6 and S_2, S_5 used for phase B and phase C. The phase voltage for phase A, phase B and phase C are shown in (2.1) when S_1, S_3 and S_5 in close condition. All the phase voltage will become negative for opposite condition of switch which means S_4, S_6 and S_2 in close condition as shown in (2.2). The output of three-phase inverter was shown in Figure 2-7 [10].

$$V_{abc,n} = \frac{V_i}{2} \tag{2.1}$$

$$V_{abc,n} = -\frac{V_i}{2} \tag{2.2}$$

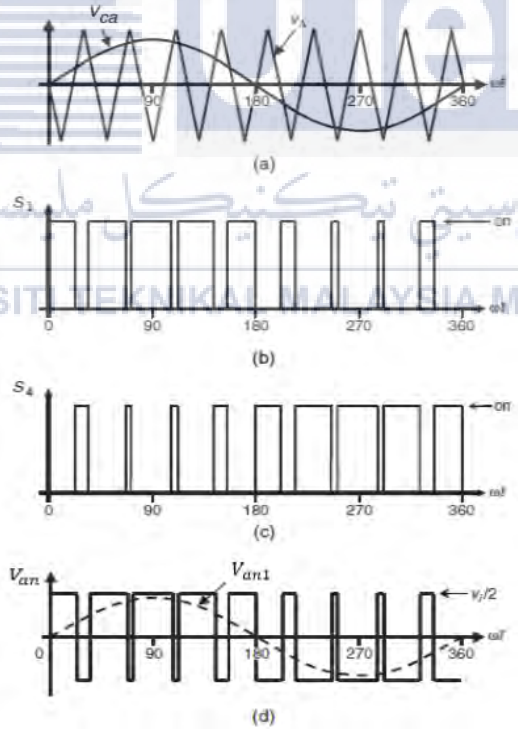

Figure 2-7: The Output of PWM Three-Phase Inverter.

PWM output voltage has same fundamental frequency with reference signal in Fourier series. Frequency modulation, m_f is a ratio of frequency of carrier signal and frequency of modulating signal. Formula used to calculate the frequency modulation was shown in (2.3). Amplitude modulation, m_a is the ratio of amplitude of modulating signal and carrier signal. Amplitude modulation of three-phase inverter can be calculated using (2.4) [9].

$$m_f = \frac{f_{carrier}}{f_{modulating}} \tag{2.3}$$

$$m_a = \frac{V_{m,modulating}}{V_{m,carrier}} \tag{2.4}$$

From Figure 2-7 if value of $m_a \leq 1$, amplitude of fundamental frequency for output voltage is shown in (2.5).

$$V_{an1} = V_{ca}\frac{V_i}{2} \tag{2.5}$$

2.2.5 Phase Locked Loop (PLL) Controller

Phase Locked Loop (PLL) was published by Appleton in 1923 and Bellescize in 1932. PLL was originally used for radio signals synchronous reception but now it was widely used in synchronization between grid-interfaced converters and utility network. PLL is used to track the phase angle of the grid voltage. By using PLL, power converter will locked to the grid voltage. So, there will be no problems if in the changes of phase angle or frequency [12].

For the PLL to synchronize the phase angle, Phase Detector (PD) was used to generate output signal by comparing the phase different between two input signals. The output was then passed through loop filter (LF). PI controller is one of loop filter which will filter the high frequency component from PD output. The output of LF will drives the voltage-controlled oscillator (VCO) which functions to generate an AC output signal which could follow the input signal [13]. Figure 2-8 shows the block diagram for synchronization of PLL.

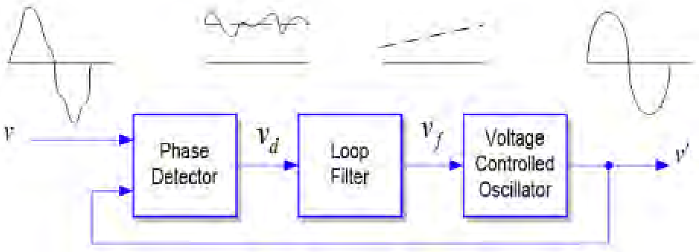

Figure 2-8: Block Diagram for Synchronization of PLL.

For the PLL to be classified as ideal PLL, it should be able to provide the fast and accurate synchronization information. The output of ideal PLL should be free from any type of disturbance and distortion in the input signal. PLL also can be used with ABC to DQ controller in three-phase system in order to transform three-phase system to two-phase system [12].

2.2.6 Proportional-Integral (PI) Controller

Proportional-Integral (PI) Controller is one of the components in Phase Locked Loop (PLL) Controller. Basically, PI controller can produce an output from the combination of proportional and integral mode. The proportional controller will amplify the error and apply it to the system that is proportional to the error. The controller is then become an integrator as the control effort is proportional to the integral [13]. Figure 2-9 shows the basic block diagram for PI controller. The analytical expression for PI controller was shown in (2.6).

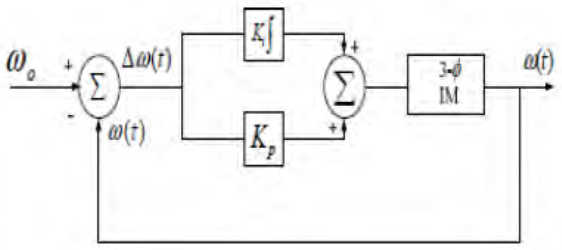

Figure 2-9: Basic Block Diagram for Proportional-Integral (PI) Controller.

$$\omega(t) = K_p e(t) + K_i \int e(t)\, dt \tag{2.6}$$

PI controller is usually used in a system that does not have a speed problems. PI controller cannot reduce the rise time and eliminate the oscillation of the system since it unable to predict the future error of the system. The net integration mode gain can be changed by the proportional gain but the integral gain can independently adjusted. When the value of output and input controller is same, the error will become zero. The proportional function will provide a correction to the system depending on sign and direction of error while integral function accumulated value will increases or decreases if the error in the system is not zero. Negative value cannot be in the integral function because it will saturate at zero [14]. The transfer function for PI controller was shown in (2.7).

$$K_p + \frac{K_i}{s} \tag{2.7}$$

2.2.7 ABC to DQ Converter

ABC to Direct-Quadrature-Zero (DQ0) transformation can define as a mathematical transformation that rotates the reference frame of three-phase system in order to simplify the analysis of three-phase system [15]. This converter will allows the three-phase voltage or current in time domain converted into two-phase form via Clarke Transformation and Park Transformation [13]. Figure 2-10 shows the Clarke and Park Transformation. 'X' in all equations in this section can be either voltage or current of the system.

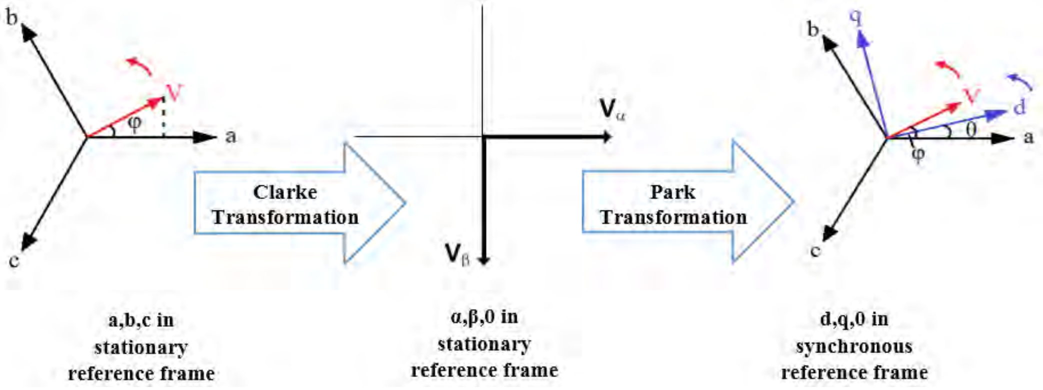

Figure 2-10: Clarke and Park Transformation.

For Clarke Transformation, the three-phase a, b, c stationary reference frame will be change to α, β, 0 stationary reference frame [13]. Equation for three-phase quantities in time domain can be calculated using (2.8), (2.9) and (2.10). The Clarke Transformation can be written as in (2.11) below.

$$X_a = X \cos \varphi \tag{2.8}$$

$$X_b = X \cos(\varphi - 120°) \tag{2.9}$$

$$X_c = X \cos(\varphi + 120°) \tag{2.10}$$

$$\begin{bmatrix} X_a \\ X_b \\ X_c \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1 & -0.5 & -0.5 \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ 0.5 & 0.5 & 0.5 \end{bmatrix} \begin{bmatrix} X_\alpha \\ X_\beta \\ X_0 \end{bmatrix} \tag{2.11}$$

For Park Transformation, the obtained α, β, 0 stationary reference frame will be transform into d, q, 0 synchronous reference frame [13]. Formula for the d, q transformation can be seen in (2.12) and (2.13). The Park Transformation formula was shown in (2.14) below.

$$X_d = X \cos(\varphi - \theta) \tag{2.12}$$

$$X_q = X \sin(\varphi - \theta) \tag{2.13}$$

$$\begin{bmatrix} X_d \\ X_q \\ X_0 \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta & 0 \\ -\sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} X_\alpha \\ X_\beta \\ X_0 \end{bmatrix} \tag{2.14}$$

In three-phase system, DQ0 to ABC converter will be use along with ABC to DQ converter. This DQ0 to ABC will transform dq0 input into abc output using formula in (2.15) [13].

$$\begin{bmatrix} X_d \\ X_q \\ X_0 \end{bmatrix} = \begin{bmatrix} \cos\theta & \cos\left(\theta - \frac{2}{3}\pi\right) & \cos\left(\theta + \frac{2}{3}\pi\right) \\ -\sin\theta & -\sin\left(\theta - \frac{2}{3}\pi\right) & -\sin\left(\theta + \frac{2}{3}\pi\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} X_a \\ X_b \\ X_c \end{bmatrix} \tag{2.15}$$

2.2.8 Filter

Filter is the important component that can be used to reject unwanted frequency in a system and smoothen the output of the system. The used of power electronic switching in a system can lead to the present of harmonic and this can be prevent by connecting a passive filter to the output of inverter. Voltage harmonics and current distortion in distributed generation system can be reduced by using passive harmonic filters [16].

A filter can be classified as passive filter if it only contents passive elements such as R, L and C. LCL-filter is one of passive filter and it can produces better attenuation of switching harmonics compared to L-filter and LC-filter. LCL-filter in a system can produces low grid current distortion and reactive power. Besides that, it also can reduce the level of harmonics distortion with lower switching frequencies. The configuration of LCL-filter in three-phase grid-connected system was shown in Figure 2-11 and resonant frequency of LCL-filter was stated in (2.16) [16].

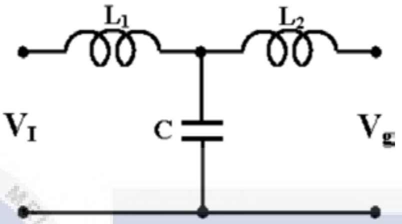

Figure 2-11: Configuration of LCL Filter.

$$f_0 = \frac{1}{2\pi}\sqrt{\frac{L_1+L_2}{L_1 L_2 C}} \tag{2.16}$$

2.3 Power Flow between Two Buses

Power flow from generation side to grid network can be represented using the connection of synchronize generator to infinite bus as shown in Figure 2-12. At the infinite bus, the voltage must have constant magnitude, phase angle and frequency. From the figure shown below, the generator voltage was labelled as E while infinite bus and synchronize reactance was labelled as V and jX_s [17].

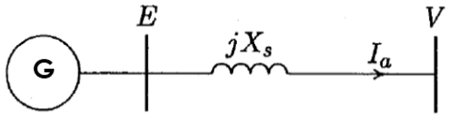

Figure 2-12: Connection of Synchronize Generator to Infinite Bus.

An efficient system should operates with unity power factor. Positive phase of load angle, δ will make the generator voltage lead the infinite bus. This will allow active power flow to the infinite bus. As the amplitude of generator voltage higher than infinite bus, reactive power will flow to the infinite bus. Figure 2-13 shows the phasor diagrams of synchronize generator [17].

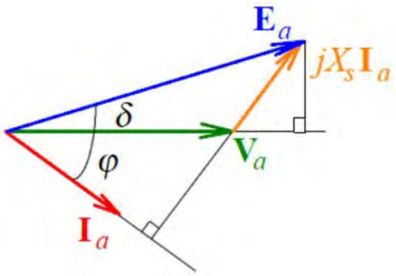

Figure 2-13: Phasor Diagrams of Synchronize Generator.

As synchronize generator delivers real and reactive power to the system, the amount of three-phase active and reactive power can be expressed in (2.17) and (2.18) [17].

$$P_{3\emptyset} = 3\frac{|E||V|}{X_s}\sin\delta \tag{2.17}$$

$$Q_{3\emptyset} = 3\frac{|E||V|\cos\delta - |V|^2}{X_s} \tag{2.18}$$

2.4 Behaviors of Three-Phase PV System

2.4.1 Normal Condition

PV arrays are known to produce DC output. The output of the PV arrays depends on the irradiation of solar energy. Based on Figure 2-14, the irradiation is considered equal to $100W/m^2$ and the output voltage of the PV unit is 250.4V. Both current and power produce by PV arrays also in DC form [18].

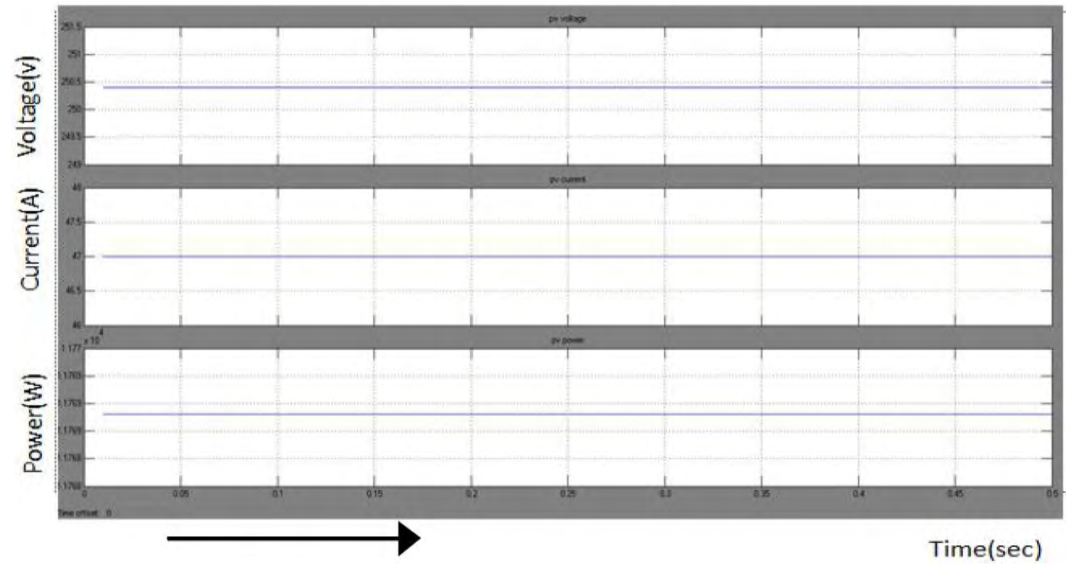

Figure 2-14: Output Voltage, Current and Power of PV Arrays for Normal Condition.

As three-phase system use PWM three-phase inverter, the final output should be in AC form which is capable to be connected to the grid. To allow the synchronization between PV system and grid network, output voltage of inverter and grid must be sync as shown in Figure 2-15. Figure 2-16 shows that the current and voltage output from grid must be in phase so that the power factor of the system is unity [18].

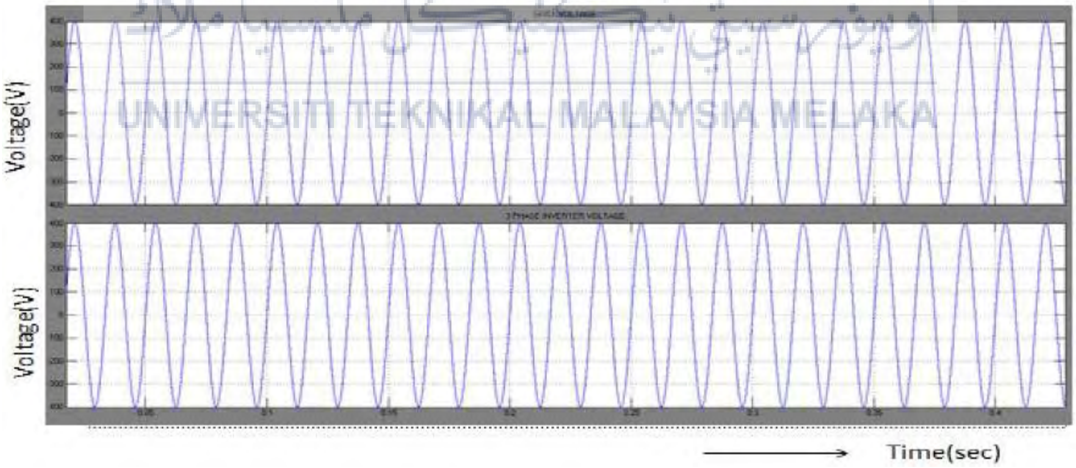

Figure 2-15: Output Voltage of Inverter and Grid during Normal Condition.

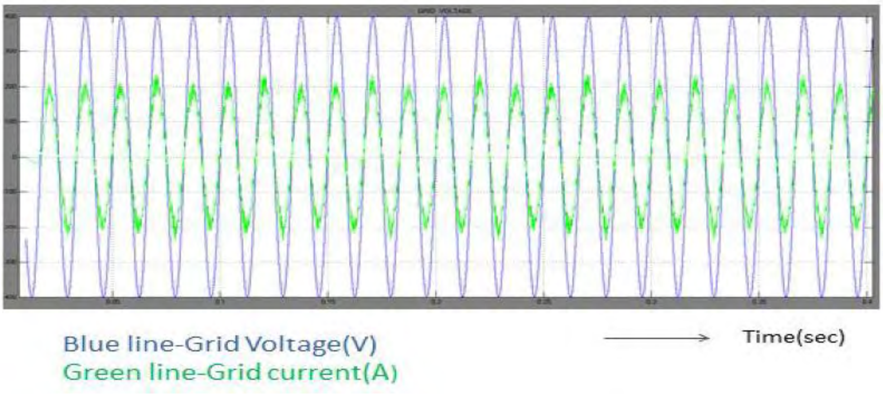

Figure 2-16: Output Voltage and Current from Grid during Normal Condition.

2.4.2 Abnormal Condition

Abnormal condition can be divided into two types of fault which is unsymmetrical fault and symmetrical fault. Unsymmetrical fault can be divided into three types which is single line-to-ground (SLG) fault, double line-to-ground (DLG) fault and line-to-line (LL) fault. Symmetrical fault also known as three-phase fault occur when all three phases are connected to the ground [13].

2.4.2.1 Single Line-to-Ground (SLG) Fault

Single line-to-ground fault occur when only one phase of the system connected to the ground. This will cause unbalance voltage in the power system. For load that is sensitive with unbalanced voltage, protection relay will be used to disconnect the load from the grid if this kind of fault was detected. SLG fault equivalent circuit can be represent by series connection of positive-sequence, negative-sequence and zero-sequence components. The fault occur on Phase A through fault impedance [13]. Figure 2-17 shows the circuit for SLG fault condition.

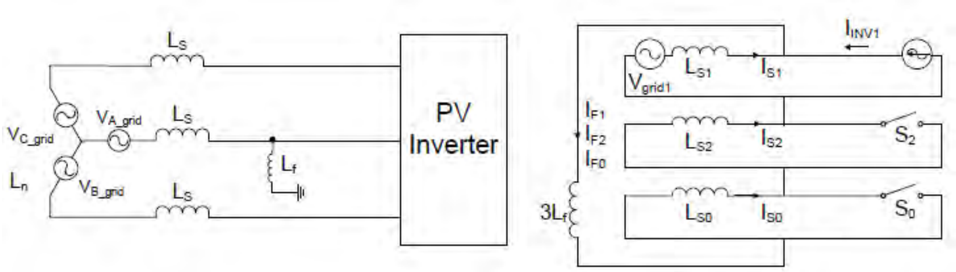

Figure 2-17: Circuit for Single Line-to-Ground Fault Condition.

Since only phase A have fault, the voltage of grid become zero when fault occur while the grid current for all phases remain constant [13]. Figure 2-18 shows the output voltage and current during SLG fault.

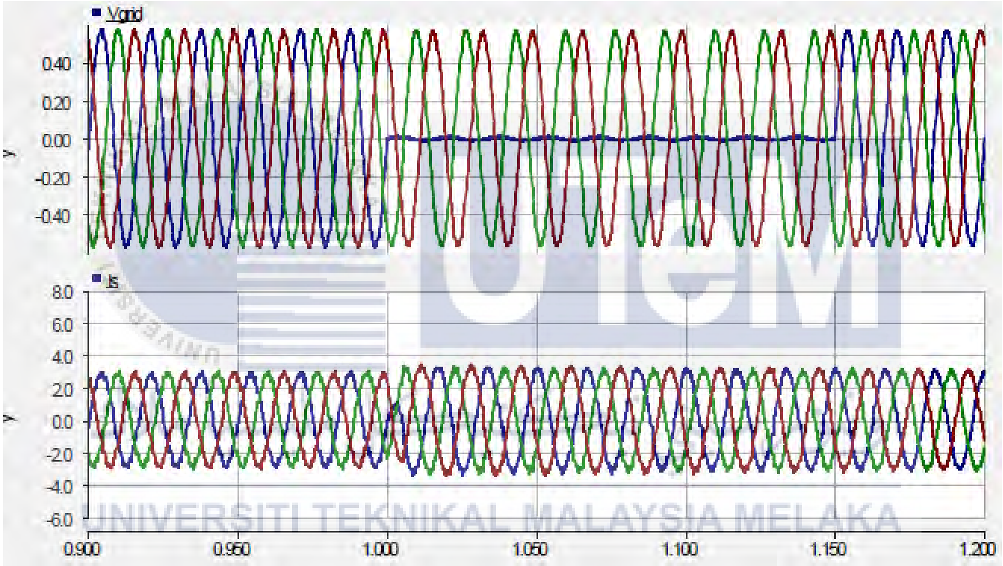

Figure 2-18: Output Voltage and Current during SLG Fault.

2.4.2.2 Double Line-to-Ground (DLG) Fault

DLG fault occur when two phases in three-phase system connected to ground. The equivalent circuit for DLG fault can be form by connecting positive-sequence, negative-sequence and zero-sequence in parallel as shown in Figure 2-19. The positive-sequence current was produced since negative-sequence and zero-sequence switch in open condition [13].

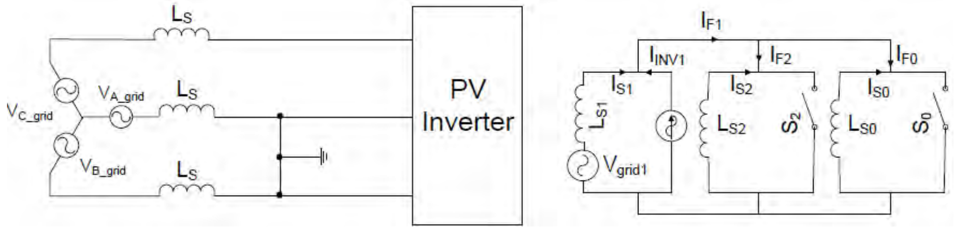

Figure 2-19: Circuit for Double Line-to-Ground Fault Condition.

The voltage of phase A and phase B is equal to zero when fault occur since both of the phases are grounded. Since this type of fault only produce positive-sequence current, the PV inverter current will not be affected during the fault. Only neutral impedance can affect the value of positive-sequence current [13]. The output voltage and current for grid and inverter during fault was shown in Figure 2-20.

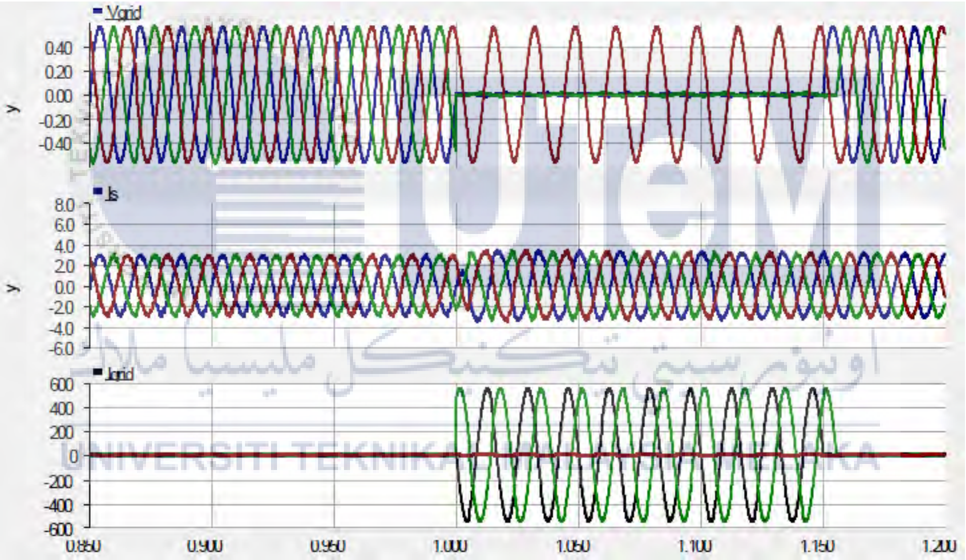

Figure 2-20: Output Voltage and Current for Grid and Inverter during Fault Condition.

2.4.2.3 Line-to-Line (LL) Fault

Line-to-line fault occur when two phases in three-phase system touch with each other without connecting to ground. This type of fault may cause by wind. The equivalent circuit was shown in Figure 2-21 in which positive-sequence and negative-sequence was connected in parallel. Zero-sequence was not present in LL fault [13].

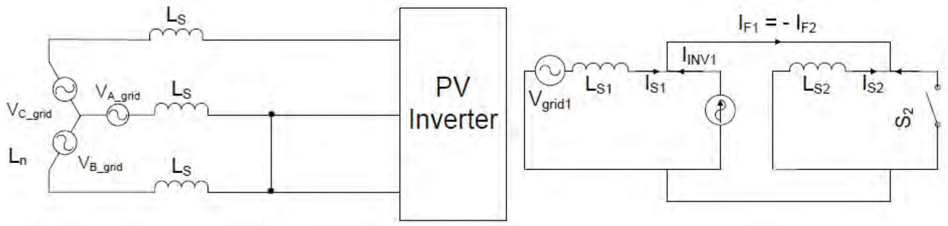

Figure 2-21: Circuit for Line-to-Line Fault Condition.

During fault, the voltage for phase A and phase B are identical since they are connected in short circuit. The resulting voltage is half of magnitude voltage in phase A with phase angle 180° in opposite polarity. The voltage is not equal to zero since there is no ground connection in the circuit. The fault current was in opposite polarity of grid current since $I_{F1} = -I_{F2}$ [13]. Figure 2-22 shows the output voltage and current for grid during line-to-line fault.

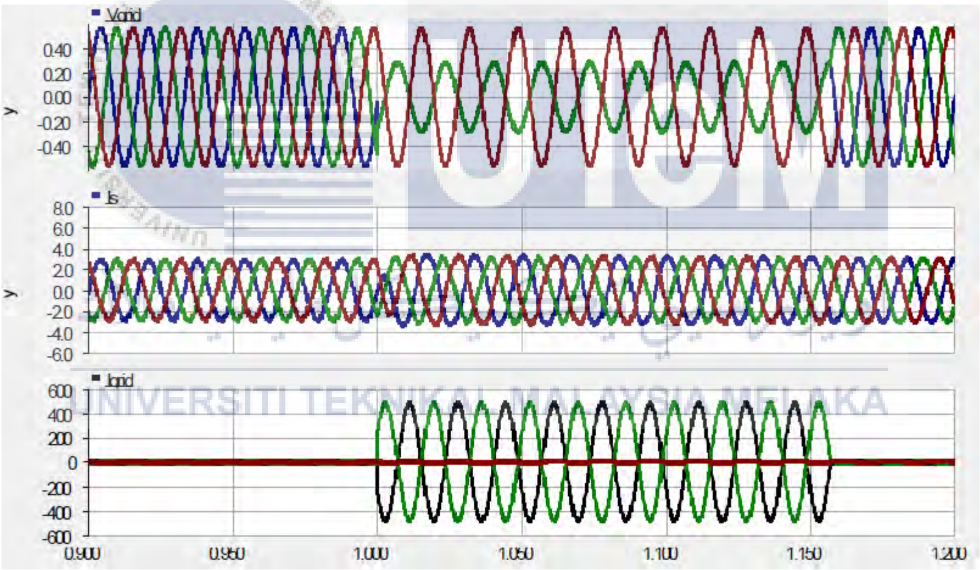

Figure 2-22: Output Voltage and Current for Grid during Line-to-Line Fault.

2.4.2.4 Three-Phase Fault

Three-phase fault is symmetrical fault which is also known as balanced fault. This type of fault occur when all three phases connected to ground. As all phases create a short circuit to the ground, the fault current is very large and only limited by ground fault resistance. In three-phase system, circuit breaker was mounted to protect transformer and other components that is in series with fault from damage. Since this is symmetrical fault, only positive-sequence equivalent circuit was presented as shown in Figure 2-23 [13].

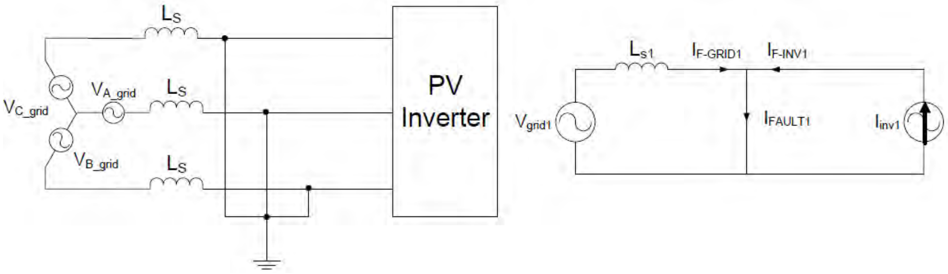

Figure 2-23: Circuit for Three-Phase Fault Condition.

As three-phase fault occur in a system, the fault current will be high during the fault while its voltage will become zero. Reactive power was contributed by three-phase current in order to maintain the voltage without exceeding current-carrying capability of power semiconductor of PV inverter. Since the output power can be absorbed by short-circuit is near zero, only reactive current was considered [13]. Figure 2-24 shows the output of voltage and current of inverter for three-phase fault condition.

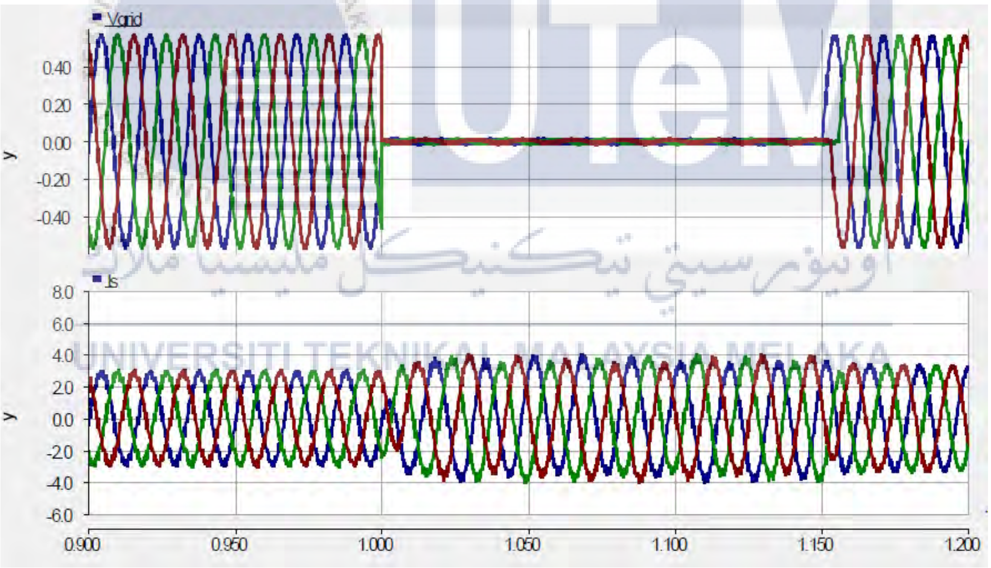

Figure 2-24: Output Voltage and Current of Inverter for Three-Phase Fault Condition.

CHAPTER 3

DESIGN AND MODELLING OF THREE-PHASE PV SYSTEM

3.1 Introduction

This chapter will discuss about the development and flow of the system including its block diagram. The three-phase PV system was modelled using Power System Computer Aided Design (PSCAD) software. Components involved in the modelled system are DC power source, inverter model, pulse width modulation, phase locked loop, ABC to DQ converter, filter and Microgrid network model.

3.2 Flow of Project

First of all, all information regarding three-phase grid-connected PV system was gathered to complete the literature review for the project. The project will focus on controlling the power generated by photovoltaic system. Based on literature review, a block diagram for three-phase grid-connected PV system will be design which represent the component used in this project. Operation of the system including power, voltage and current flow will be shown in the block diagram.

Three-phase grid-connected photovoltaic system will be modelled using PSCAD software based on the block diagram. The modelled photovoltaic system should be able to help grid in supplying active and reactive power for load demand which is residential area. The output power for the system must equal with reference power injected to photovoltaic model. Filter was used to reduce harmonic distortion in the system. Otherwise, troubleshoot will be done.

Several case studies will be used to test the system which includes power contribution at point of common coupling (PCC), effect of excessive power to support load demand without grid connection, effect of generated power against voltage impact and abnormal condition at photovoltaic model. Microgrid will be modelled in radial network system and voltage drop will be observed in order to find optimum point of connection of photovoltaic model. Performance of the system will be analyzed based on all case studies. Figure 3-1 shows the flow of the project.

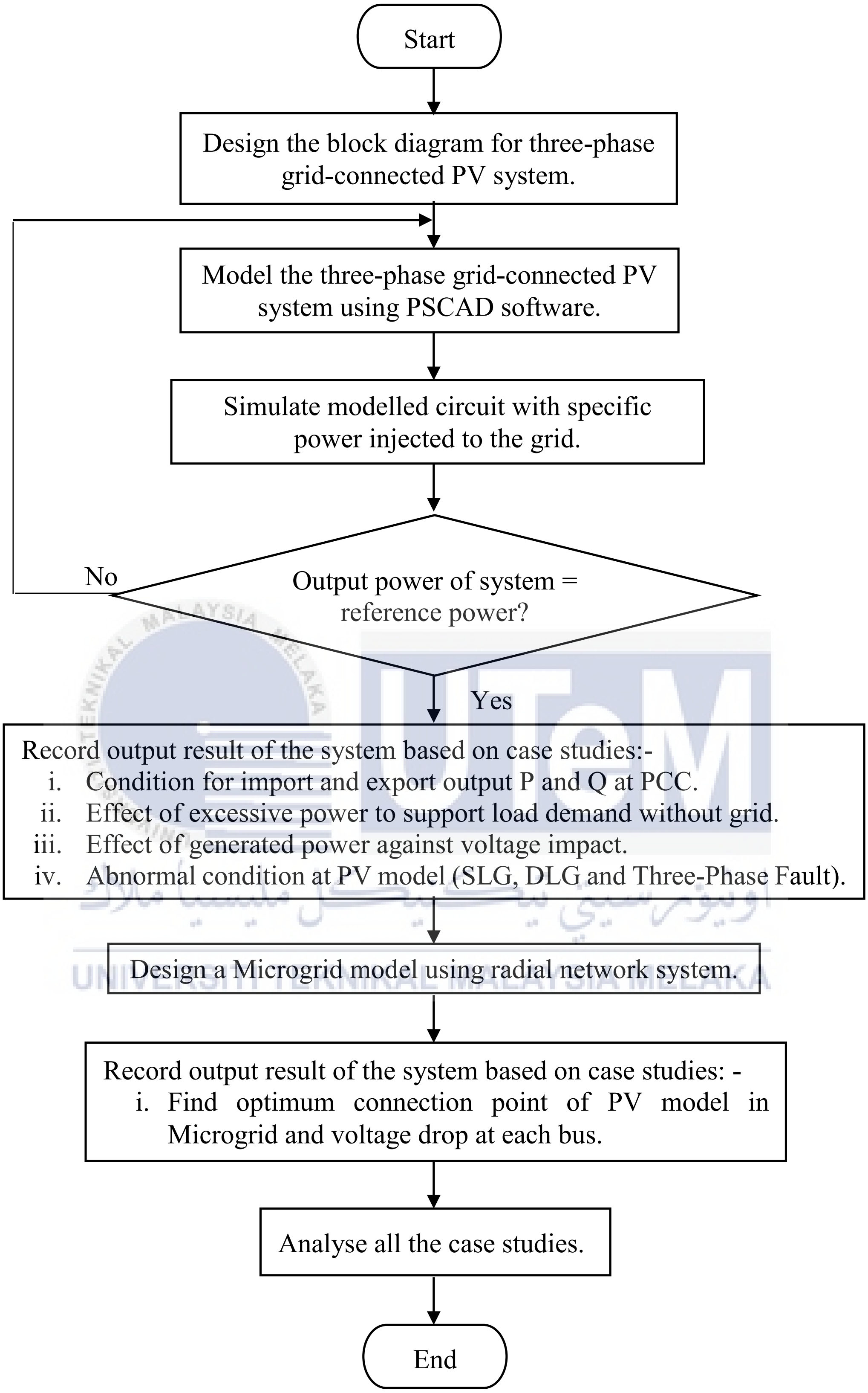

Figure 3-1: Flow of the Project.

3.3 Block Diagram of Three-Phase Grid-Connected PV System

The output voltage generated by PV arrays is in DC form which is not suitable to connect directly to grid. Basically, DC voltage can be transform into AC form using inverter. The three-phase PV system was designed in order to control the power that generated from PV system to grid system. Even though the voltage was converted to AC form, it still cannot be connected with grid if the voltage, frequency and phase angle is not equal with grid network.

As the system is in three-phase connection, there are several additional components that must be used in converting the DC voltage into AC form. From the block diagram for three-phase grid-connected PV system shown in Figure 3-2, the output voltage and current from inverter will be convert into DQ form by using ABC to DQ converter. The ABC to DQ converter will allow the three-phase voltage or current to convert into two-phase form.

Power controller is used to compare between reference active power and reactive power with the power produced by the inverter. The output of the power controller is in current form which is obtained from the present of PI controller. Both of the current from ABC to DQ0 converter and power controller will be used in current controller to get the output in m_d and m_q form. Both of these outputs will converted back to three-phase form using DQ0 to ABC converter which labelled as m_a, m_b and m_c. Output from the DQ0 to ABC converter is in sine wave. As this three-phase system use PWM three-phase inverter, the output of DQ0 to ABC converter will be compared with triangular input to produce the switching scheme for IGBT. PLL was used to determine the angle of the voltage that will be used in ABC to DQ0 converter.

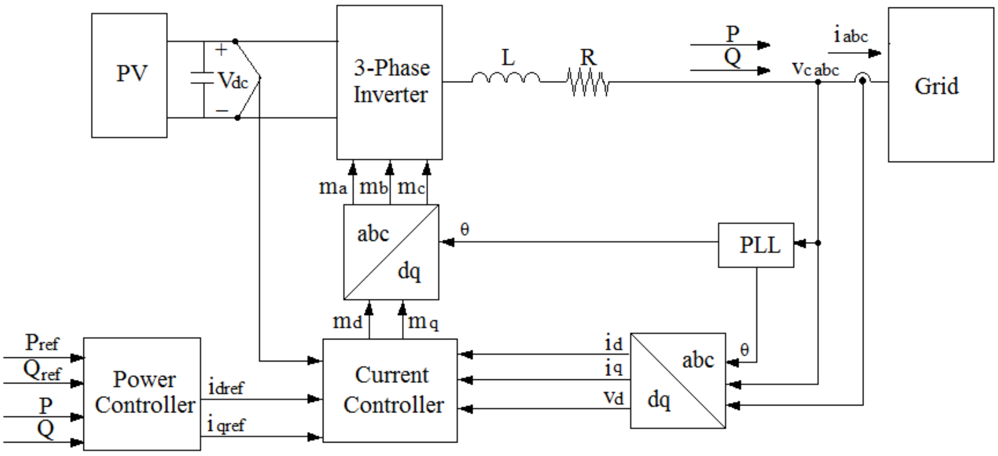

Figure 3-2: Block Diagram for Three-Phase Grid-Connected PV System.

3.4 Detailed Components in Three-Phase Grid-Connected PV System

Three-phase grid-connected system involved PV array, PWM three-phase inverter with IGBT power switching, Phase-Locked Loop (PLL), Proportional-Integral (PI) controller, ABC to DQ converter and filter. Modelled circuit is based on the block diagram described in this chapter.

3.3.1 PV Arrays

As PV array produced DC power, DC voltage source was used in the simulation circuit to replace the PV arrays. According to [19], magnitude of DC voltage, E_a must be high enough to constantly block the diode in inverter and maintain the stability of controller. Value for DC source can be decided using formula stated in (3.1).

$$V_{dc} > \sqrt{2}\,.\,\sqrt{3}\,.\,V_{rms} \tag{3.1}$$

From (3.1), V_{dc} decided for this modelled circuit is set to 1000V which is 1.7 times higher than 587.77V. Capacitor presented at DC source is used to filter the ac component so that constant dc voltage can be obtained. Figure 3-3 shows the DC supply used in modelled circuit.

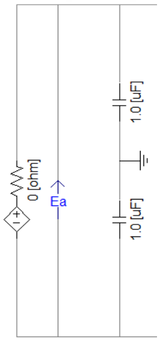

Figure 3-3: Modelled DC Power Source.

3.3.2 Inverter Model

This three-phase grid-connected PV system use three-phase inverter to convert the DC output voltage into AC form. In this design, PWM three-phase inverter was used along with filter to reduce the harmonics produced in the output voltage of inverter. The inverter consists of three pairs of power electronics switches which is IGBT. As discussed in [11], IGBT is used as it require simple gate drives and it is suitable for application that require high switching frequency. Each pair of power switches will be turned on at different time in order to allow current to flow through each phase. Function of each diode connected with IGBT is to prevent short path for the current. Figure 3-4 shows the three-phase inverter used for the system.

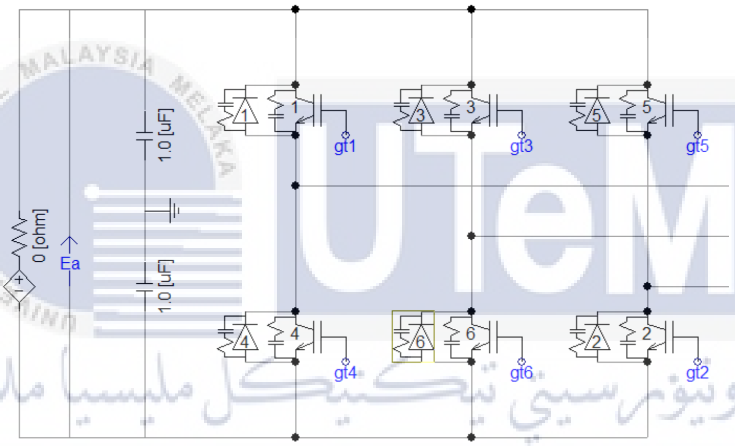

Figure 3-4: Modelled Three-Phase Inverter.

3.3.3 Pulse Width Modulation (PWM)

As mention in [19], PWM was used for IGBT switching in the inverter as it have low harmonic distortion of line current and controllable power factor. Modulating signal (output for each phase) will be compared with carrier signal (triangular signal) in order to produce PWM output. Frequency of modulating signal is set to 50 Hz while frequency of carrier signal was set to 3.3 kHz with maximum output level equal to 1 and minimum output level set to -1. From information discussed in [20], frequency of carrier signal must be 21 times higher than frequency set for modulating signal. In order to balance the rising and falling edges of carrier signal, duty cycle was set to 50% with 90º initial phase of the signal. The output voltage for each phase will be compared with the carrier signal using a comparator. In order to get the PWM output, the level of comparator was set to 1 for reference signal higher than carrier signal while -1 when reference signal lower than carrier signal. Over modulation phenomenon will occur if the amplitude modulation of PWM exceed 1. Output of the comparator will become the gate signal for IGBT. Figure 3-5 shows the modelled PWM output for inverter switching. The not gate was used to differentiate the input for each pair of IGBT.

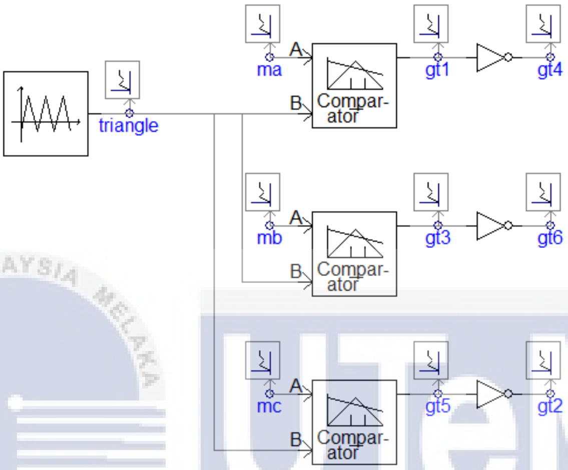

Figure 3-5: Modelled PWM Output for Inverter Switching.

3.3.4 Phase Locked Loop (PLL) Controller

Phase Locked Loop (PLL) was use in the modelled system to get the angle that need to be used for ABC to DQ0 converter. From Figure 3-6 shown below, the voltage from the filtered output of inverter will be used as the input of PLL. The output angle is then being compared with angle from carrier signal which is 90° before convert into ω in radian. The angle with label ‘theta’ will be used as transformation angle for ABC to DQ0 converter. The frequency of the PLL was set to $50H_z$ compatible with the whole three-phase system.

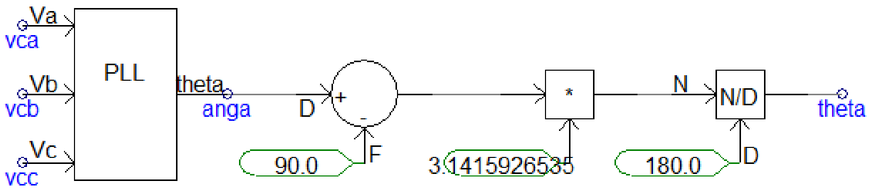

Figure 3-6: Modelled PLL used for Three-Phase Grid-Connected PV System.

3.3.5 Proportional-Integral (PI) Controller

For three-phase grid-connected PV system, PI controller is use to adjust the settling time of the system and produce zero steady-state error in current control loop. The PI controller also used for power controller to produce reference current in current controller model which labelled as i_{dref} and i_{qref} as shown in Figure 3-7.

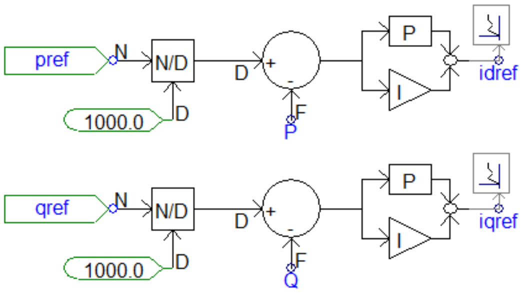

Figure 3-7: Modelled Circuit for Power Controller.

The outputs is then used to compare with actual i_d and i_q from ABC to DQ0 converter as shown in Figure 3-8. PI controller is used to produce d_d and d_q output from the output of the summing junction. Both of the outputs from current controller will produce m_d and m_q which is connected with DQ0 to ABC converter.

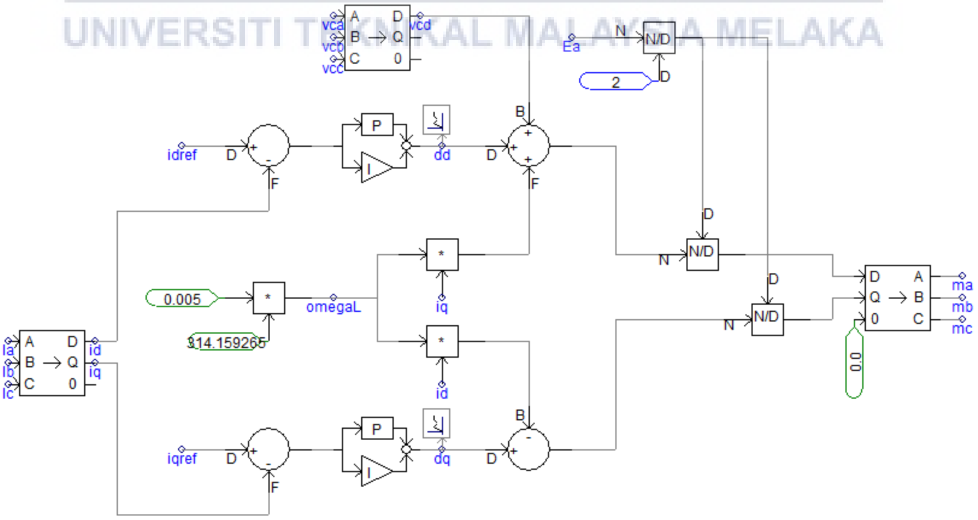

Figure 3-8: Modelled Circuit for Current Controller.

As discussed in [19], zero steady-state error and fast response can be achieved when PI controller is used. From Figure 3-9, (3.2) can be achieved.

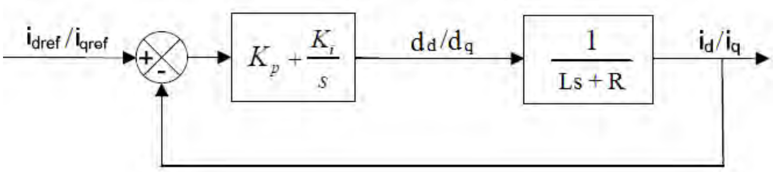

Figure 3-9: Block Diagram from Current Controller and Power Controller.

$$\frac{i_d}{i_{dref}} = \frac{i_q}{i_{qref}} = \frac{K_p s + K_i s}{Ls^2 + (R + K_p)s + K_i} \tag{3.2}$$

3.3.6 ABC to DQ0 Converter

ABC to DQ0 converter will be used in converting the filtered output current and voltage from inverter to be used in power controller and current controller. The I_a, I_b and I_c will convert into i_d and i_q form while v_{ca}, v_{cb} and v_{cc} converted into v_{cd} output. DQ0 to ABC converter will convert the output of current controller to produce reference signal for the system which labelled as ma, mb and mc that shown in Figure 3-10. These converters will use 'theta' from PLL as its transformation angle.

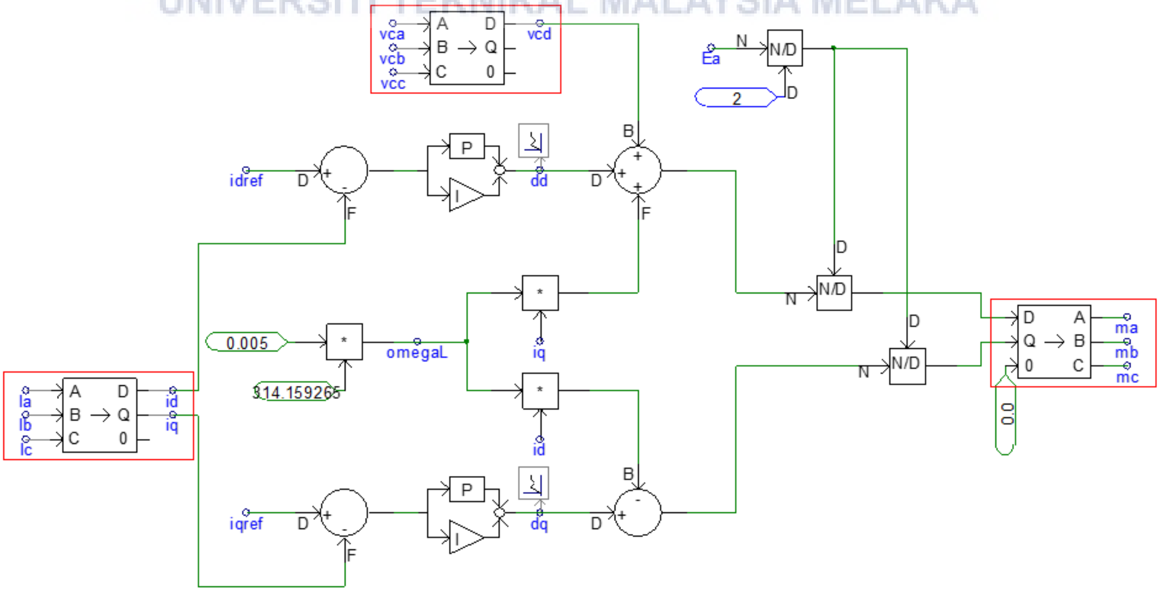

Figure 3-10: ABC to DQ0 Converter used in Modelled Circuit.

From [19], value of P_{in} and P_{out} as shown in (3.3) and (3.4) can be achieved by using (2.14).

$$P = \frac{3}{2} v_d i_d \tag{3.3}$$

$$Q = -\frac{3}{2} v_d i_d \tag{3.4}$$

3.3.7 Filter

Output parameter from three-phase inverter will be filtered using LCL filter. This filter is used as it can produce better attenuation of switching harmonics compared to LC filter. It also can produces low grid current distortion with low switching frequency. The value of capacitor needed in the filter circuit can be calculate using (2.16) with resonant frequency is set to 100Hz and both inductor are set to 1mH.

$$[100Hz \times 2\pi]^2 = \frac{1mH + 1mH}{(1mH \times 1mH)C} \tag{3.5}$$

$$C = 5.1\mu F \tag{3.6}$$

By using value of capacitor in (3.6), LCL filter was developed as shown in Figure 3-11.

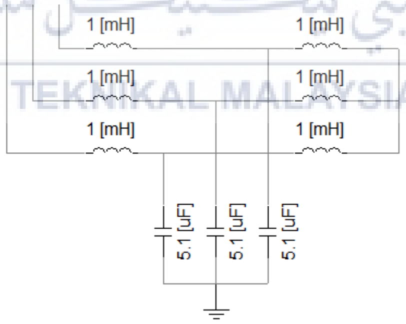

Figure 3-11: Developed LCL Filter Circuit.

3.3.8 Microgrid Network Model

Microgrid network was modelled to test the performance of PV model in term of voltage profile. There are several types of network connection such as mesh network system, ring network system and radial network system. For this Microgrid model, radial network system was chosen. In a phase, there will be four loads with different capacity. Load connected near the utility grid has lower capacity than load connected the furthest from utility grid. Different capacity of load represent the typical demand from customers. In this modelled Microgrid network, $120mm^2$ multi-core aluminium PVC insulated distribution cable was chosen. The details about the cable was based on standard BS6346:1989 600/1000V as shown in APPENDIX E. Calculation for line impedance used for Microgrid network was shown in APPENDIX D.

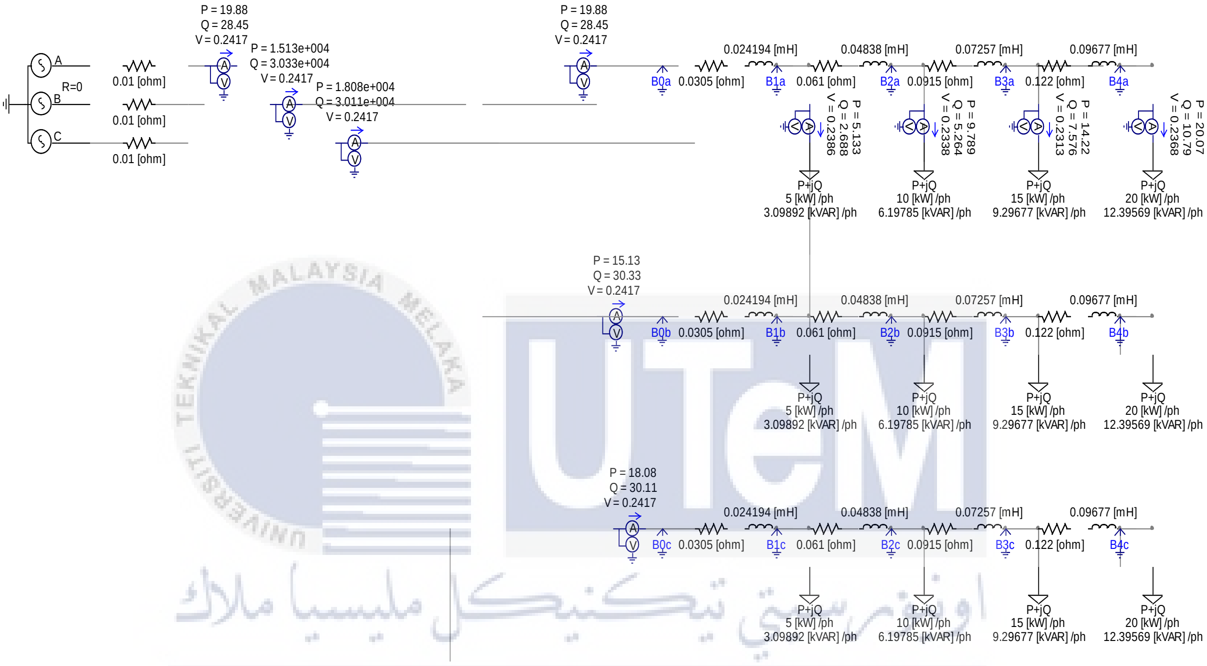

Figure 3-12: Microgrid Network Model.

3.5 Gantt Chart

Table 3-1: Project Gantt chart.

Activity	**Final Year Project 1**					**Final Year Project 2**				
	Sept	**Oct**	**Nov**	**Dec**	**Jan**	**Feb**	**March**	**April**	**May**	**June**
Meet supervisor and decide project title	🟦									
Do literature review and data collection		🟦	🟦							
Design block diagram of the system			🟦	🟦						
Complete progress report for FYP 1				🟦						
Presentation for FYP 1				🟦						
Submit finalize report for FYP 1				🟦						
Circuit development using PSCAD				🟦	🟦	🟦	🟦			
Troubleshoot the modelled circuit					🟦	🟦	🟦	🟦	🟦	
Circuit analysis					🟦	🟦	🟦	🟦	🟦	
Writing report for FYP 2						🟦	🟦	🟦	🟦	
Presentation for FYP 2									🟦	
Submit Final Report for FYP 2										🟦

CHAPTER 4

RESULT AND DISCUSSION

4.1 Introduction

This section will discuss results obtained from the whole modelled system. These results will be used to analyze the performance of the system as mention in objectives of this project. Several case studies will be carried to analyze the performance of the three-phase grid-connected PV system. All data obtained in this project was summaries by using Microsoft Excel and Origin Pro 8.5.

4.2. Case Studies of Condition to Import and Export Output of Active and Reactive Power at Point of Common Coupling (PCC)

Distributed Generation (DG) is a system that was designed to help grid in fulfil the load demand. In this case study, power contribution from PV will be observed at point of common coupling (PCC) either the PV model capable to distribute its generated power to load and grid.

4.2.1 Case 1: PV Model Set to Have Priority to Supply Constant Active Power

Inverter is set to have priority in supplying constant 40kW active power at each phase. The modelled circuit was divided into three elements which are grid, inverter and load. Figure 4-1 shows the PV model have priority to supply constant active power. The system is test with sudden load change at each phase from 30kW+j25kVar, 80kW+j15kVar and to 120kW+j50kVar. The result was measured at point of common coupling (PCC) between grid, inverter and load.

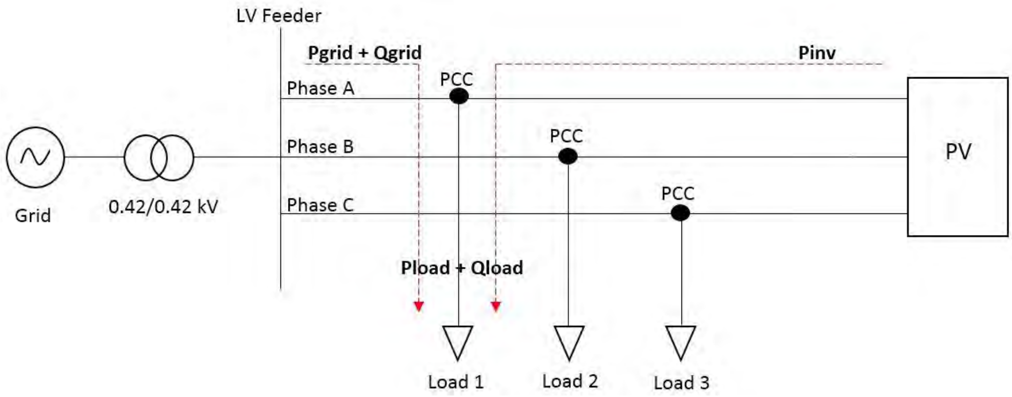

Figure 4-1: PV Model Have Priority to Supply Constant Active Power.

At PCC, the power contribution between grid, inverter and load can be observed and Figure 4-2 shows the result for export and import of active and reactive power with 120kW injected active power. From the figure, the positive value represent the exported power while negative value shows the imported power at PCC.

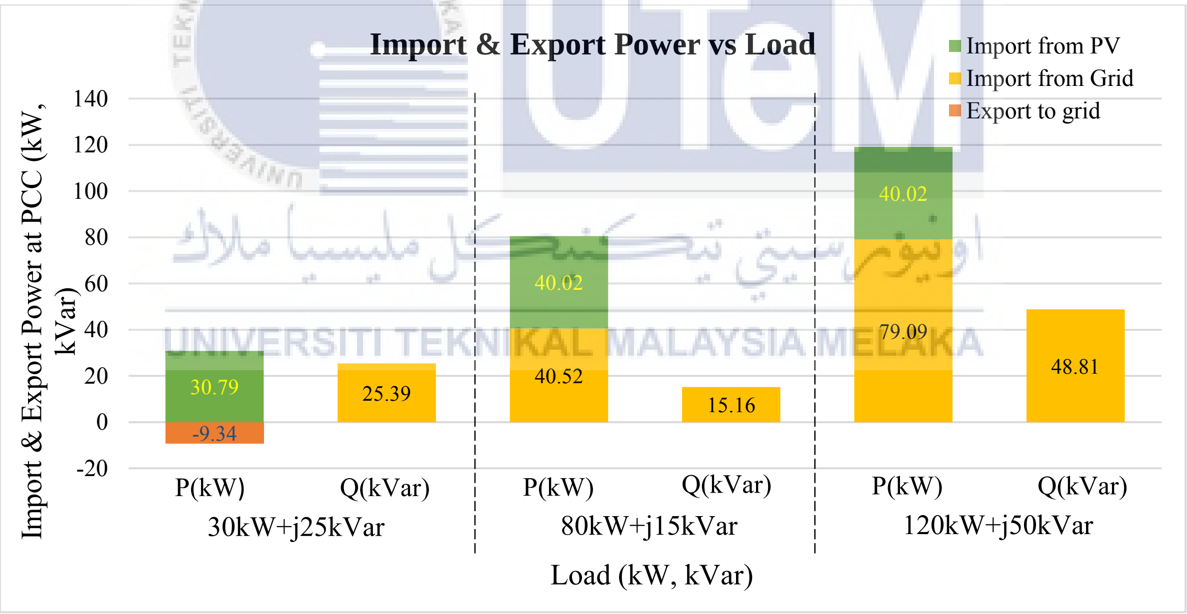

Figure 4-2: Result for Export and Import of Active and Reactive Power with 120kW Injected Active Power.

4.2.2 Case 2: The PV Model Set to Supply Constant Complex Power

Inverter is then tested with constant apparent power ($S = P + jQ$). 120kW+j60kVar apparent power is the total power generated by PV model to the system. The system is then tested with sudden load change from 10kW+j5kVar, 30kW+k25kVar, 80kW+j15kVar and to 120kW+j50kVar. Figure 4-3 PV model have priority to supply constant apparent power.

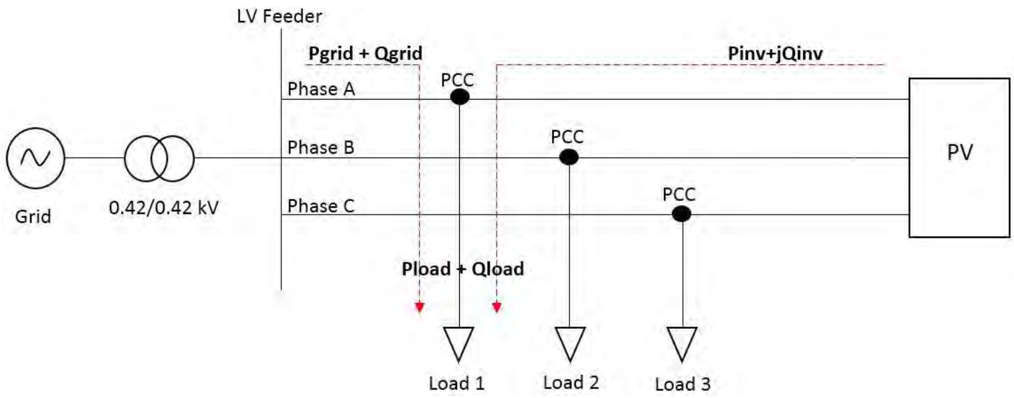

Figure 4-3: PV Model Have Priority to Supply Constant Apparent Power.

The power contribution between grid, inverter and load are observed at PCC same with Case 1. Figure 4-4 shows the result for export and import of active and reactive power with 120kW+j60kVar apparent power. All measured parameter was done for Phase A, Phase B and Phase C.

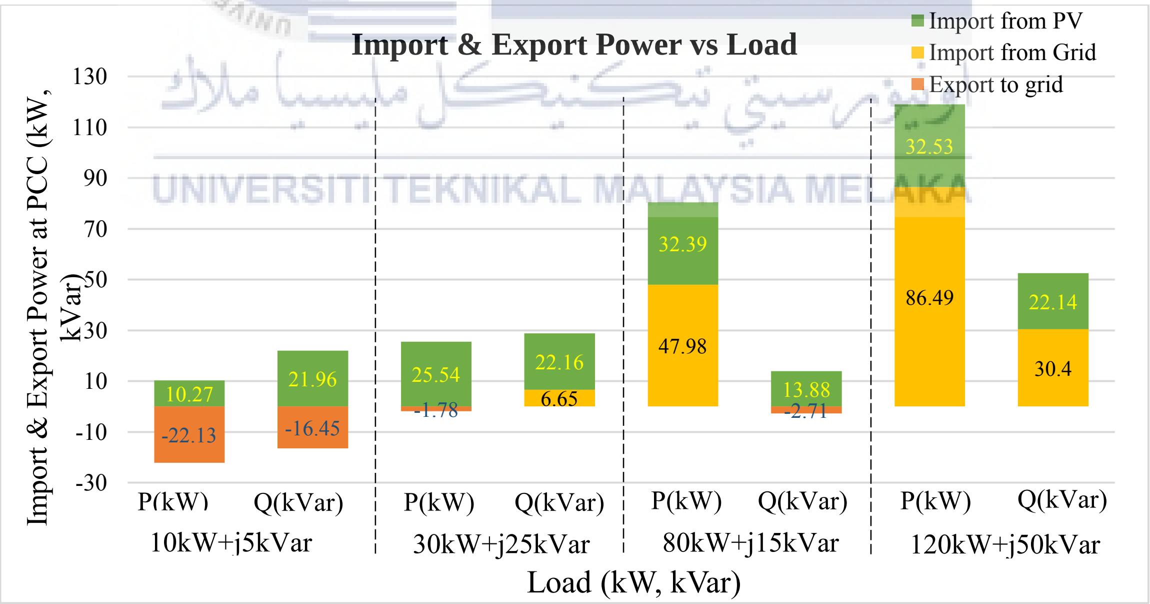

Figure 4-4: Result for Export and Import of Active and Reactive Power with 120kW+j60kVar Apparent Power.

4.2.3 Discussion

From Case 1, the inverter prioritized in supplying active power to the system through PCC. Load that was tested using the system are 30kW+j25kVar, 80kW+j15kVar and 120kW+j50kVar. For 30kW+j25kVar load, inverter able to produce 40.13kW output power. As load demand is lower than power produced by inverter, the active power at load is fully supplied from inverter. Amount of active power produced by inverter is more than enough for load, so grid will receive the remaining amount of power from inverter which is -9.34kW. Inverter only have priority to supply active power, so, load will receive reactive power from grid. From Figure 4-2 (30kW+j25kVar), the inverter able to export the active power to grid and load as the value of active power at grid denotes negative value while the reactive power at inverter was imported from grid. This can be conclude that inverter export active power to load and grid, and load import reactive power from grid. Figure 4-5 below shows the inverter export active power to load and grid, load import reactive power from grid.

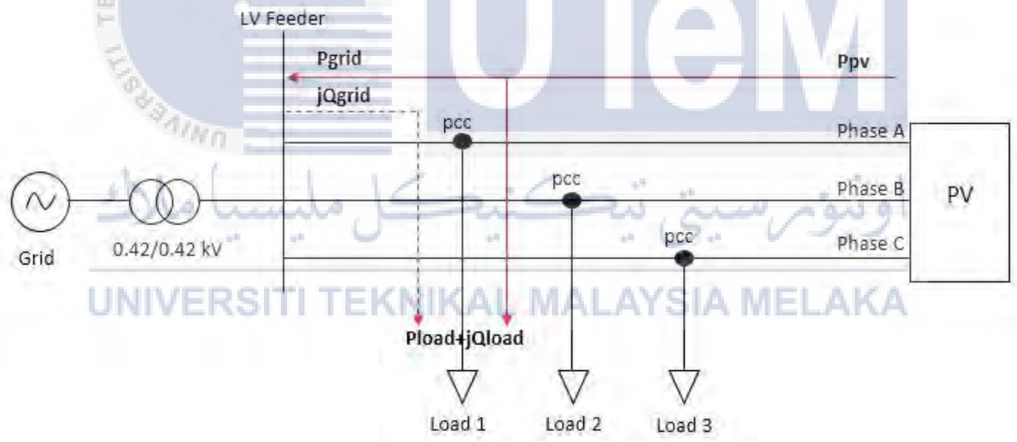

Figure 4-5: Inverter Export Active Power to Load and Grid, Load Import Reactive Power from Grid.

As the load is change to 80kW+j15kVar, it can be seen in Figure 4-2 that the inverter and grid supply active power to load as both of inverter and grid active power are in positive value. Inverter only able to supply 40.02kW to load and grid support the other load demand. The reactive power at load was supplied by grid as inverter only have priority to supply constant active power. This can be conclude that the load import active power from inverter and grid while reactive power was imported from grid. 120kW+j50kVar load produce the same pattern of power contribution with 80kW+j15kVar load. Figure 4-6 shows the load import active power from inverter and grid, load import reactive power from grid.

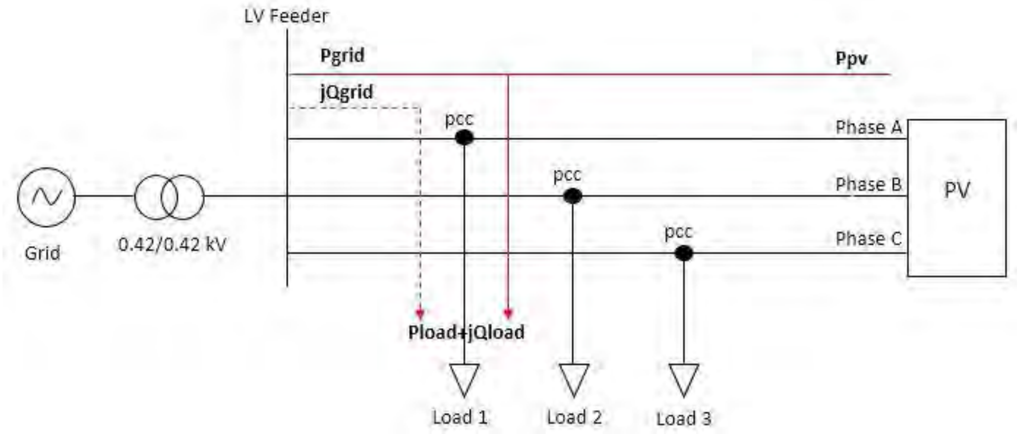

Figure 4-6: Load Import Active Power from Inverter and Grid, Load Import Reactive Power from Grid.

From Case 2, the inverter have prioritized to supply apparent power to the system. As the load is set to 10kW+j5kVar, the active and reactive power at grid have negative value. From the result in Figure 4-4, inverter able to produce 32.41kW and 21.96kVar active and reactive power which is higher than load demand. As the load is much lower than the output of inverter, the inverter able to export both active and reactive power to grid and load. The remaining power that are able to be exported to grid are -22.13kW-j16.45kVar. Figure 4-7 shows the inverter export active and reactive power to grid and load.

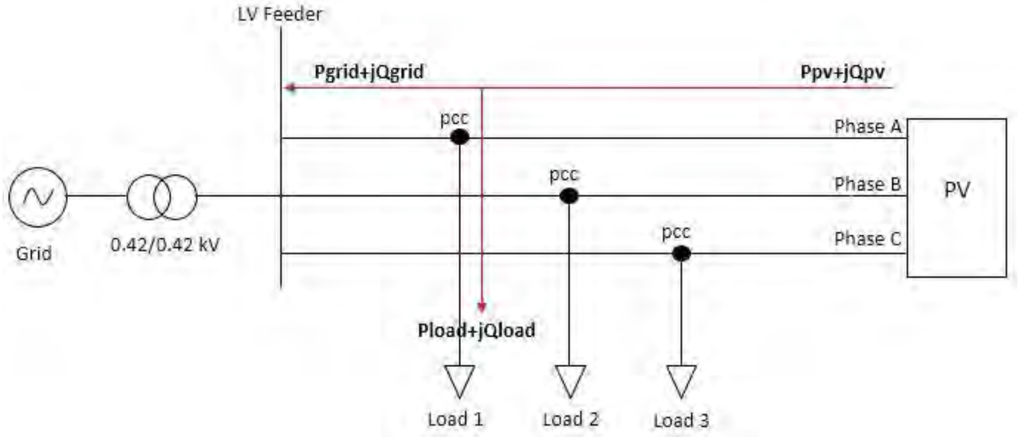

Figure 4-7: Inverter Export Active and Reactive Power to Grid and Load.

The system is then tested with 30kW+j25kVar load. Active power produced by inverter is 32.41kW and reactive power is 21.96kVar. Power produced by inverter is higher than load demand and remaining of the produced power will be transferred to grid which is 1.78kW. From the result in Figure 4-4, it shows that the active power at grid have negative value. This denotes that the grid received active power from inverter. The inverter able to supply active and reactive power to load but the load need additional reactive power from grid. This can be conclude that the inverter export active power to load and grid, and load import reactive power from grid and inverter. Figure 4-8 shows the inverter export active power to load and grid, load import reactive power from grid and inverter.

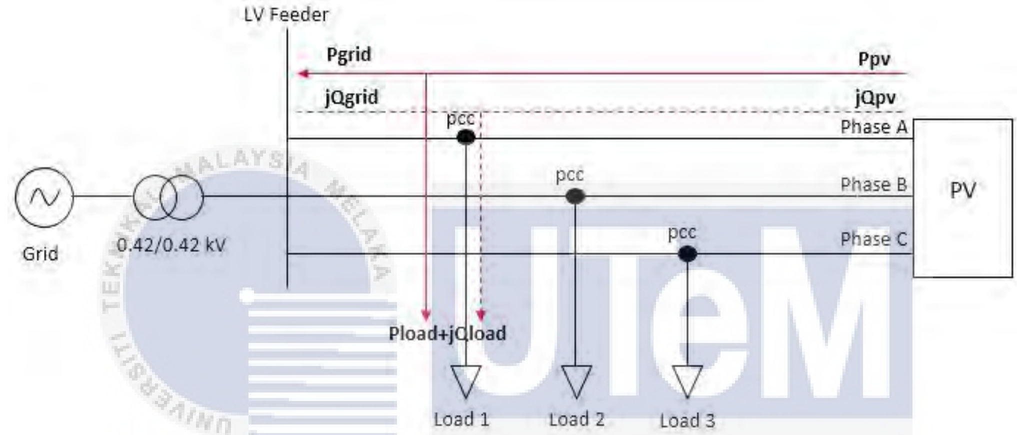

Figure 4-8: Inverter Export Active Power to Load and Grid, Load Import Reactive Power from Grid and Inverter.

As the load increase to 80kW+j15kVar, the power contribution at PCC changed. Inverter able to produce 32.46kW and 21.82kVar. Load demand is much higher than produced power from inverter. The remaining insufficient load demand will be supported by grid. As inverter able to supply 21.82kVar, the load received reactive power fully from inverter and inverter also able to export the reactive power to grid. Load was supplied with active power from grid and inverter as shown in Figure 4-4. This can be concluded that the load import active power from inverter and grid, and inverter able to export the reactive power to load and grid as shown in Figure 4-9.

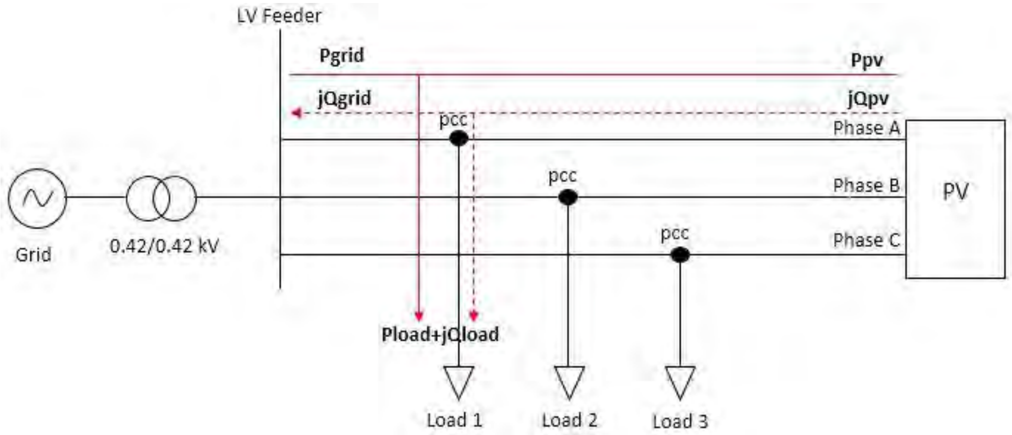

Figure 4-9: Load Import Active Power from Inverter and Grid, Inverter Export Reactive Power to Load and Grid.

Load is then set to 120kW+j50kVar which is almost the same with apparent power supplied to inverter. Inverter able to produce 32.53kW and 22.14kVar. As the load become heavy, the power contribution at PCC also change. The inverter was no longer able to export active and reactive power to grid. The remaining load demand was supported by grid. Grid contribute 86.49kW and 30.4kVar to load. The results was shown in Figure 4-4. In Figure 4-10, it can be seen that the load import active and reactive power from grid and inverter.

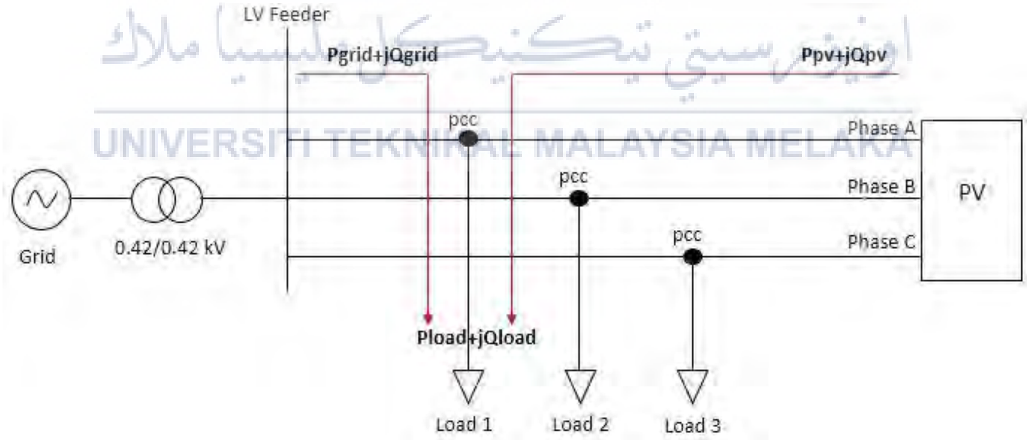

Figure 4-10: Load Import Active and Reactive Power from Grid and Inverter.

According to Case 1 and Case 2, it can be conclude that power contribution depends on the requirement of load demand. If inverter tend to supply active power and load active power demand is less than active power from inverter, the inverter would be able to fully support the load and even able to export the remaining active power to grid. Load demand will be supported by both inverter and grid if amount of load active power demand is higher than active power from inverter. When inverter tend to supply apparent power, inverter able to export both active and reactive power to grid if the load demand is lower than output power from inverter. Grid will support the inverter to fulfil the load demand if load demand is higher than the complex power produced by inverter.

4.3 Case Studies for Impact of Excessive Power to Support Load Demand without Grid Connection

In this modelled circuit, PV model has priority to supply active power and it was not designed as voltage and frequency control. There are three cases that will be observed based on the power produced by PV, power received by load and load voltage. These parameters was observed at each phase. The cases that will be tested are when power generated by PV is lower than load demand, power generated equal to load demand and power generated higher than load demand. Circuit breaker was used to cut the connection from grid to the load and PV model. At 3 seconds, circuit breaker will start to open. Figure 4-11 shows the circuit connection of PV and load without grid connection.

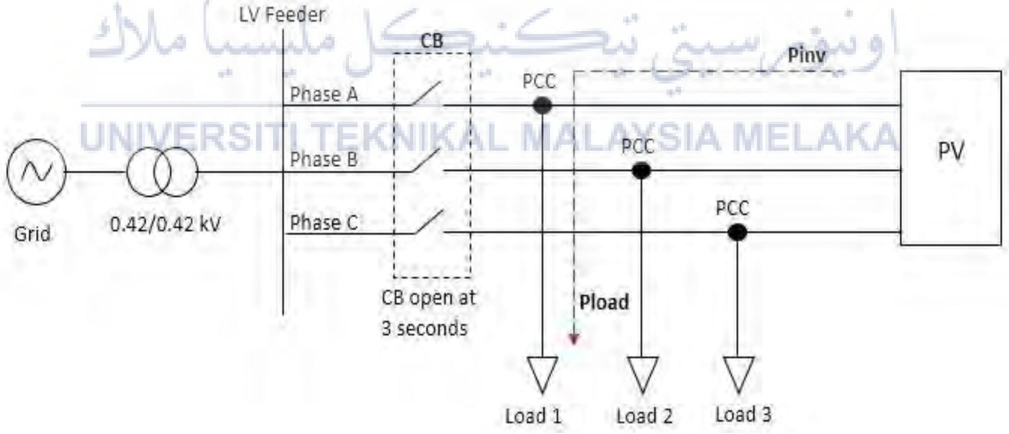

Figure 4-11: Circuit Connection of PV and Load without Grid Connection.

4.3.1 Case 1: Power Generated by PV at Each Phase < Load Demand

Reference power which is the actual total active power from PV was set to 60kW which means 20kW was flow at each phase. Load demand will be varies from 20kW, 25kW, 30kW, 35kW and to 40kW at each phase. Circuit breaker used in the circuit will start to open at 3 seconds which will cut the connection of grid to the system. Output power from PV at each stage was recorded along with power received by load and voltage at load after the connection of grid was cut. Figure 4-12 shows the result for condition of power generated by PV less than load demand.

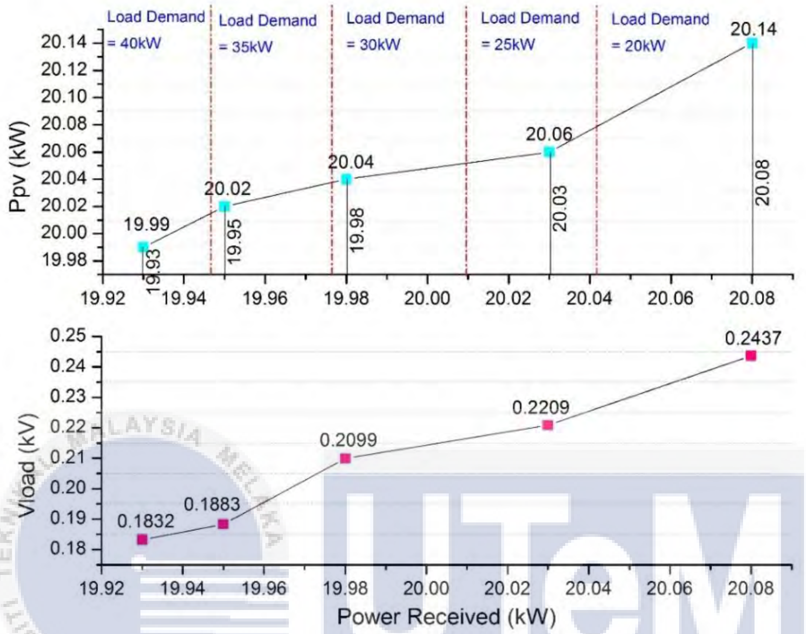

Figure 4-12: Result for Condition of Power Generated by PV Less Than Load Demand.

4.3.2 Case 2: Power Generated by PV at Each Phase = Load Demand

For this condition, load was set to 10kW, 20kW, 30kW, 40kW and 50kW which is same with power generated by PV model at each phase. Circuit breaker will start to operate at 3 seconds which cause grid disconnected from PV model and grid. This means that the load demand was fully supported by PV model. All parameter needed for this case was recorded. Figure 4-13 shows the result for condition of power generated by PV equal to load demand.

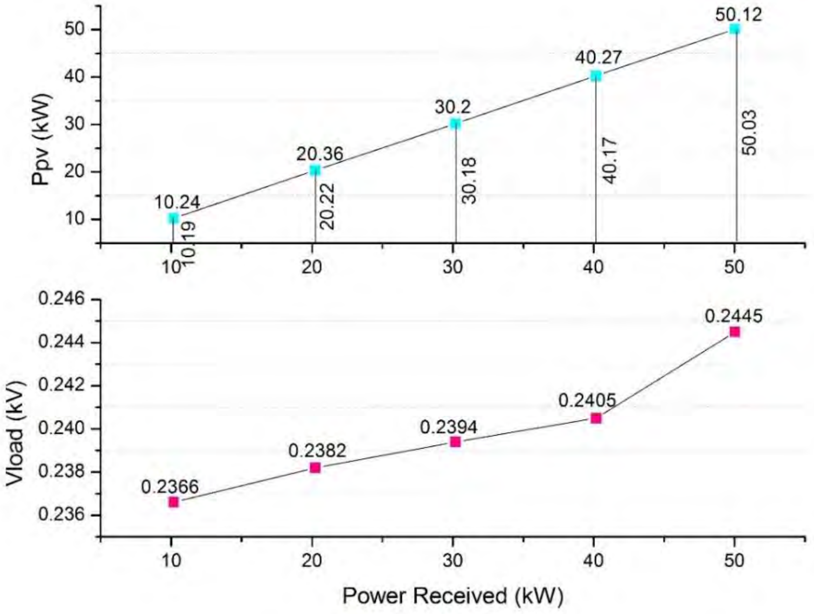

Figure 4-13: Result for Condition of Power Generated by PV Equal to Load Demand.

4.3.3 Case 3: Power Generated by PV at Each Phase > Load Demand

In this case, load demand was fixed to 10kW at each phase and power generated by PV at each phase was set to 10kW, 12kW, 14kW, 16kW, 18kW and 20kW. Parameters was recorded after circuit breaker start to operate which is at 3 seconds. As each phase of PV model set to 10kW, total power from PV model is 30kW. Parameter recorded was in root mean square (RMS) value. Figure 4-14 shows the result for power generated by PV higher than load demand.

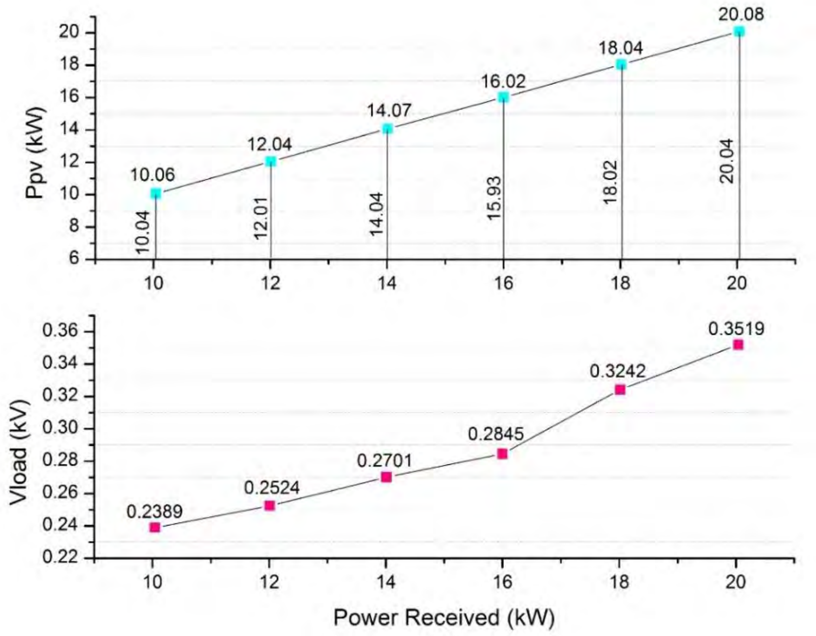

Figure 4-14: Result for Condition of Power Generated by PV Higher Than Load Demand.

4.3.4 Discussion

Usually, electrical equipment can be operate as long as it have supply voltage in range of 0.23kV to 0.24kV. Most equipment was designed to operate within ±5% of its nominal value. From all these case, it can be observed either equipment are able to operate or it will damaged based on the power received by load and its amount of voltage. As this case was observed without connection of grid to PV model and load, circuit breaker was used in order to cut the supply from grid. The circuit breaker will operate at 3 seconds.

In Case 1, power generated by PV model at each phase was fixed to 20kW which mean total power is 60kW. The system was tested using different value of load which is 20kW, 25kW, 30kW, 35kW and 40kW. System used in this case studies is a balanced system. From the result, 20kW load demand able to be supported by PV. Power generated by PV model at each phase is 20.14kW and load able to receive 20.08kW from PV model. Since the system is balanced, total power received by load is 60.24kW which is almost the same with total power generated by PV model. With these amount of power received, voltage at load is 0.2437kV which is near to 0.24kV. As load demand was changed to 25kW at each phase, power received by load is 20.03kW which is less than load demand. Voltage at load also decreased to 0.2209kV. Power received by load continuously dropped as the value of load demand increase. 50kW load demand have the lowest power received and voltage. From this case, it can be conclude that lower amount of power generated could lead to insufficient power for heavy load. Besides that, voltage at load was affected by the power received by the load. With 20kW active power generated by PV model at each phase, only 20kW load demand able to operate as it able to receive 0.2437kV while the other load will not operate at all. Insufficient power received by loads was due to disconnection of grid to the system

According to Case 2, power generated by PV model at each phase was set to have the same value of load demand which is 10kW, 20kW, 30kW, 40kW and 50kW. These values was set for each phase of the system. From the result, as the amount of load increased, the power supplied to load is still sufficient since it have the same amount of load demand. The highest load demand used in Case 2 is 50kW and it able to receive 50.03kW with 0.2445kV. 10kW load demand able to receive 10.19kW with 0.2366kW. From this case, it can be conclude that the higher the amount of power received by load, the higher the voltage across the load. Voltage across all the load are within 0.24kV and 0.23kV which allow all of the load to operate.

From Case 3, power generated by PV model at each phase was set higher than load demand. Load was fixed to 10kW at each phase while power generated by PV at each phase varies from 10kW, 12kW, 14kW, 16kW, 18kW and to 20kW. This means that total power generated by PV model is 30kW, 36kW, 42kW, 48kW, 54kW and 60kW. Circuit breaker will start to operate at 3 seconds causing grid to disconnect with the system. From the result, it shows that the load able to receive 10.04kW when 10kW was set to be generated by PV model at each phase. Voltage across the 10kW load is 0.2389kV. As power generated increase to 14kW and 16kW, load received 14.04kW and 15.93kW with voltage across the load equal to 0.2701kV and 0.2845kV. With 20kW power from PV, 10kW load received 20.04kW with voltage equal to 0.3519kV. In this case, it can be conclude that load fully receive active power from PV model even when generated power is higher than load capacity. This cause overvoltage problem at the load as the voltage is higher than specific voltage range. From the result, load only can operate for 10kW power generated by PV model at each phase as the voltage across the loads are within 0.23kV and 0.24kV.

In conclusion, voltage across load need to be within 0.23kV and 0.24kV in order to allow the load to operate. As the power generated is lower than load demand, the voltage will drop causing failure operation of load. When power generated are equal to load demand, load able to operate as the voltages are within 0.23kV and 0.24kV. Amount of power generated must be equal to load demand in order to avoid operation failure of load. If the power generated by PV is higher than load, it could lead to overvoltage problem which can damage the load. Even though power generated was high, power receive by load must not exceed 5% of its nominal value. So, balancing the amount of power generated by PV model with load demand is the best way to avoid any excessive power in the system.

4.4 Case Studies for the Effect of Generated Power at PV Model against Voltage Impact at Low Voltage Distribution Network

In this case study, the effect of power generated from PV model towards voltage across the load will be observed. PV model was designed to help grid network in supplying sufficient power to load demand. The voltage across the load will be observed using different amount of load demand. PV model and grid will be connected with load at point of common coupling (PCC). Figure 4-15 shows flow of power from grid and PV model to support the load.

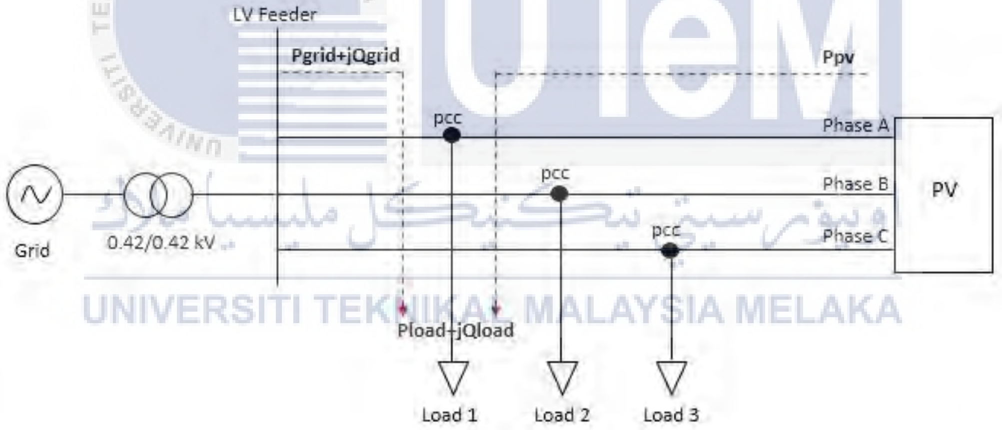

Figure 4-15: Flow of Power from Grid and PV Model to Support Load.

In Microgrid model, there are four different size of load connected at each phase of the system. Each load was set to have a different gap from each other. For bus 1, load was set to have 100m gap from grid while bus 2 is 200m gap from bus 1. Bus 3 was connected 300m away from bus 2 and bus 4 is 400m away from bus 3. The total distance from grid to load at bus 4 is 1km. The system will be observed through two condition which is with and without PV model. Output from inverter will be connected at each bus one at a time to created point of common coupling (PCC). Load from bus 1 until bus 4 was set in increasing order which means the load at bus 4 is the highest load in the phase. Load at each phase are same in order to create balanced three-phase system. The optimum point of connection will be determined based on the voltage profile of the system. Figure 4-16 shows the circuit connection of Microgrid network with grid connected to system.

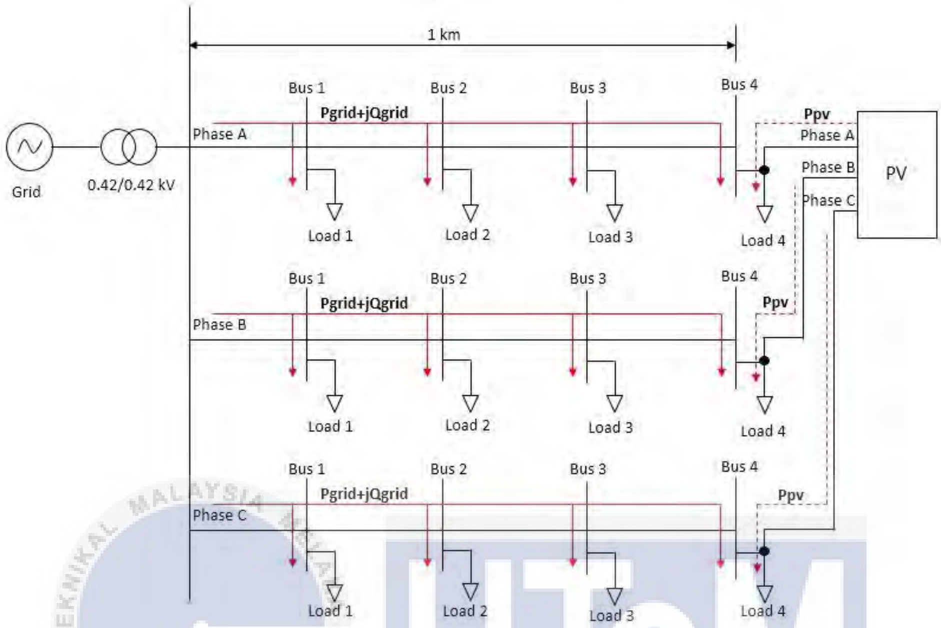

Figure 4-16: Circuit Connection of Micro-Grid Network with Grid Connected to System.

4.4.1 Case 1: Effect on Voltage Profile for Light Load

In this case, voltage at load was measured when PV model and grid was connected at point of common coupling (PCC). Light load case represent the situation when residents went to work from 8a.m until 5p.m or factories which are not operate 24 hours are shutdown at night.. For light load case, load demand at each phase was set to 60kW with 0.85 lagging power factor. Power generated from PV model at each phase was set to 10kW, 20kW, 30kW, 40kW and 50kW. Since the system is three-phase system, the total power generated by PV model equal to 30kW, 60kW, 90kW, 120kW and 150kW. The measured value for maximum load voltages are taken in root mean square (RMS) and converted into percentages. As the system is a balanced system, load voltage at each phase are same. Figure 4-17 shows the results for percentage of voltage increment for light load demand.

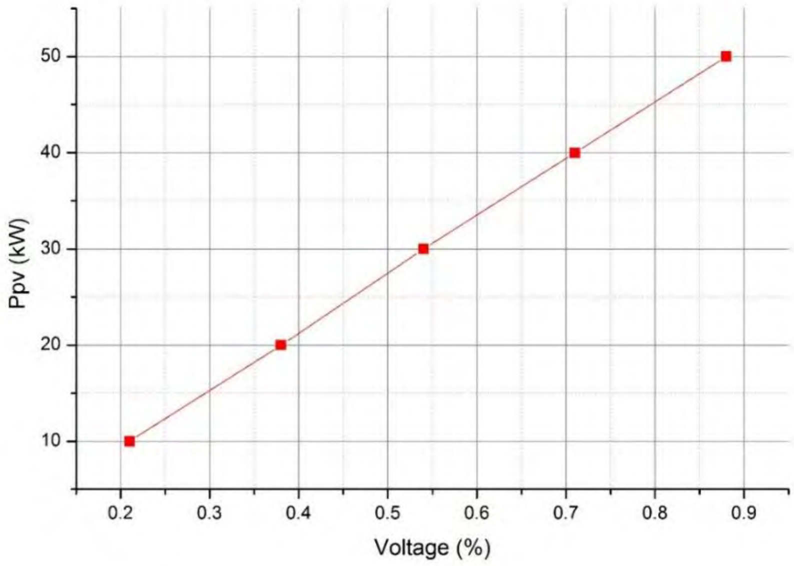

Figure 4-17: Percentage of Voltage Increment for Light Load.

4.4.2 Case 2: Effect on Voltage Profile for Heavy Load

Load at each phase is then changed to 200kW with 0.85 lagging power factor which is classified as heavy load. Heavy load demand represent the situation where the residential area is having a big event such as wedding ceremony. The load demand was tested with the same amount of power generated from PV model at each phase for light load demand which is 10kW, 20kW, 30kW, 40kW and 50kW. The result for percentage of voltage increment for heavy load was shown in Figure 4-18. The result was measured in maximum root mean square (RMS). Since the system is balanced, output load voltage for each phase are same. Further discussion for this case was discuss at end of this section.

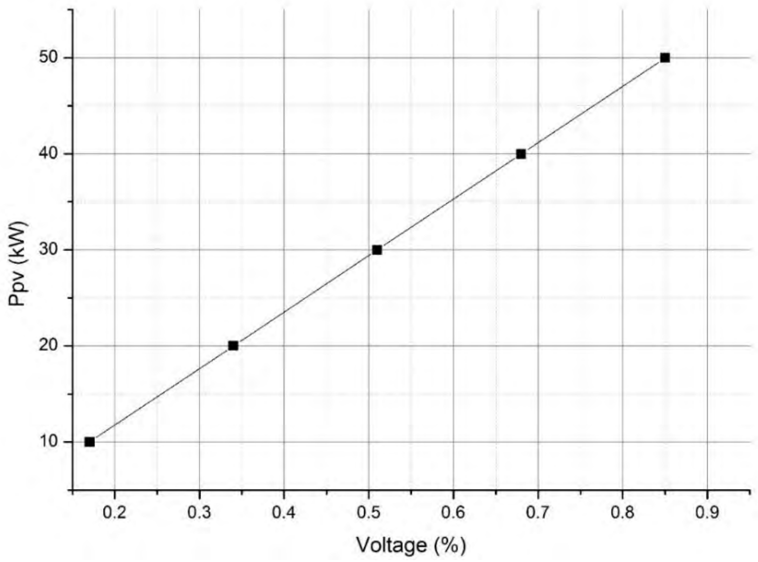

Figure 4-18: Percentage of Voltage Increment for Heavy Load.

4.4.3 Case 3: Find Optimum Connection Point of Voltage Profile and Voltage Drop at Each Bus on the Microgrid Model

In this case, the output voltage at each bus of Microgrid was observed as the distance of the load from grid increases. The output from PV model and grid network will be connected at point of common coupling (PCC) which is near to load demand. As the length of cable increases, the load demand also increases which is represent at different point of buses. The three-phase system was a balanced system which means same amount of load was connected at each bus for each phase. The smallest amount of load at bus 1 represent small residential area while load demand was highest at bus 4 which represent as larger residential area. The purpose of this case study is to find the optimum connection point of voltage in Microgrid model. Total power generated by PV model is 90kW which means each phase able to supply around 30kW for each load. Load demand at each bus are 5kW at bus 1, 10kW at bus 2, 15kW at bus 3 and 20kW at bus 4. Each load demand have 0.85 power factor lagging. The maximum output voltage for each load at each bus connected with PV model was recorded in root mean square (RMS). In order to find the optimum connection point of voltage which should be maintain around 0.24kV, the voltage drop at each load was analyzed. Figure 4-19 shows the result for voltage profile at different point of connection in Microgrid model.

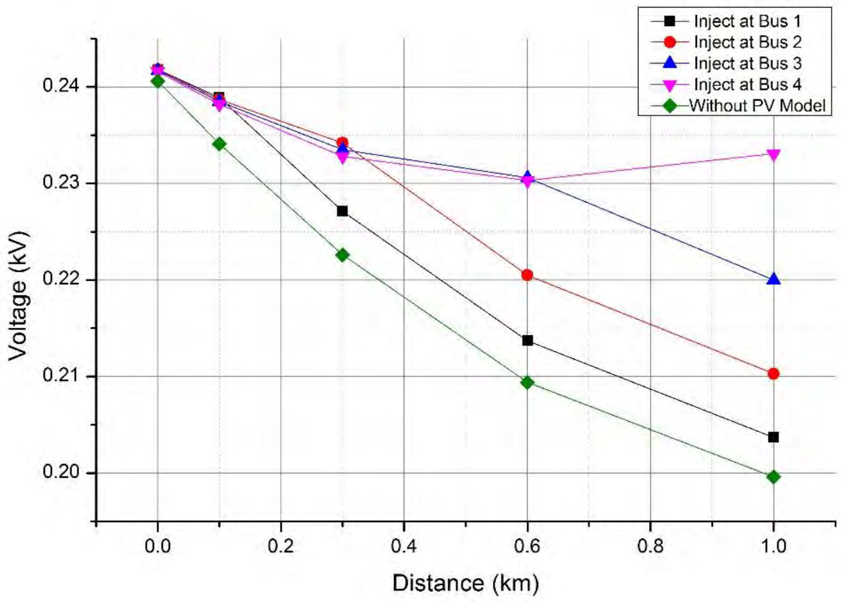

Figure 4-19: Voltage Profile for Different Point of Connection in Microgrid Model.

4.4.4 Discussion

All of cases in this case study basically shows the effect of voltage at load demand for excessive power from PV model. Range of voltage for equipment was supposedly within 0.23kV to 0.24kV with ±5% tolerance from its normal value in order to avoid the equipment from damage.

For Case 1, result shows that the percentage of load voltage increases as power generated by PV model increased. As the system is balanced, percentage of voltage increment at each phase are same. For light load demand, 10kW generated power at each phase from PV model able to give 0.2404kV output voltage which is 0.21% higher than 0.2399kV. 0.2399kV is a voltage at load when PV model is not connected with the system. The value of generated power at each phase from PV model was then increased to 20kW, 30kW, 40kW and 50kW. All of these generated power able to give 0.38%, 0.54%, 0.71% and 0.88% increment of voltage with RMS voltage produced equal to 0.2408kV, 0.2412kV, 02416kV and 0.2420kV. From the result, it can be conclude that 10kW until 50kW power generated from PV model at each phase can cause overvoltage for load as it is higher than 0.24kV. This means that PV model is capable to support load higher than 60kW with 0.85 lagging power factor. Figure 4-20 shows the phasor diagram for voltage increment using light load.

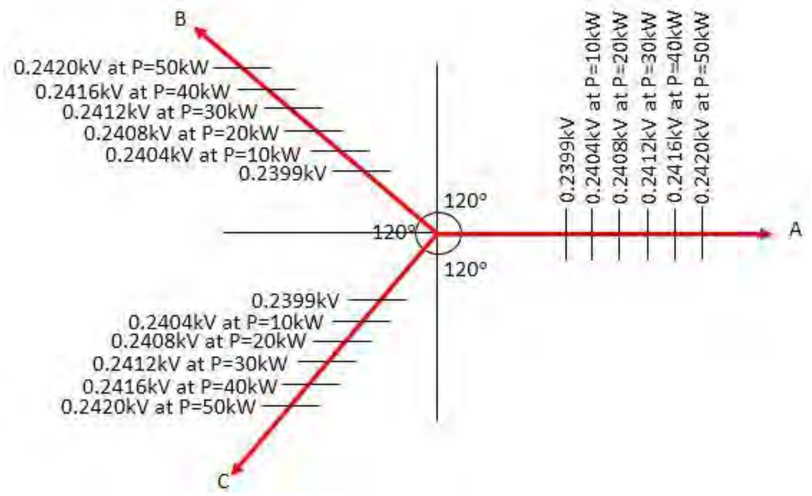

Figure 4-20: Phasor Diagram for Voltage Increment Using Light Load.

For Case 2, load was changed to heavy load which is 200kW with 0.85 lagging power factor. Percentage for increment of voltage equal to 0.17% when 10kW power was generated at each phase. The RMS voltage for this increment was from 0.2343kV to 0.2347kV. 0.2343kV is the voltage at load for each phase when PV model was disconnected from the system. The percentage of output voltages at load continue to increase as the generated power increased. 20kW, 30kW, 40kW and 50kW generated power at each phase able to produce 0.2351kV, 0.2355kV, 0.2359kV and 0.2363kV which give 0.34%, 0.51%, 0.68% and 0.86% increment of voltage. From these results, it can be conclude that amount of 10kW until 50kW power generated at each phase capable to support 200kW load with 0.85 lagging power factor. This is because the voltage across the load is within 0.23kV to 0.24kV. It seem that the PV model still capable to support load higher than 200kW. Figure 4-21 shows the phasor diagram for voltage increment using heavy load.

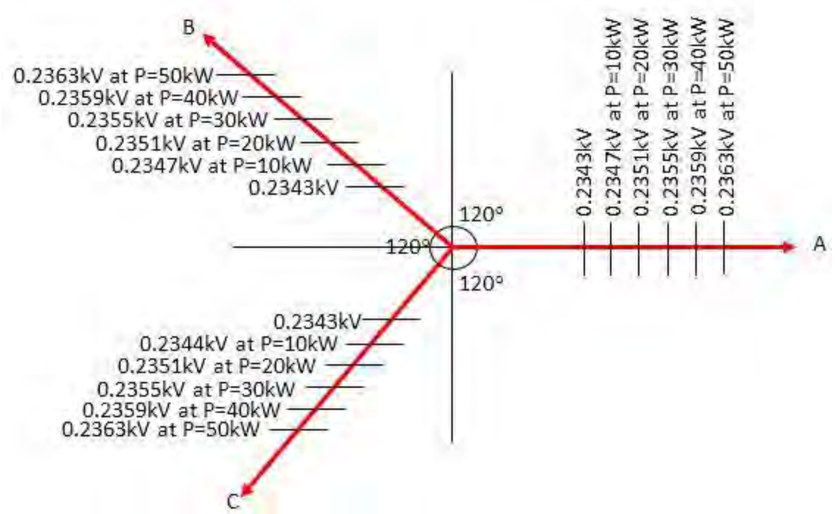

Figure 4-21: Phasor Diagram for Voltage Increment Using Heavy Load.

By comparing Case 1 and Case 2, it seem that the changed of load demand at each phase cause the occurrence of voltage drop. Percentage of voltage drop for 10kW, 20kW, 30kW, 40kW, and 50kW power generated by PV model at each phase is almost the same which is around 2.36% and 2.37%. This can be conclude that the increment of voltages was linear with different amount of power generated by PV model. Figure 4-22 shows the summary of comparison between Case 1 and Case 2.

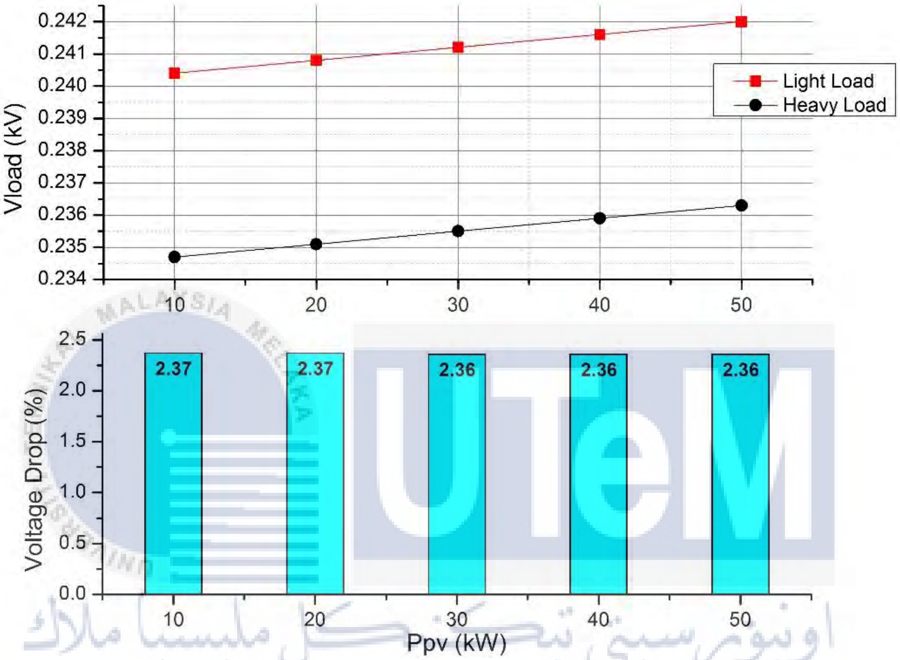

Figure 4-22: Summary of Comparison between Case 1 and Case 2.

For Case 3, grid network and PV model was connected to Microgrid. This case study was tested to observe the effect of length of cable towards voltage at point of connection. The optimum connection point of voltage profile will be determined based on the voltage received by the load which should be maintain near to 0.24kV. There are four buses in the Microgrid model which each of the bus consist different amount of load demand. The system is a balanced system. Output of power generated by PV model was connected at each point of bus to ensure the load demand able to have efficient electricity. The PV model was set to generate 90kW total active power which means each phase have approximately 30kW active power. From the results, as PV model was connected at bus 1 and bus 2, the voltage was continuously dropped below 0.23kV starting from 0.1km until 1.0km. There is a small improvement of voltage profile at distance 0.6km when PV model connected at bus 3. It seem that connection of PV model at bus 4 give the best voltage profile which is within

0.23kV and 0.24kV as the length of the cable achieved 1.0km. The voltage at each bus is 0.2382kV, 0.2328kV, 0.2303kV and 0.2331kV when PV model was connected near load at bus 4. The system is then tested without connection of PV model into the system. From the result, it shows that the voltage at bus 1, bus 2, bus 3 and bus 4 is 0.2341kV, 0.2226kV, 0.2094kV and 0.1996kV. There is no improvement of voltage profile as PV model not connected with the system. The voltage profile for each phase are same as it is a balanced system.

As conclusion, from Case 1 and Case 2, the generated power at each phase are directly proportional with load voltage. Besides that, it can be conclude that output voltage will drop as the load become heavier. From Case 3, it can be conclude that the further the distance of load from grid, the higher the losses which cause voltage drop. Voltage will be increase as the power generated from PV model at each phase increase. This shows that generated power should be controlled in order to avoid overvoltage or undervoltage problem. From this case, it also can be conclude that connection of PV model at bus 4 give the best voltage profile as the voltage is between 0.23kV and 0.24kV while point of connection at bus 1 give the worse voltage profile.

4.5 Case Studies for Abnormal Condition at PV Model

4.5.1 Case 1: Single Line to Ground (SLG) Fault at Modelled Circuit

Loads used in the system are balanced which is 60kW+j10kVar. With constant load value, the total active power generated by PV model varies from 30kW, 60kW, 90kW and to 120kW. The PV model only prioritized to supply active power to the system. Connection of modelled circuit is shown in Figure 4-23 below. Single line-to-ground fault occur at phase A of the output of inverter.

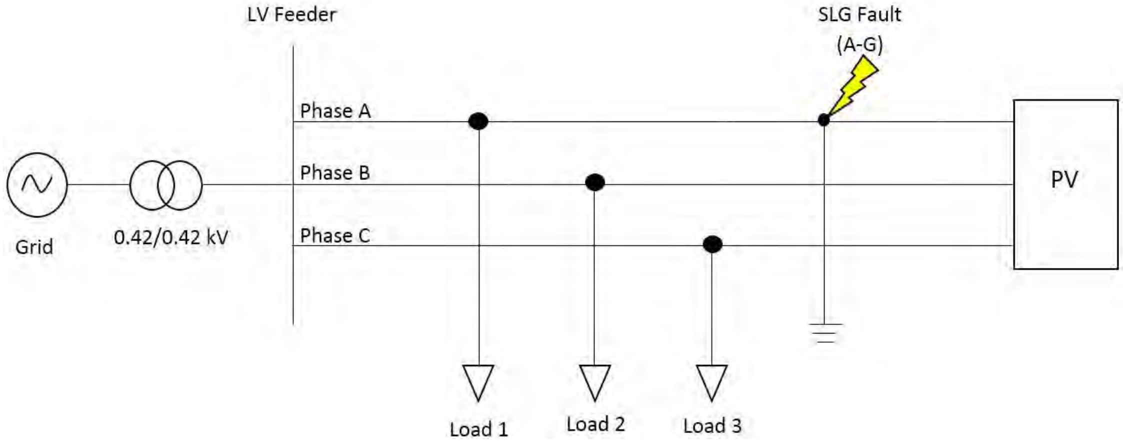

Figure 4-23: Connection of Circuit with Single Line to Ground Fault at Phase A.

Theoretically, single line-to-ground fault caused current at the faulted phase become higher than the other phases. As the fault occur, the current will be higher while voltage will drop. Figure 4-24 shows the output fault voltage and current waveform of single line-to-ground fault for 30kW generated power. From the figure, it can be seen that the voltage waveform for phase A will be drop when fault occur at 1.5 seconds and back to normal condition at 2.5 seconds. At the same period of fault, current for phase A increase while current for phase B and phase C remain the same. The system was continued to be tested with 60kW, 90kW and 120kW total active power generated by PV model. Same pattern of waveform obtained for different active power. The whole results will be discuss in discussion section for this case studies.

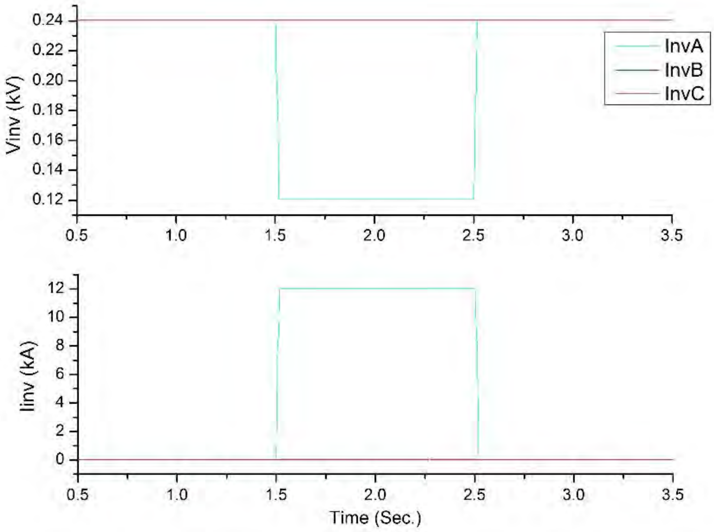

Figure 4-24: Output Fault Voltage and Current Waveform of Single Line-to-Ground Fault for 30kW Generated Power.

4.5.2 Case 2: Double Line to Ground (DLG) Fault at Modelled Circuit

Using the same amount of active power and load, the system tested with presence of double line to ground fault at Phase A and Phase B. The circuit connection of DLG fault was shown in Figure 4-25.

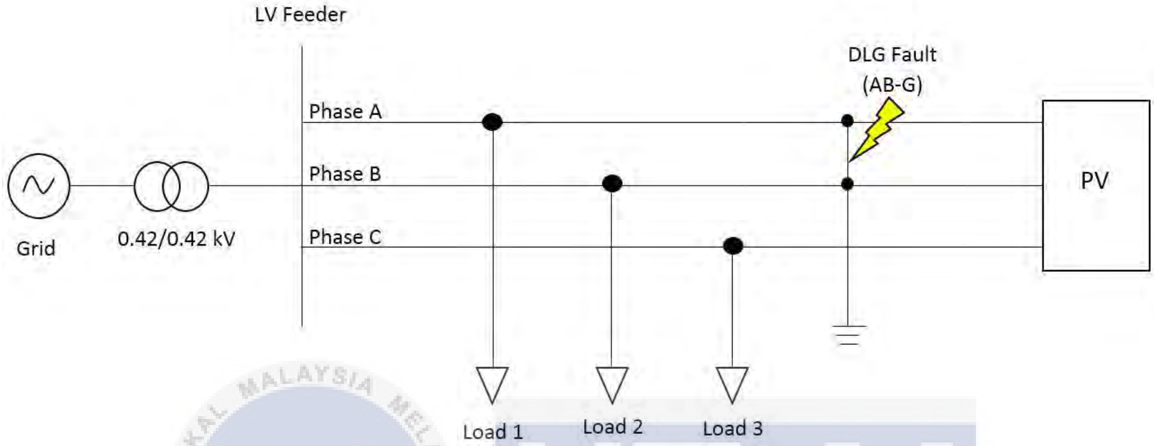

Figure 4-25: Circuit connection for Double Line to Ground Fault.

Theoretically, double line to ground fault cause current at the faulted phases higher than the other phase and voltage will drop. The output fault voltage and current waveform of double line-to-ground fault for 30kW generated power was shown in Figure 4-26. From the figure, it can be seen that both voltage at Phase A and Phase B dropped while the current increase at 1.5 seconds until 2.5 seconds. The other result was shown in discussion section for this case studies.

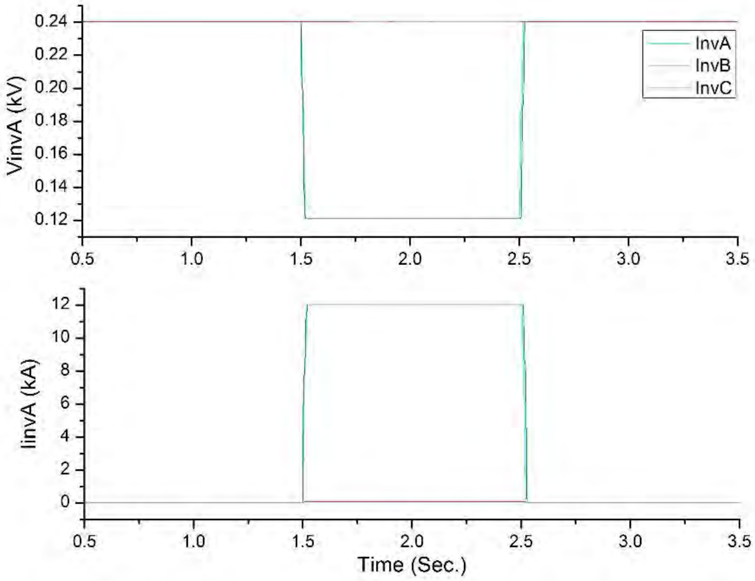

Figure 4-26: Output Fault Voltage and Current Waveform of Double Line-to-Ground Fault for 30kW Generated Power.

4.5.3 Case 3: Three-Phase Fault at Modelled Circuit

Three-phase fault known as balanced fault occur when three phases connected to ground. 60kW+j10kVar load connected to the system and various value of active power was supplied to the inverter. Figure 4-27 shows the circuit connection for three-phase fault for the system.

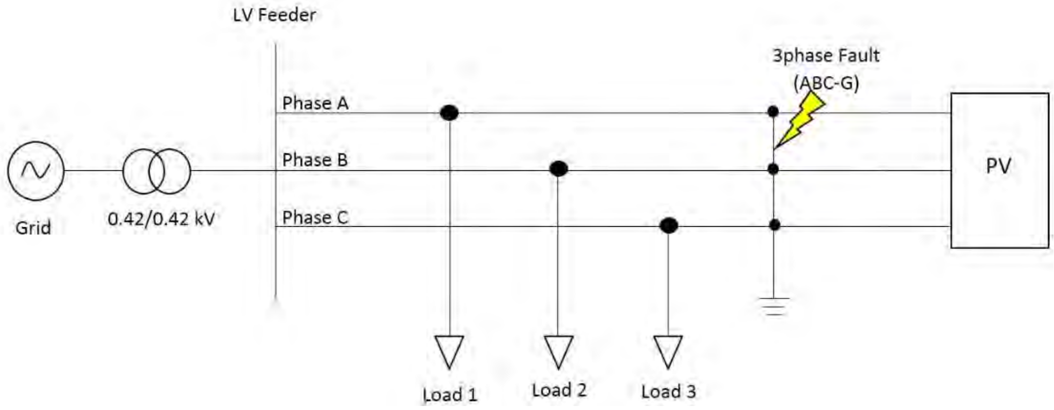

Figure 4-27: Circuit Connection for Three-Phase Fault.

Balanced three-phase fault will give same output for all three phases of the system. The concept of the fault is same with the other types of fault. Voltage will be drop while current will increase during fault at 1.5 seconds until 2.5 seconds. Fault voltages almost zero as the phases are connected to ground. Different amount of active power give same pattern of fault waveform. Figure 4-28 shows the output waveform for three-phase fault occur in the system for 30kW generated power.

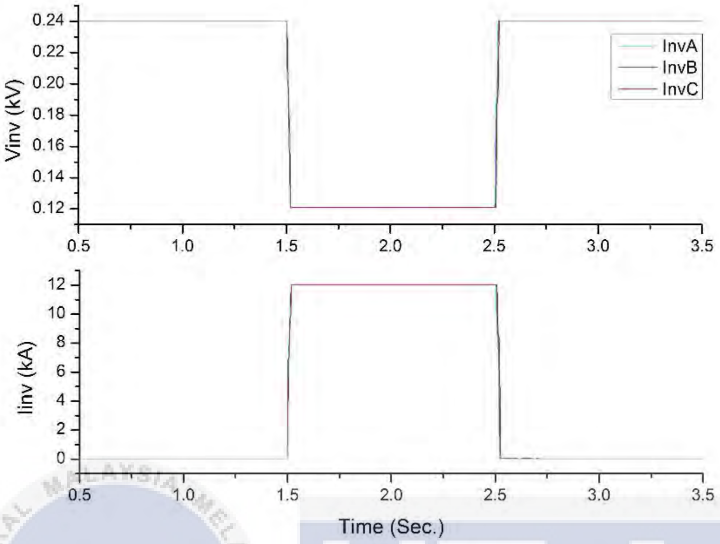

Figure 4-28: Output Fault Voltage and Current Waveform of Three-Phase Fault for 30kW Generated Power.

4.5.4 Discussion

Single line to ground fault occur when only one phase of the system was grounded. In this case studies, fault occur at Phase A. As fault occur at 1.5 seconds until 2.5 seconds, voltage for Phase A dropped and current will increase. Fault current at Phase A become the highest among the three phases as shown in Figure 4-29. As the active power increase, voltage and current at each phase also increase. From the figure, 120kW active power will give higher fault voltage and current which is 0.1217kV and 12.0306kA. Value of voltage and current at Phase B and Phase C remain the same even during fault as shown in figure below. Supposedly, voltage for Phase A will become nearly zero during fault. But for this case, voltage only drop half of the normal value due to the connection of grid with the system. From the result, current at Phase B and Phase C is very small which is nearly zero.

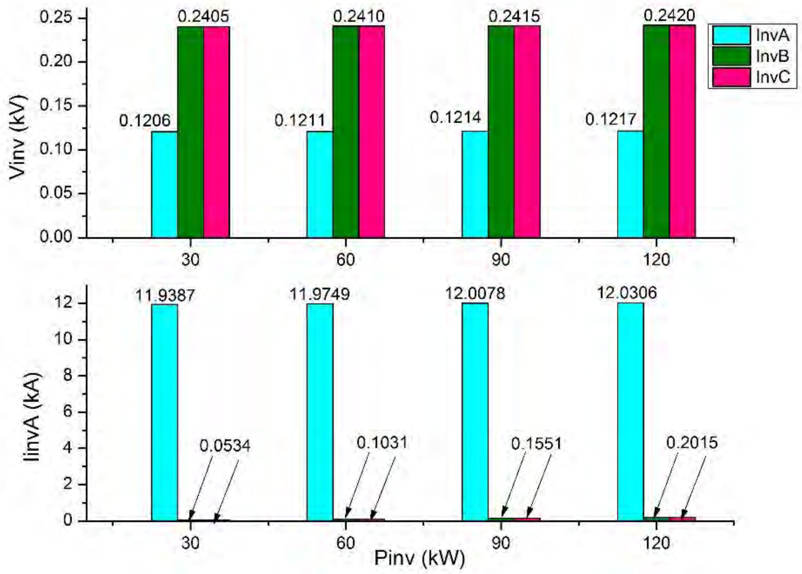

Figure 4-29: Single line-to-ground Fault at Phase A.

Double line to ground fault only involve Phase A and Phase B of the system connected to ground. Figure 4-30 shows the output fault voltage and current for double line to ground fault. Since Phase A and Phase B are grounded, fault current for both phases will be higher than Phase C. The voltage for both faulted phases will become zero and current for free fault phase will become zero. As system was connected with grid, voltage only decrease half of its normal value. Basically, voltage and current will be increase as power increase. From the result, fault current with 120kW active power supplied to inverter for Phase A and Phase B is 12.0358kA. It is highest fault current produced by the system. As the voltage at Phase C is 0.2423, the current is remains the same which is 0.2384kA.

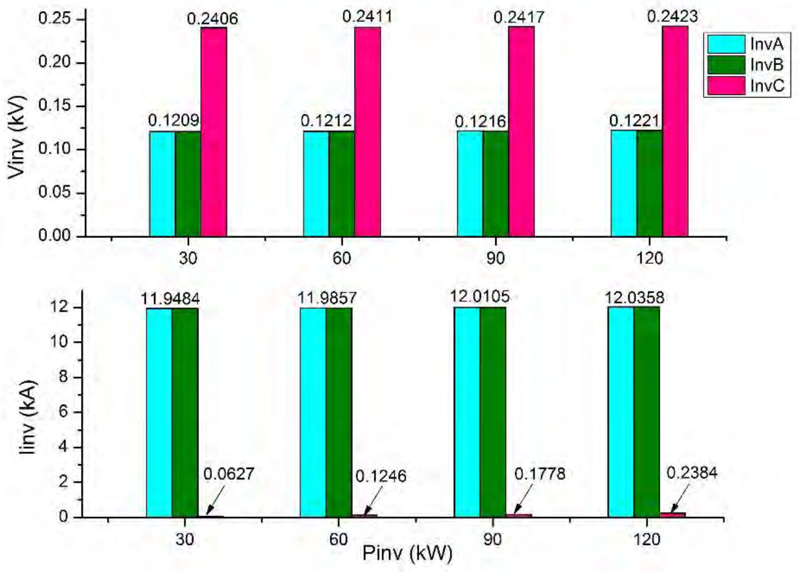

Figure 4-30: Double Line to Ground Fault at Phase A and Phase B.

Basically, balance three-phase fault will produce same amount of fault voltage and current for all phases. The system was tested using different amount of active power supplied to inverter which is 30kW, 60kW, 90kW and 120kW. Figure 4-31 shows the output of fault voltage and current for three-phase fault. During fault, voltage of the system will drop to zero but since the system was connected with grid, fault voltages are half of the original voltages as shown in the figure below. From the result, it shows that the amount of voltage and current produced was increased as the power increased. Fault voltage for 30kW supplied power is lower than fault voltage produced by 120kW supplied power. With 0.1257kV produced, the fault current for 30kW supplied power is 12.0739kA. The more power applied, the more voltage and current produced.

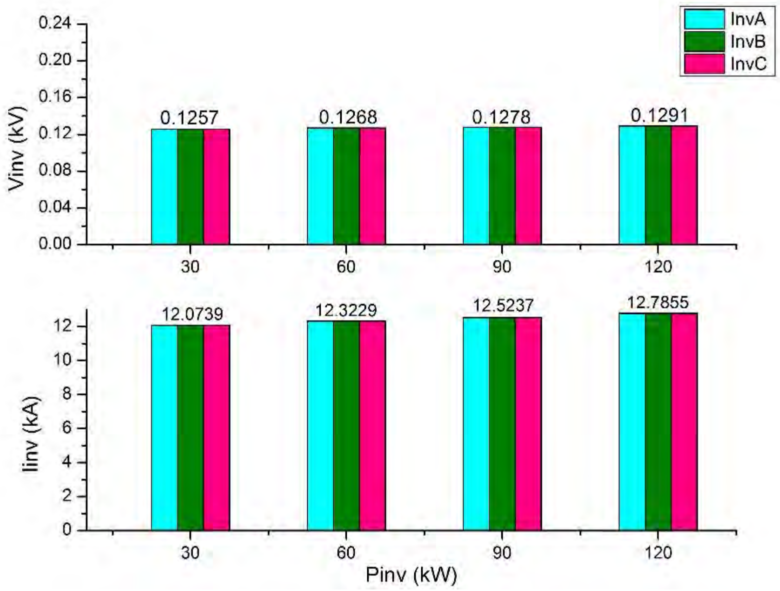

Figure 4-31: Output of fault Voltage and Current for Three Phase Fault.

As conclusion, different types of fault will produced different value of voltage and current at each phase. Figure 4-32 shows the summary for different types of fault with 120kW power supplied to inverter. From the figure, it can be seen that single line to ground fault will produce 0.1217kV and 12.0306kA fault voltage and current. Double line to ground fault produce 0.1221kV and 12.0358kA fault voltage and current, and three phase fault produce 0.1291kV and 12.7855kA fault voltage and current. It can be conclude that three-phase fault will produce the highest fault current while single line to ground fault will produce the lowest fault current. When fault occur, very low impedance path was created which cause the current flow extremely high. Abnormal flow of current can lead to power surge that damage equipment or possibly charge the devices and cause shock which can lead to death. Basically, there are several protection device that could be used to reduce the effects of fault in the system. Relays, fuses, circuit breaker and lighting arrestor and grounding can be used in limiting the effect of fault.

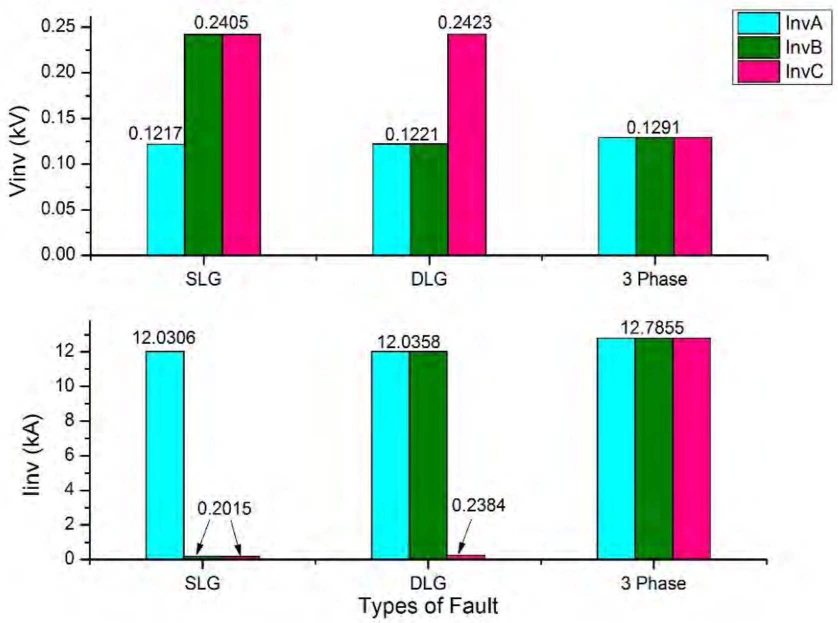

Figure 4-32: Summary for Different Types of Fault with 120kW Power Supplied to Inverter.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

As conclusion, three-phase grid-connected photovoltaic system can be used in order to help grid network in supplying sufficient power for load demand. PV system usually connected near with load demand to reduce losses in the transmission system. Besides that, PV generation system take construction period shorter than traditional power plant. However, the use of PV generation system could give pros and cons towards users. From the case studies, it can be conclude that voltage across load was affected by the amount of power generated from PV model and capacity of load itself. Besides helping grid in supporting load, PV model also have a capability to export its generated power to grid and load. This means that load demand can be fully satisfied by power generated from PV model. As PV model was used without connection with grid, overvoltage and undervoltage issue can exist. This is due to generated power from PV model exceed of less than load demand. PV model must able to generated power equal with load demand to prevent these problems. Overvoltage and undervoltage problem can cause damage to equipment as it receive more or less than 5% of its nominal value. Efficient PV generation system should be able to generate sufficient power to support load demand. In Microgrid system, voltage will collapse at load that are connected further than utility grid. PV generation system can be used to prevent this problem. Optimum point of connection which could give the best voltage profile can be determined by connecting each of the load with PV model. From here, it can be conclude that by connecting the PV model to the furthest load from utility grid can improves its voltage profile. This can make the system more efficient. Since three-phase grid-connected photovoltaic system is a balanced system, load at each phase during each of case studies are same. There is no exception from fault in a system but it can be prevented using protection device such as fuses and protection relays. Fault can be occur in different types which are single line-to-ground (SLG), double line-to-ground (DLG) and three-phase fault. From the case study, it can be conclude that different types of fault give different amount of fault current. Three-phase fault will provide the highest fault current in the system. Amount of generated power from PV model also can affect the amount of fault current in a system. The modelled PV system using PSCAD software could give satisfying result for case studies conducted for this project. However, application of three-phase grid-connected photovoltaic system using real components are not able to be conducted including applying voltage control technique and protection system into the three-phase grid-connected PV system.

As recommendation, real PV model could be used in order to see the capability of the system in real life. Protection system also could be applied in the system to prevent cons that exist as mentioned in the following case studies. For future research, design of photovoltaic generation system should be more advance which could be used as superb distributed generation (DG) system in Malaysia.

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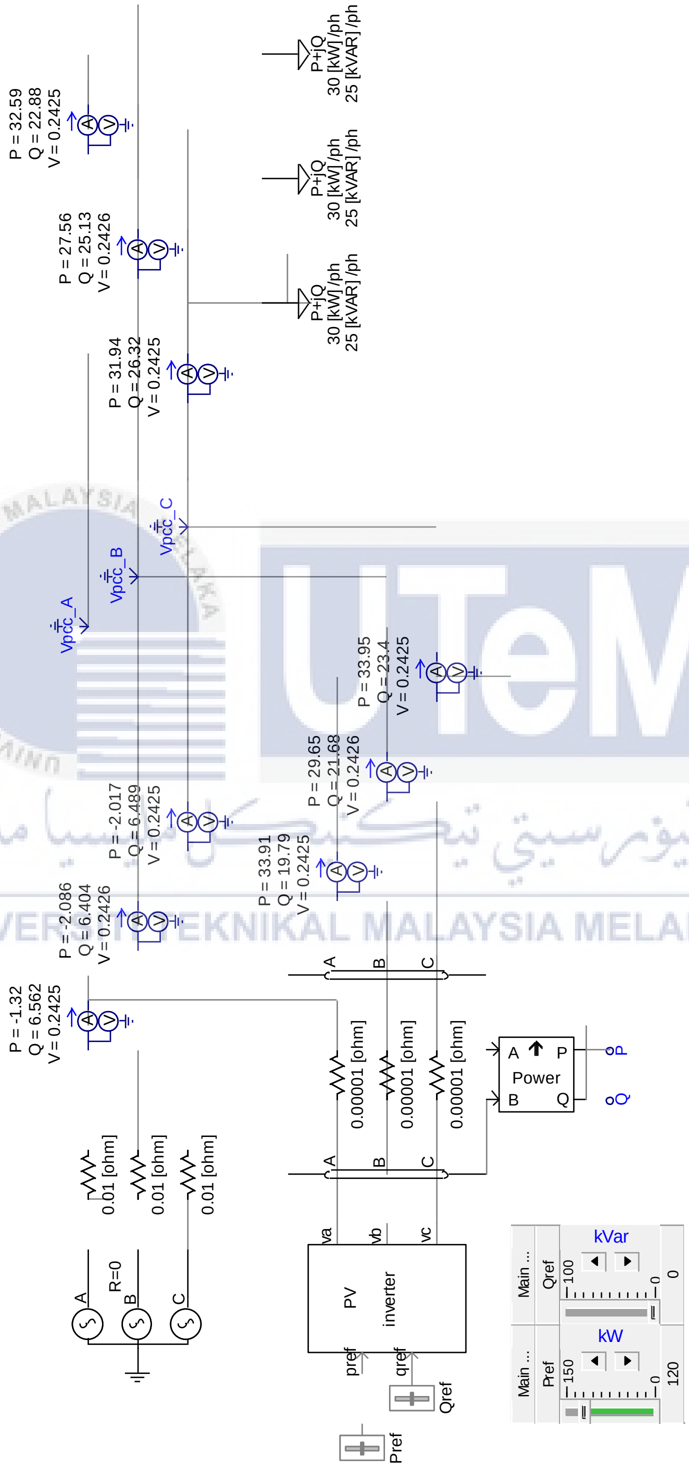
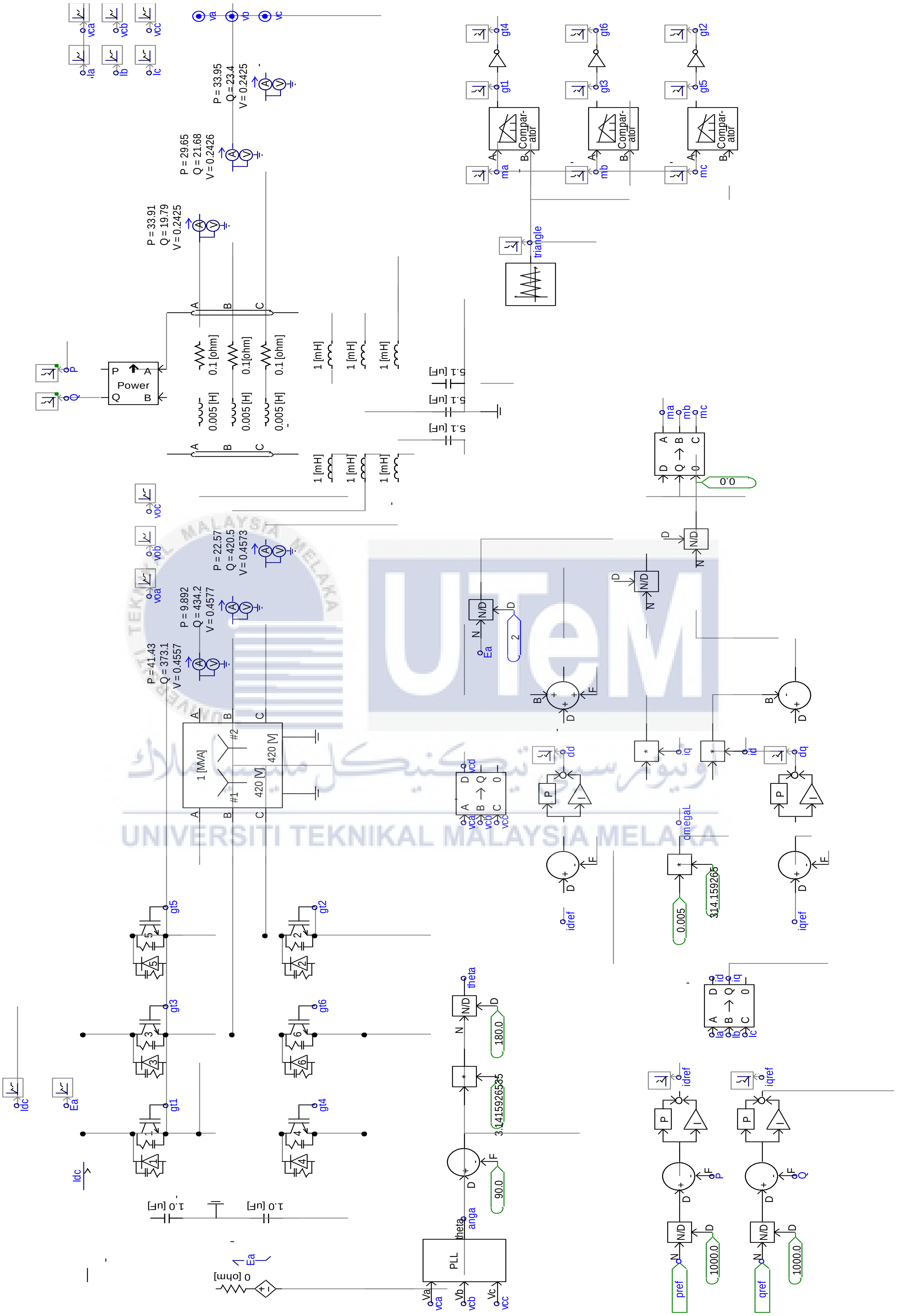
APPENDIX A

Proposed Three-Phase Grid-Connected Photovoltaic System

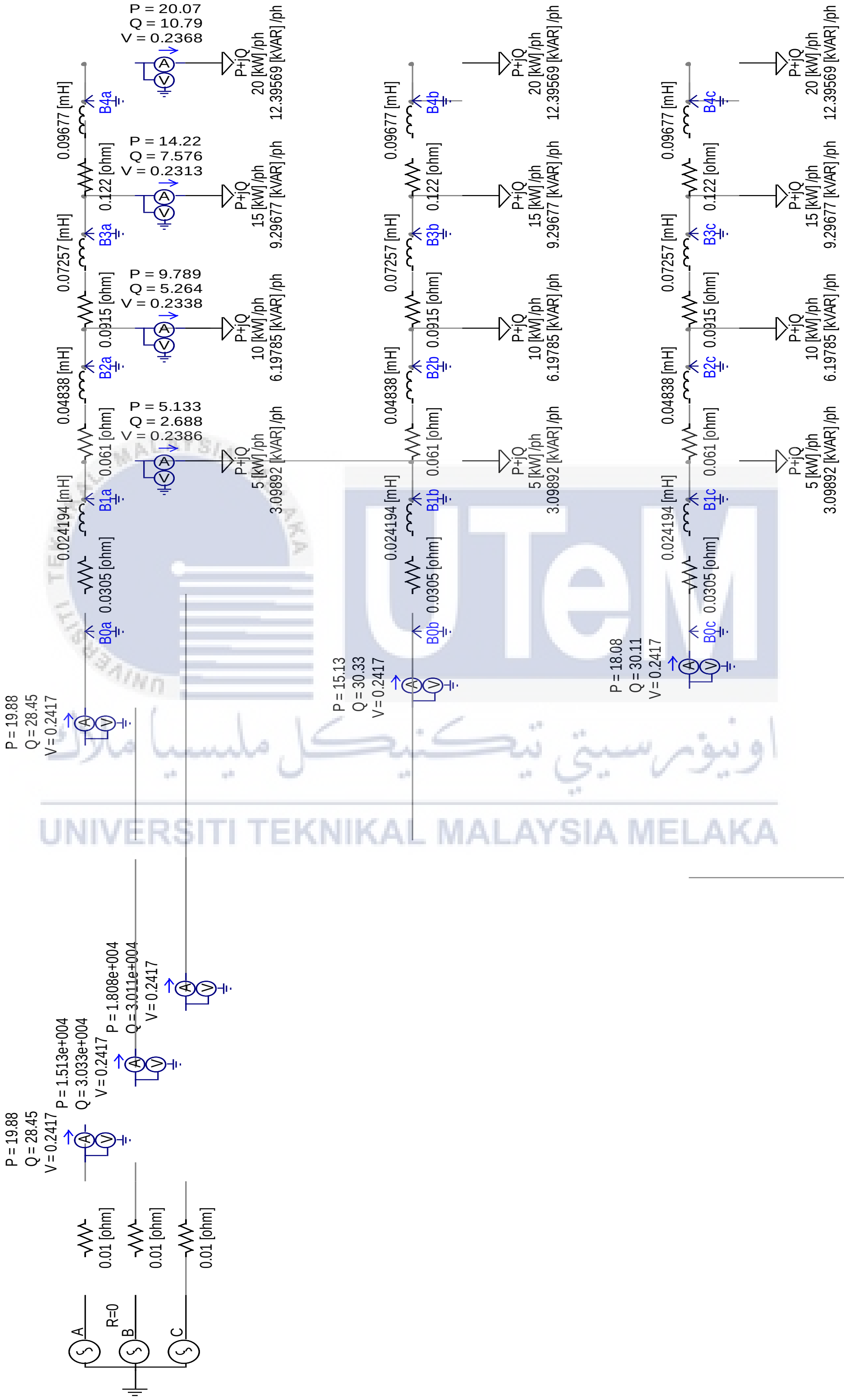




Ia
Ib
Ic
vca
vcb
vcc
va
vb
vc
P = 33.95
Q = 23.4
V = 0.2425
P = 29.65
Q = 21.68
V = 0.2426
P = 33.91
Q = 19.79
V = 0.2425
gt4
gt6
gt2
gt1
gt3
gt5
Compar-ator
ma
mb
mc
triangle
Power
P
Q
0.1 [ohm]
0.005 [H]
1 [mH]
5.1 [uF]
0.0
voc
vob
voa
N/D
Ea
2
P = 22.57
Q = 420.5
V = 0.4573
P = 9.892
Q = 434.2
V = 0.4577
P = 41.43
Q = 373.1
V = 0.4557
1 [MVA]
420 [V]
#1
#2
vcd
dd
iq
id
dq
omegaL
0.005
314.159265
idref
iqref
theta
180.0
3.14159265
90.0
anga
PLL
Va
Vb
Vc
Idc
1.0 [uF]
0 [ohm]
idref
iqref
pref
qref
1000.0

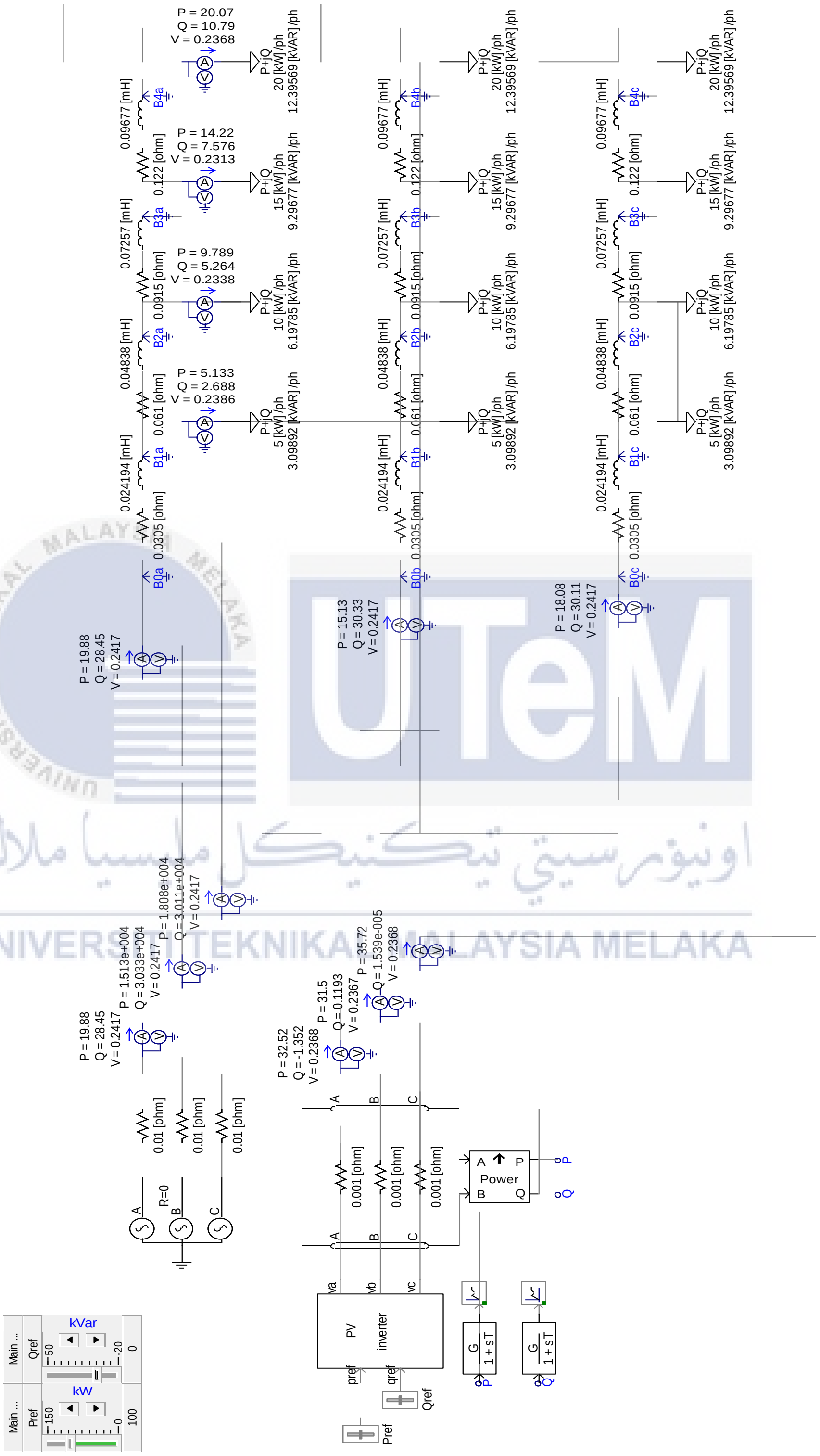
APPENDIX B

Microgrid Network Model



APPENDIX C

Proposed Three-Phase PV Model Connected with Microgrid Network



APPENDIX D

Calculation for Line Impedance in Microgrid Network Model

Value of line impedance in Microgrid network can be designed using datasheet of PVC Insulated Distribution Cable (BS6346:1989) 600/1000V as shown in APPENDIX E. Length of cable used to represent distance between bus and each bus in Microgrid model will be used in the calculation of line impedance. From the datasheet, multi-core aluminium cable with conductor size of $120\mathrm{mm}^2$, with AC resistance of $R = 0.305\ \Omega/km$ at 70℃, and reactance of $X = 0.076\ \Omega/km$ at 50 Hz was chosen.

$$\mathrm{Z_{line\ (length)}} = \frac{\mathrm{(R + jX)\Omega}}{\mathrm{km}} \times \mathrm{length\ in\ km}$$

$$Z_{line\ (0.1km)} = \frac{(0.305 + j0.076)\Omega}{km} \times 0.1km = 0.0305 + j0.0076\Omega$$

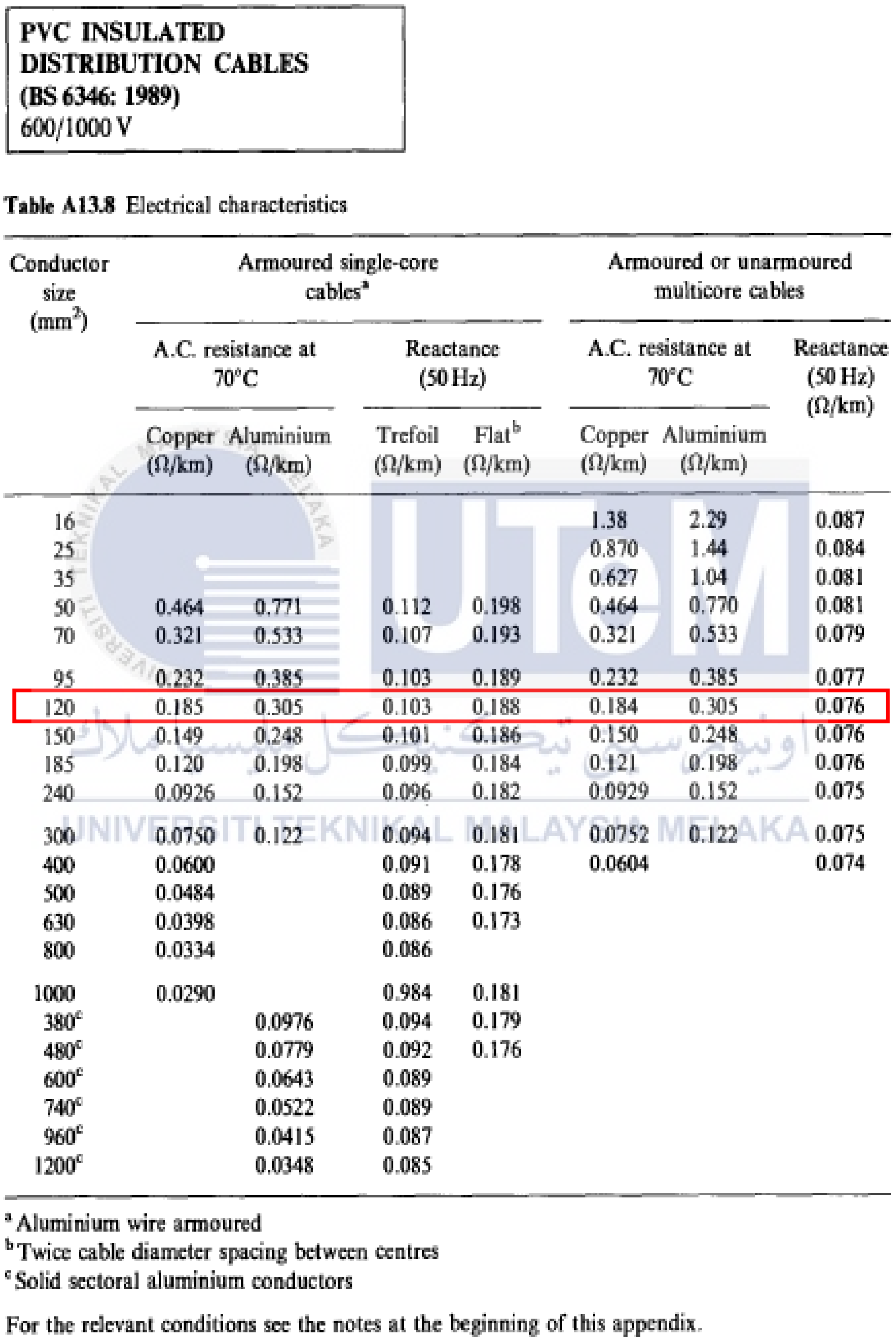
$$Z_{line\ (0.2km)} = \frac{(0.305 + j0.076)\Omega}{km} \times 0.2km = 0.061 + j0.0152\Omega$$

$$Z_{line\ (0.3km)} = \frac{(0.305 + j0.076)\Omega}{km} \times 0.3km = 0.0915 + j0.0228\Omega$$

$$Z_{line\ (0.4km)} = \frac{(0.305 + j0.076)\Omega}{km} \times 0.4km = 0.122 + j0.0304\Omega$$

APPENDIX E

Datasheet of PVC Insulated Distribution Cable (BS6346:1989) 600/1000V



PVC INSULATED
DISTRIBUTION CABLES
(BS 6346: 1989)
600/1000 V

Table A13.8 Electrical characteristics

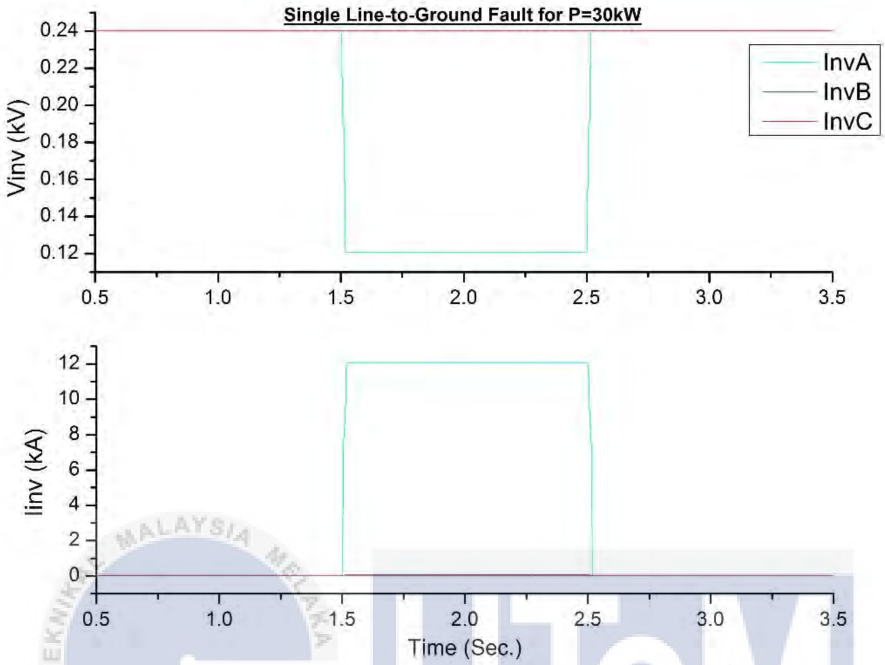
Conductor size (mm^2)	Armoured single-core cables[a]				Armoured or unarmoured multicore cables		
	A.C. resistance at 70°C		Reactance (50 Hz)		A.C. resistance at 70°C		Reactance (50 Hz) (Ω/km)
	Copper (Ω/km)	Aluminium (Ω/km)	Trefoil (Ω/km)	Flat[b] (Ω/km)	Copper (Ω/km)	Aluminium (Ω/km)	
16					1.38	2.29	0.087
25					0.870	1.44	0.084
35					0.627	1.04	0.081
50	0.464	0.771	0.112	0.198	0.464	0.770	0.081
70	0.321	0.533	0.107	0.193	0.321	0.533	0.079
95	0.232	0.385	0.103	0.189	0.232	0.385	0.077
120	0.185	0.305	0.103	0.188	0.184	0.305	0.076
150	0.149	0.248	0.101	0.186	0.150	0.248	0.076
185	0.120	0.198	0.099	0.184	0.121	0.198	0.076
240	0.0926	0.152	0.096	0.182	0.0929	0.152	0.075
300	0.0750	0.122	0.094	0.181	0.0752	0.122	0.075
400	0.0600		0.091	0.178	0.0604		0.074
500	0.0484		0.089	0.176			
630	0.0398		0.086	0.173			
800	0.0334		0.086				
1000	0.0290		0.984	0.181			
380[c]		0.0976	0.094	0.179			
480[c]		0.0779	0.092	0.176			
600[c]		0.0643	0.089				
740[c]		0.0522	0.089				
960[c]		0.0415	0.087				
1200[c]		0.0348	0.085				

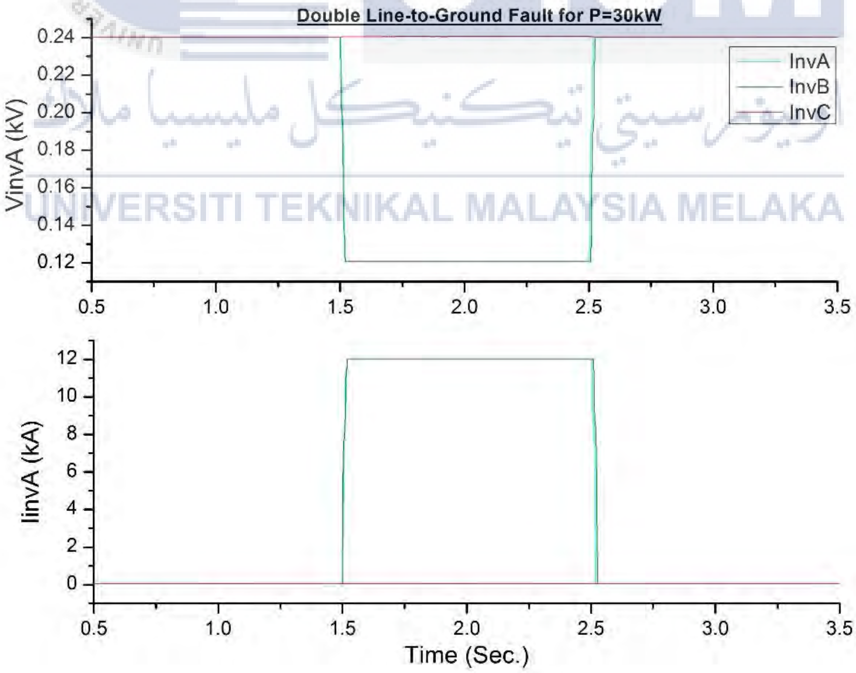
[a] Aluminium wire armoured
[b] Twice cable diameter spacing between centres
[c] Solid sectoral aluminium conductors

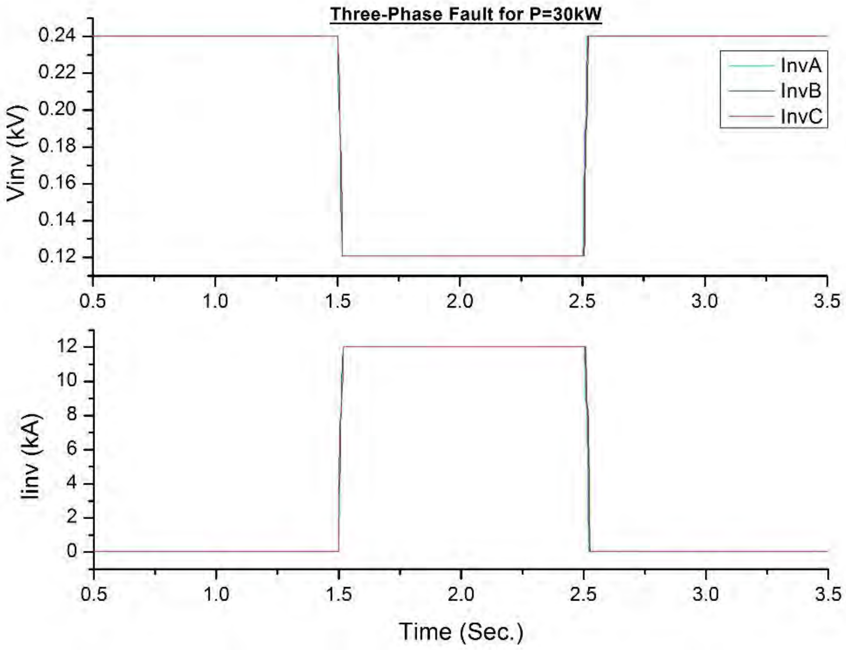
For the relevant conditions see the notes at the beginning of this appendix.

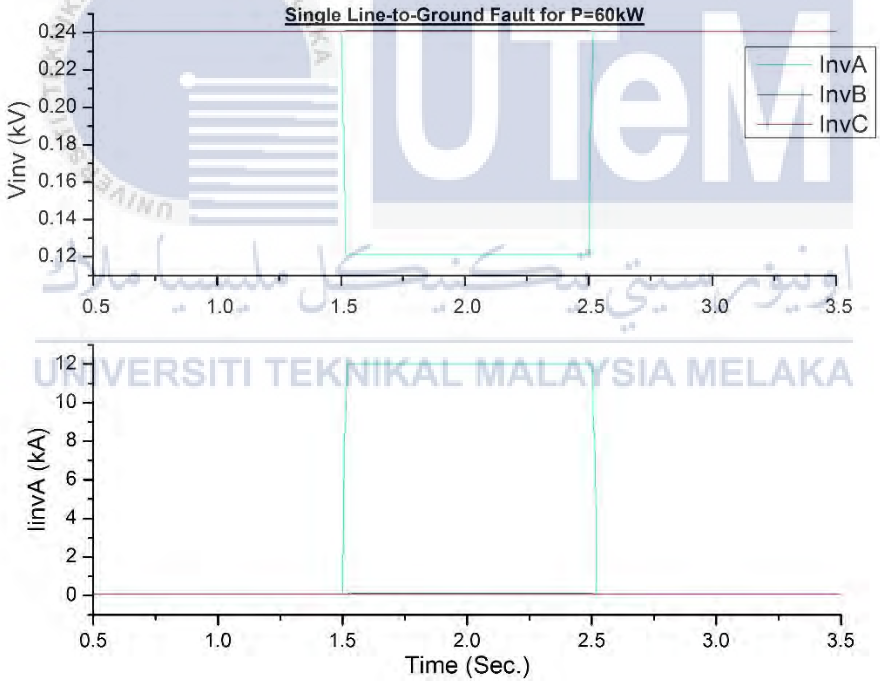
APPENDIX F

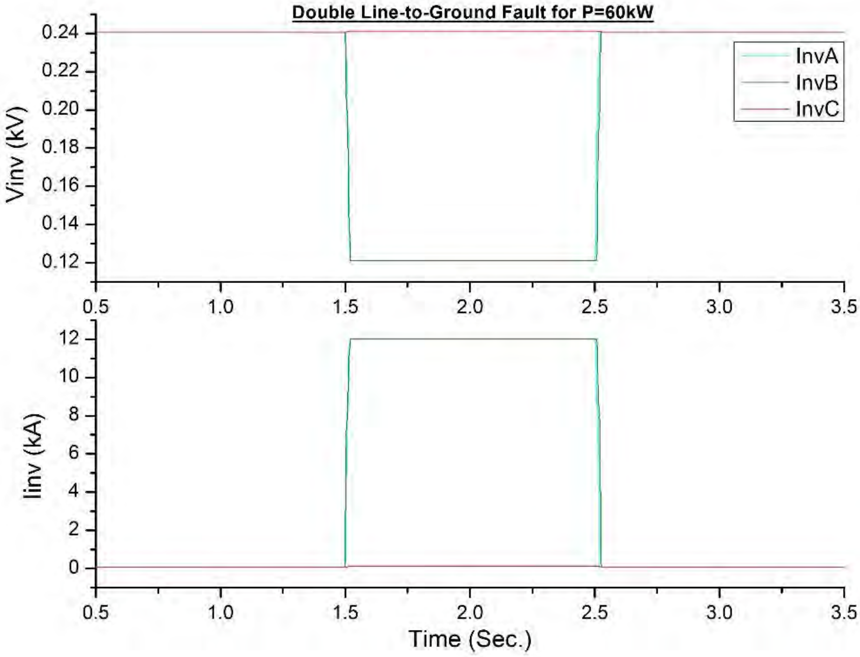
Output Waveforms for Case Studies of Abnormal Condition

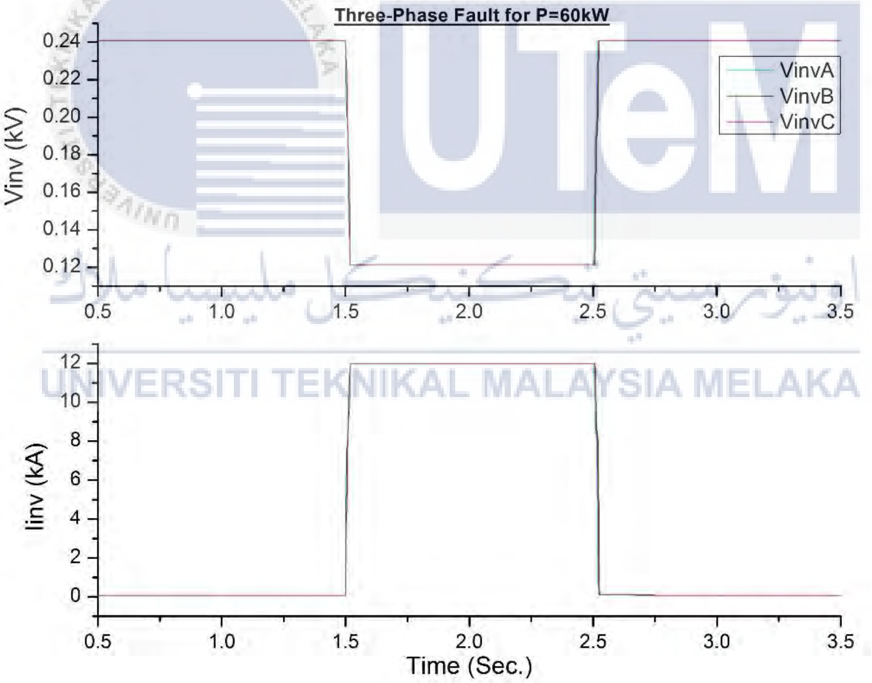


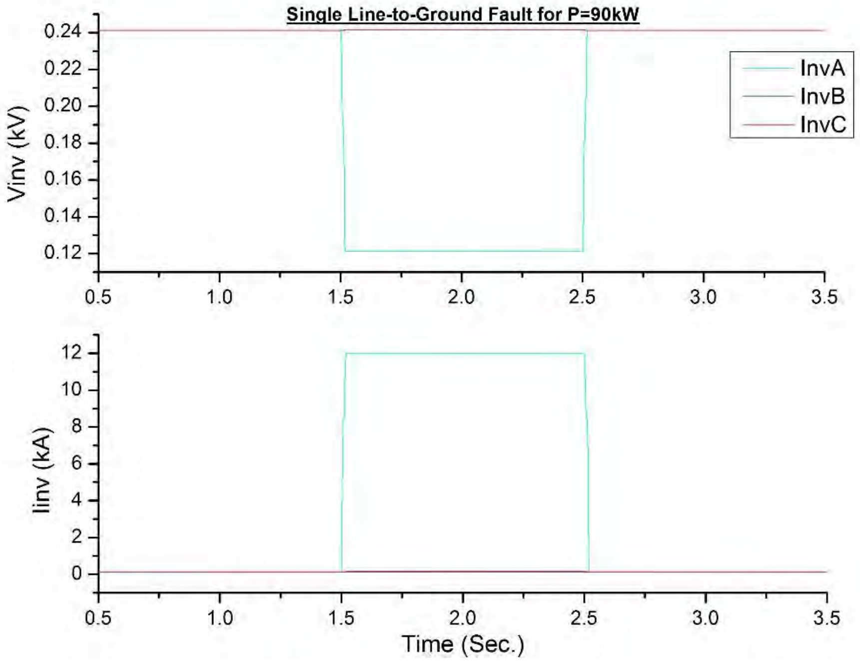


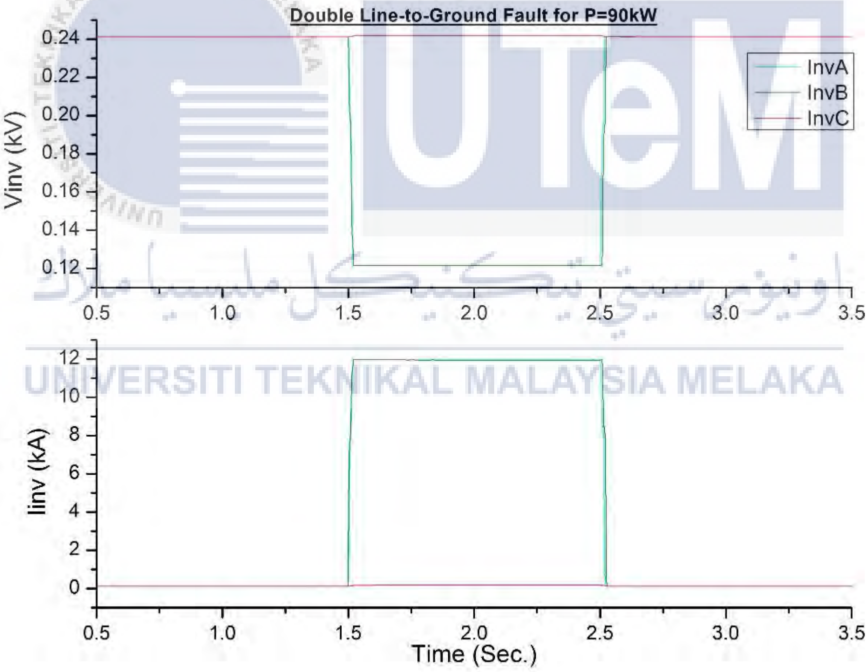

Three-Phase Fault for P=30kW
Vinv (kV)
0.24
0.22
0.20
0.18
0.16
0.14
0.12
InvA
InvB
InvC
0.5
1.0
1.5
2.0
2.5
3.0
3.5
Iinv (kA)
12
10
8
6
4
2
0
Time (Sec.)

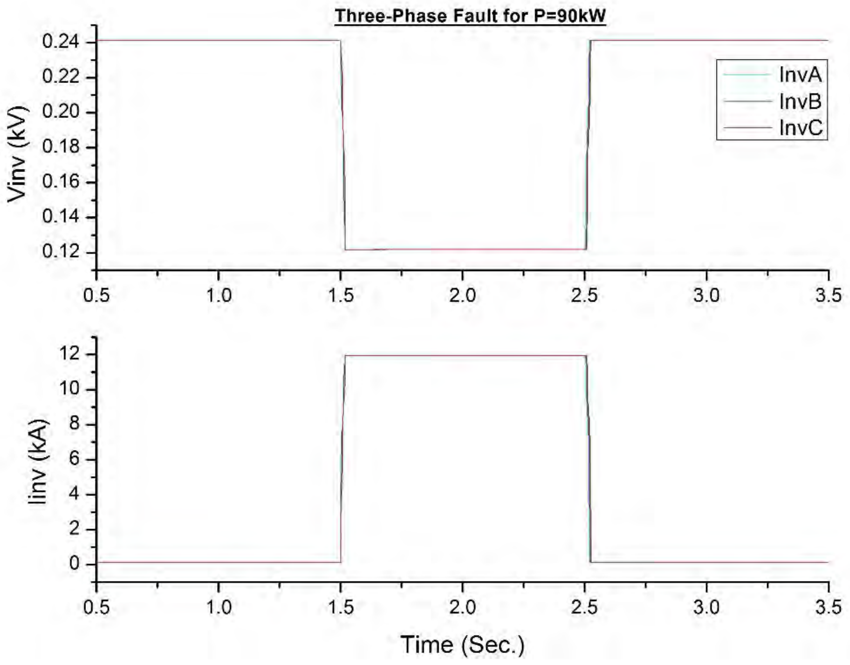

Single Line-to-Ground Fault for P=60kW
Vinv (kV)
0.24
0.22
0.20
0.18
0.16
0.14
0.12
InvA
InvB
InvC
0.5
1.0
1.5
2.0
2.5
3.0
3.5
IinvA (kA)
12
10
8
6
4
2
0
Time (Sec.)

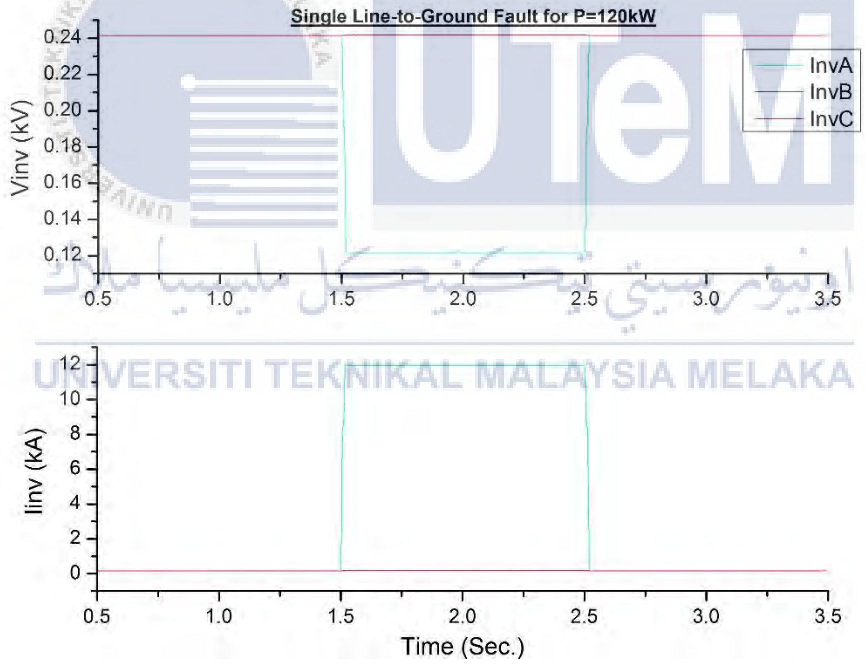

Double Line-to-Ground Fault for P=60kW
Vinv (kV)
0.24
0.22
0.20
0.18
0.16
0.14
0.12
InvA
InvB
InvC
Iinv (kA)
12
10
8
6
4
2
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
Time (Sec.)

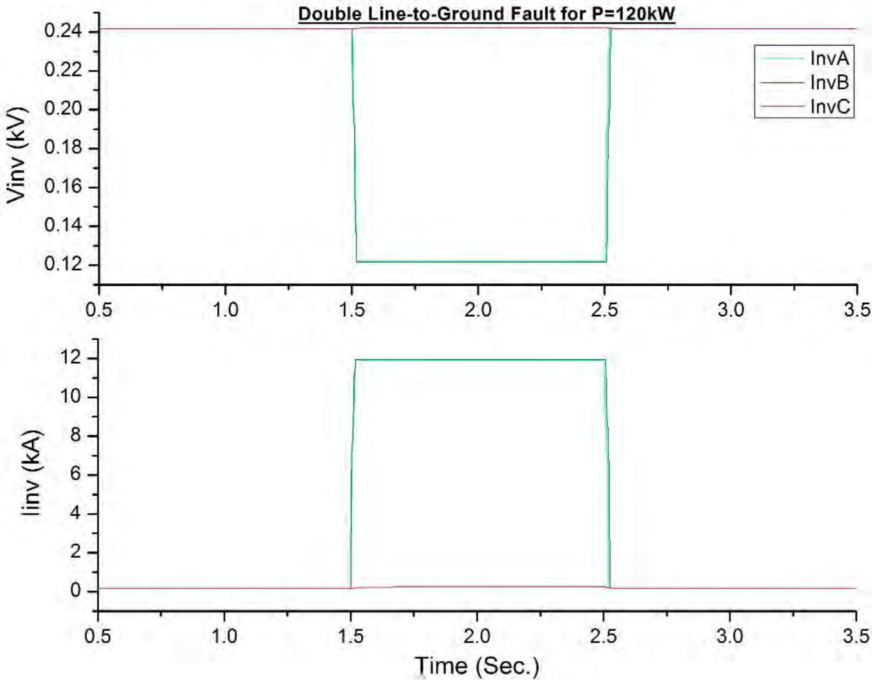

Three-Phase Fault for P=60kW
Vinv (kV)
0.24
0.22
0.20
0.18
0.16
0.14
0.12
VinvA
VinvB
VinvC
Iinv (kA)
12
10
8
6
4
2
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
Time (Sec.)

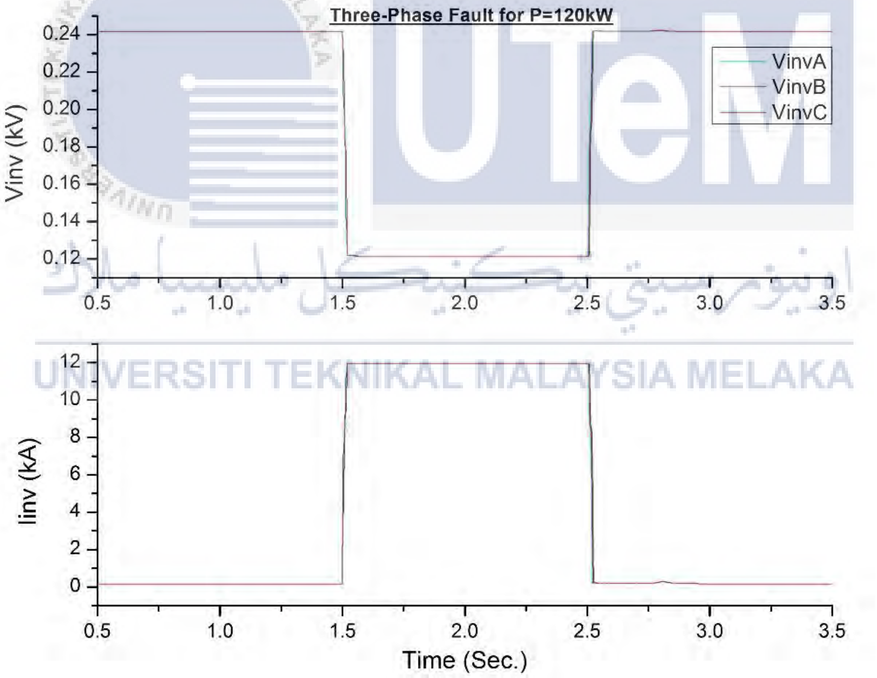

Single Line-to-Ground Fault for P=90kW


Double Line-to-Ground Fault for P=90kW


Three-Phase Fault for P=90kW


Single Line-to-Ground Fault for P=120kW


Double Line-to-Ground Fault for P=120kW


Three-Phase Fault for P=120kW