Study on the Impact of a Three-Phase Grid-Connected Photovoltaic at Low Voltage Network by using PSCAD Software

Nurul Nadia Aminuddin[1], Mohd Hendra Hairi[1*], Muhammad Nizam Kamarudin[1], Mohd Khairi Mohd Zambri[1], Ahmad Sadhiqin Mohd Isira[2], Muhammad Herman Jamaluddin[1]
Center for Robotics and Industrial Automation (CeRIA),
[1]Fakulti Kejuruteraan Elektrik,
[2]Fakulti Kejuruteraan Elektronik & Kejuruteraan Komputer,
Universiti Teknikal Malaysia Melaka,
Hang Tuah Jaya, 76100 Durian Tunggal, Melaka, Malaysia
[*]corresponding authors: hendra@utem.edu.my

Abstract – *Solar photovoltaic generation system is a type of distributed generation (DG) that can generate electricity to support load demand. Since the output of the PV generation needs to be connected with grid network, a few issues could occur. The issues that may occur are synchronization, overvoltage, undervoltage, and stability. The aim for this project is to analyse 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 performance of three-phase grid-connected photovoltaic system was analysed 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 and effect of generated power from PV model toward voltage at distribution network including microgrid.*

Keywords: *distributed generation, excessive power, import and export, three-phase grid-connected PV system, voltage profile*

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I. Introduction

Electrical power network is a system that consists of several electrical components that are able to produce electrical power. There are four 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 stepped up and transmitted to distribution network. At distribution side, the voltage will be stepped down before it is being distributed 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 is 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 is one of the alternatives to produce electricity as it is convenient to avoid transmission and distribution losses. DG also requires lower infrastructure cost as it is in small size. Besides that, DG technologies can produce near-zero or zero pollution [2].

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 initial cost as it is long lasting renewable energy technology [3].

Three-phase inverter was required to convert the DC electricity produced onto AC form before it is connected 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 is also suitable to scale in current handling capability at higher voltage levels [4]. Each phase from solar PV system is rated at

240V and 50Hz which will be connected to the three-phase grid network.

II. Background Theory

Power flow from generation side to grid network can be represented by using the connection of synchronize generator to infinite bus as shown in Fig. 1. 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 [5].

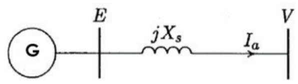

Fig 1: Connection of synchronize generator to infinite bus

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 is higher than the infinite bus, reactive power will flow to the infinite bus. Fig. 2 shows the phasor diagram of synchronous generator [6-8].

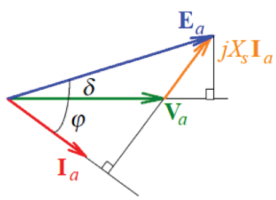

Fig. 2: Phasor diagrams of synchronous generator

As synchronous generator delivers real and reactive power to the system, the amount of three-phase active and reactive power can be expressed in (1) and (2) [5].

$$P_{3\phi} = 3\frac{|E||V|}{X_s}\sin\delta \quad (1)$$

$$Q_{3\phi} = 3\frac{|E||V|\cos\delta - |V|^2}{X_s} \quad (2)$$

III. Design and Modelling

A. Photovoltaic Model

DC voltage source was used to replace PV array in the system. The voltage set for the DC source is 1000V which is 1.7 times higher than (3).

$$V_{dc} > \sqrt{2}\,.\sqrt{3}\,.V_{rms} \quad (3)$$

Three-phase inverter was used in the model with IGBT as power switches. IGBT was chosen as it suitable for application that require high switching frequency. In order to produce PWM output, frequency for carrier signal block was set to 3.3 kHz and 50 Hz was set for modulating signal. Output from inverter will be transform into angle form by using PLL and the angle will be used in ABC to DQ converter.

Proportional Integral (PI) controller was used in power controller and current controller circuit. PI controller was used to adjust the settling time of the system and produce zero steady-state error in current control loop. ABC to DQ converter was used to convert filtered current and voltage for power and current controller while DQ to ABC converter used to transform the output from current controller. The transformation was called as Park transformation. LCL filter used in the modelled circuit was set to have 100Hz resonance frequency and 1mH for both inductors. Value of capacitor used in the filter is 5.1µ. Fig. 17 shows the designed three-phase PV model.

B. Microgrid Network Model

Microgrid network was modelled to test the performance of PV model in terms 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 chose. In a phase, there will be four loads with different capacity. Load connected near to utility grid has lower capacity than load connected further from utility grid. Different capacities 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 detail about the cable was based on BS6346:1989 600/1000V standards. Fig. 18 shows the proposed three-phase grid-connected PV model with Microgrid network.

IV. Result and Discussion

A. Introduction

This section discussed the results obtained from the whole modelled system. These results will be used to analyse the performance of the system as mentioned in the objectives of this project. All results were obtained by using PSCAD software.

B. 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.

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 which means the total injected active power to PV system is 120kW. The modelled circuit was divided into three elements which are grid, inverter and load. Fig. 3 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.

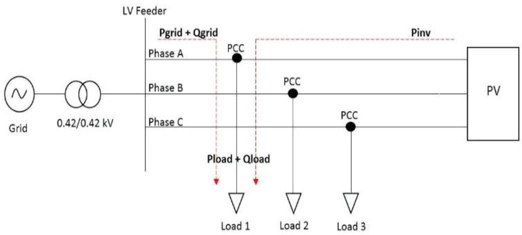

Fig. 3: PV model have priority to supply constant active power

At PCC, the power contribution between grid, inverter and load can be observed. Fig. 5 shows the result for export and import of active and reactive power with 120kW injected active power to PV model. From the figure, the positive value represent the exported power while negative value shows the imported power at PCC.

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

Inverter is then tested with constant apparent power. 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. The design of the system for this case was shown in Fig. 4. The power contribution between grid, inverter and load are observed at PCC same with Case 1. Fig. 6 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.

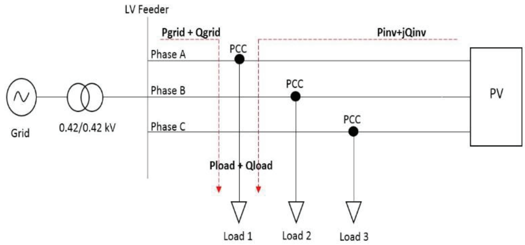

Fig. 4: PV model have priority to supply constant apparent power

According to Case 1 and Case 2, it can be conclude that power contribution is 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.

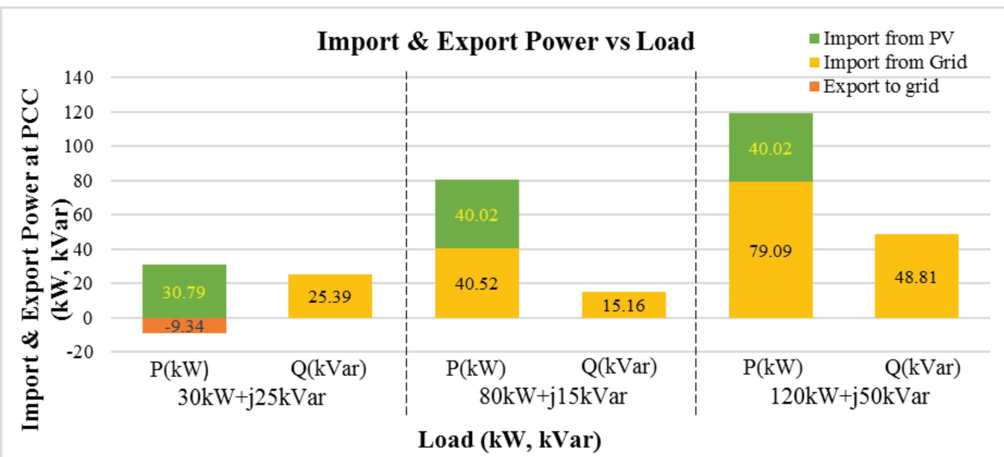

Fig. 5: Result for export and import of active and reactive power with 120kW active power

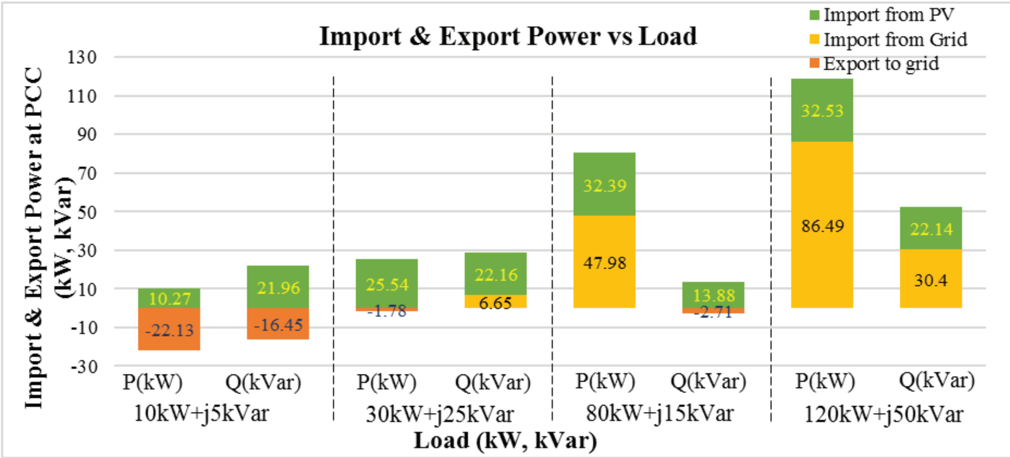

Fig. 6: Result for export and import of active and reactive power with 120kW+j60kVar apparent power

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

In this modelled circuit, PV model has the priority to supply active power and it was not designed as voltage and frequency control. Circuit breaker was used to disconnect the connection from grid to the load and PV model. At 3 seconds, circuit breaker will start to open. Fig. 7 shows the circuit connection of PV and load without grid connection.

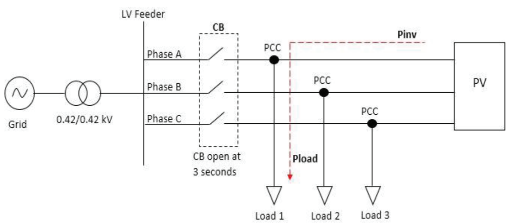

Fig. 7: Circuit connection of PV and load without grid connection

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

Reference of 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 varied 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. Fig. 8 shows the result for condition of power generated by PV less than load demand.

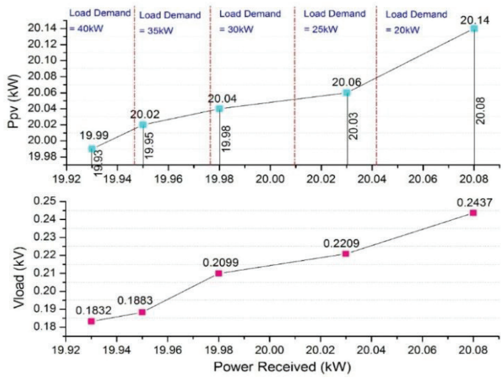

Fig. 8: Result for condition of power generated by PV less than load demand

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 are the same to the power generated by PV model at each phase. Circuit breaker will start to operate at 3 seconds which cause the grid to be disconnected from PV model and grid. This means that the load demand was fully supported by PV model. Fig. 9 shows the result for condition of power generated by PV equal to load demand.

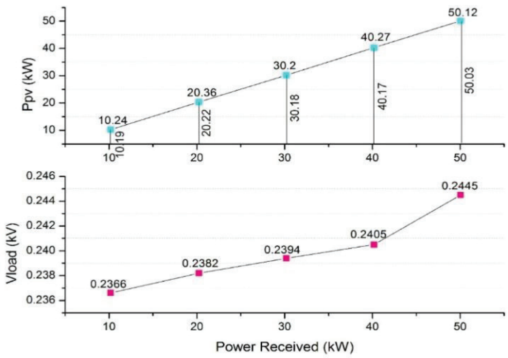

Fig. 9: Result for condition of power generated by PV equal to load demand

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 recorded were in root mean square (RMS) value. Fig. 10 shows the result for power generated by PV higher than load demand.

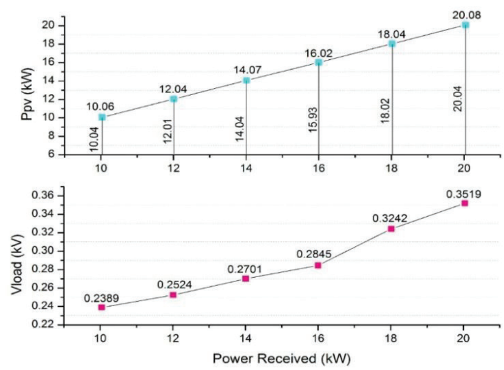

Fig. 10: Result for condition of power generated by PV higher than load demand

From Case 1, Case 2, and Case 3, voltage across load needs to be within 0.23kV and 0.24kV in order to allow the load to operate. Equipment are usually designed with ±5% of its nominal value. As the power generated is lower than load demand, the voltage will drop causing failure operation of load. When power generated is equal to load demand, load is 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. 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.

D. 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 by using different amount of load demand. Fig. 11 shows flow of power from grid and PV model to support the load.

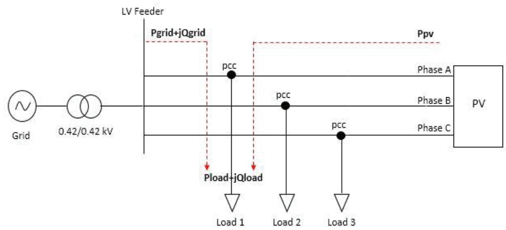

Fig. 11: Flow of power from grid and PV model to support load

In microgrid model, there are four different sizes 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. 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. Fig. 12 shows the circuit connection of microgrid network with grid connected to system.

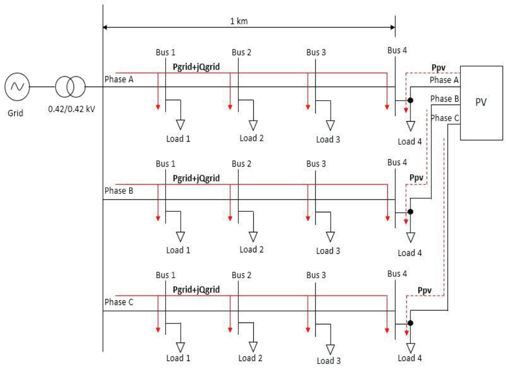

Fig. 12: Circuit Connection of microgrid network with grid connected to system

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). For this 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. Voltage across load equal to 0.2399kV when PV model not connected with the system. As the system is a balanced system, load voltage at each phase are same. Fig. 13 shows the results for percentage of voltage increment for light load demand.

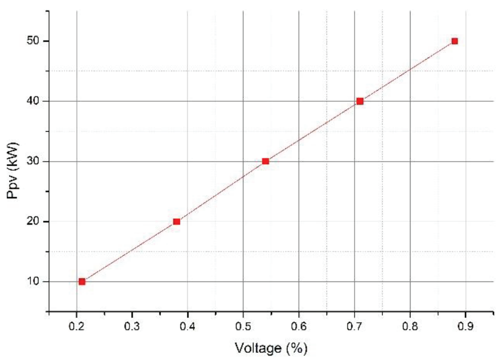

Fig. 13: Percentage of voltage increment for light load

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. Voltage across load is equal to 0.2343kV when the PV model is not connected with the system. The result for percentage of voltage increment for heavy load was shown in Fig. 14.

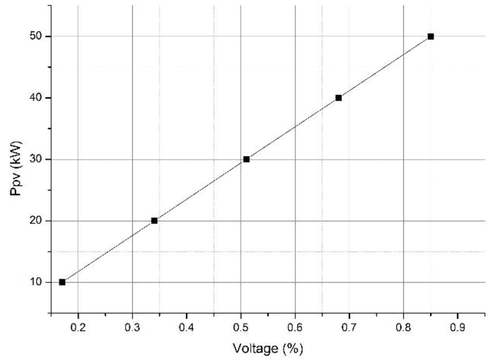

Fig. 14: Percentage of voltage increment for heavy load

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. As the length of cable increases, the load demand also increases which is represented at different point of buses. 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. 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 maintained at around 0.24kV, the voltage drop at each load was analysed. Fig. 15 shows the result for voltage profile at different point of connection in Microgrid model.

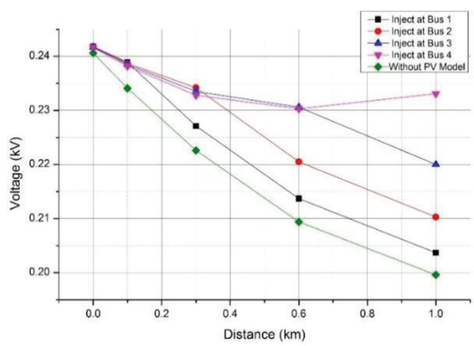

Fig. 15: Voltage profile for different point of connection in Microgrid model

By comparing Case 1 and Case 2, it seems 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 concluded that the increment of voltages was linear with the different amount of power generated by PV model. Fig. 16 shows the summary of comparison between Case 1 and Case 2.

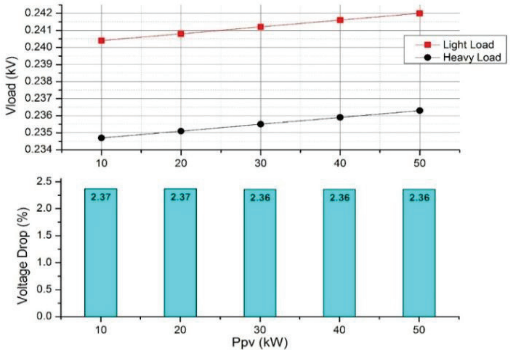

Fig. 16: Summary of comparison between Case 1 and Case 2

As conclusion, from Case 1 and Case 2, the generated powers at each phase are directly proportional with load voltage. Besides that, it can be concluded 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 increased as the power generated from PV model at each phase increased. This shows that generated power should be controlled in order to avoid overvoltage or undervoltage problem. From this case, it can also be concluded 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 gives the worst voltage profile.

V. Conclusion

As a conclusion, three-phase grid-connected photovoltaic system can be used in order to help grid network in supplying sufficient power for load demand. From the case studies, it shows 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 the capability to export its generated power to grid and load. As PV model was used without connection with grid, overvoltage and undervoltage issue can exist. This is due to the generated power from PV model that exceed or less than the load demand. PV model must be able to generated power which is equal to the load demand to prevent these problems. On the other hand, overvoltage and undervoltage problem can cause damage to equipment if it receives 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 loads that are connected further than utility grid. By connecting the PV model to the furthest load from utility grid its voltage profile can be improved. This can make the system to be more efficient. The modelled PV system using PSCAD software could give acceptable result for case studies conducted in this project. However, application of three-phase grid-connected photovoltaic system by using real components including applying voltage control technique to the system are not able to be conducted due to time constraint.

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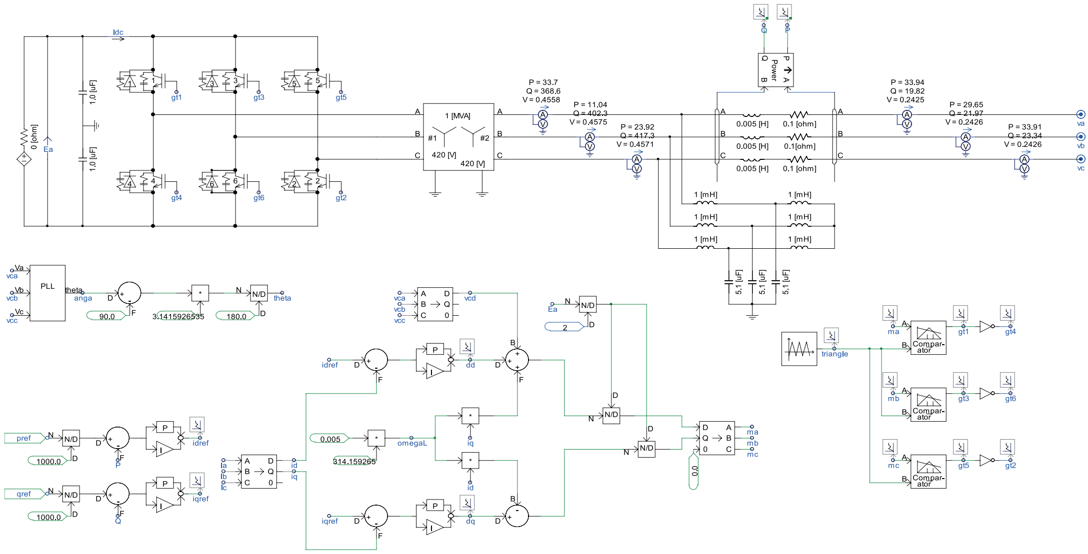

Fig. 17: Designed three-phase PV model

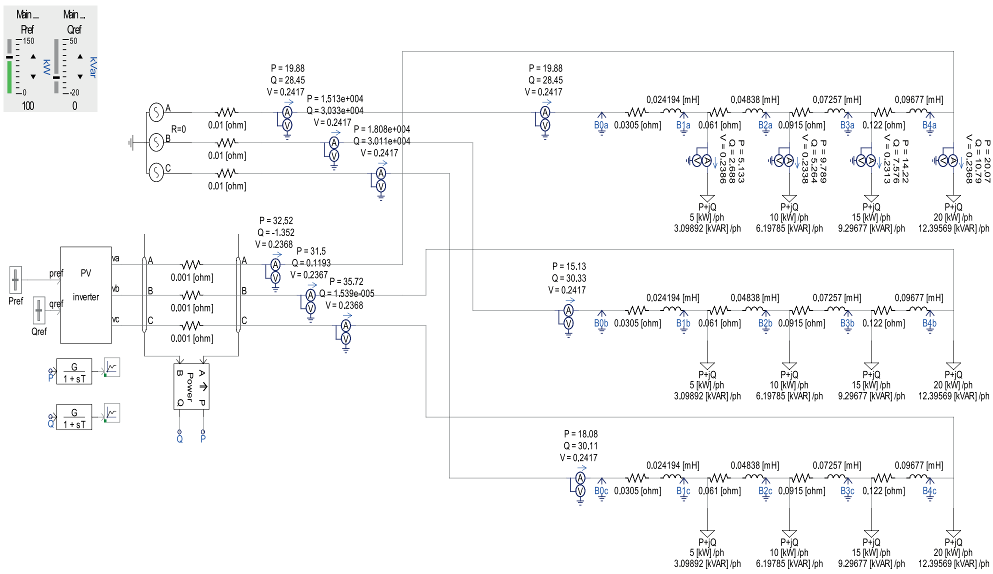

Fig. 18: Proposed three-phase PV model connected with Microgrid network