Design and Modelling of Single-Phase Grid-connected Photovoltaic at Low Voltage Network using PSCAD Software

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Abstract— _The objective of this paper is to design and model a single-phase grid-connected photovoltaic (PV) system at low-voltage network. The system consists of PV as the main source of energy, single-phase inverter, Proportional Integral (PI) controller, low-pass filter, load, and low-voltage distribution network. The model was developed using PSCAD-EMTDC software. The design was tested in terms of active power (P) and reactive power (Q) produced the to support the load demand. The results showed that the PV model was able to meet the load demand by properly tuning the PI controller. Simulation studies demonstrate the effectiveness of the controller and confirmed that the system are robust with acceptable performance._

Keywords— _Photovoltaic, Single-phase grid-connected PV, low-voltage network, PSCAD software, distributed generation._

I. Introduction

Single-phase PV system is considered one type of distributed generation (DG) that can be divided into two types which are stand-alone and grid-connected mode. For stand-alone system, it is used to provide power directly to loads and not connected to the grid whereas grid-connected PV system is used to provide energy for local loads and for the exchange of power with utility grid if needed. However, the integration of PVs towards electrical grid may leads to different issues for electrical engineer such as power quality, power imbalance between generation and load demand, voltage and frequency variation [1]-[2]. In order to investigate possible issues at the grid interface, operational and control interactions in the presence of single grid-connected PV systems, a detailed model of a grid-connected single-phase PV system is necessary. All the model and the simulation have been done by using PSCAD-EMTDC software.

II. PV Modelling

The designed single-phase PV system must able to fulfil requirements for synchronization in order to connect with grid network. Single-phase PV system consist of solar panel, single-phase inverter, low-pass filter, transformer, PWM circuit, and power controller with two separate PI controller connected between utility grid and load. Inverter will convert power generated by PV into AC form. Gate signal for the inverter is controlled by PWM circuit. The low-pass filter was used to smoothen the output of the inverter to produce sinusoidal waveform and power controller was used to inject the active and reactive power at point of common coupling (PCC) at grid network.
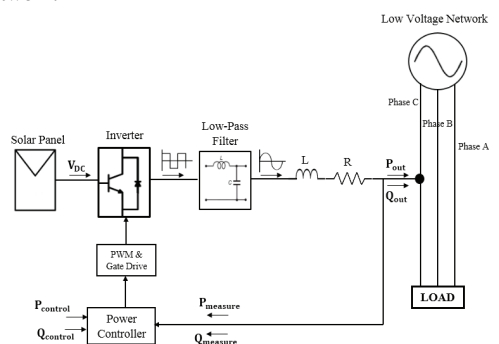

Fig. 1. Block Diagram of single-phase grid-connected PV system

Basically, $P_{control}$ and $Q_{control}$ are the values of injected power to the grid and classified as reference values. It will be compared with the power from the

inverter which are $P_{measure}$ and $Q_{measure}$ in order to generate P_{error} and Q_{error}. The error values are then passed to the PI controller to eliminate the steady-state error and maintain the exact set point value. Active power, P_{out} can be produced by adjusting the phase angle. The phase angle will be added with the angle from grid and generate new phase angle for output voltage of inverter. Adjusting the amplitude voltage of inverter can produce reactive power, Q_{out}. The amplitude voltage of inverter is then added with amplitude voltage of grid to generate new output voltage of inverter. If the value of new amplitude output voltage of inverter is higher than the grid voltage, the reactive power will flow to the grid, otherwise, reactive power will not be produced. If the reactive power is set to zero, active power will transfer from PV to the grid without much losses. Fig. 1 shows the block diagram for single-phase grid-connected PV system.

III. Design and Control

Single-phase grid-connected PV system consist of a power source, an inverter, pulse-width modulation, PI controller, filter, transformer, and fixed load. The details of components used are described below. The proposed photovoltaic system that was developed is as shown in Fig. 13.

A. DC Power Source

The model of the chosen DC voltage source can be found in the PSCAD library.

DC voltage source $> \sqrt{2} \ V_{rms}$

$$= \sqrt{2} \times 240V = 339.41V \qquad (1)$$

The minimum DC voltage source using (1) is 339.41V. To produce the required active power at 50kW, the 1.54 kV voltage was chosen as it is 4.54 times higher than 339.14V. Higher value of DC voltage source can ensure the system to be able to operate efficiently to inject output power to the grid. Fig. 2 shows the DC voltage source in PSCAD software.
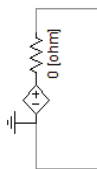

Fig. 2. DC voltage source in PSCAD software

B. Inverter

There are two types of inverter which are voltage-source inverters (VSI) and current-source inverters (CSI). VSI is independently controlled AC output voltage waveform, while CSI is independently controlled AC output current waveform [3]. Basically, IGBT is the simplified version of two-transistor circuit model which are MOSFET and BJT. IGBT has high input impedance of MOSFET along with high current gain and small on-state conduction voltage of BJT [4]. Single-phase inverter used consist of four IGBTs as power switches. The IGBT was used because it can handle very high voltage level and fast switching. Fig. 3 shows the single-phase inverter model.
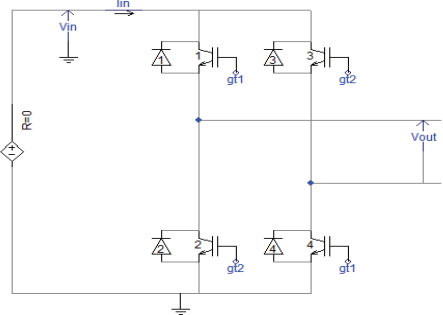

Fig. 3. Single-phase inverter model

C. Pulse-Width Modulation (PWM)

For bipolar PWM, the output become $+V_{dc}$ when the sinusoidal reference signal is larger than triangular signal and $-V_{dc}$ when the sinusoidal reference signal is less than triangular signal. Fig. 4 shows the comparison between reference signal and carrier signal using bipolar PWM [4].
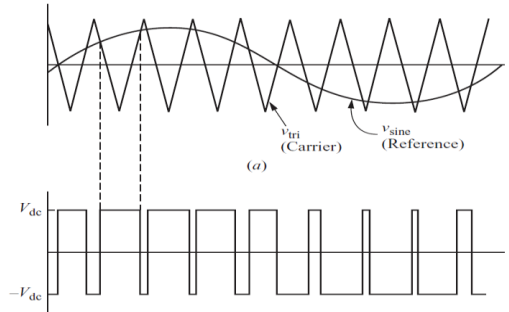

Fig. 4. Bipolar PWM switching scheme

Bipolar PWM was used to create a proper gate signal for IGBT. Fig. 5 shows the modelled circuit for PWM output. From the modelled circuit, frequency for sine wave block is set to 50Hz. This block will produce reference waveform for the system with magnitude produced from active power and angle produced from reactive power. Triangular waveform will be produced by signal generator block. The frequency of triangular waveform is set to 4 kHz.
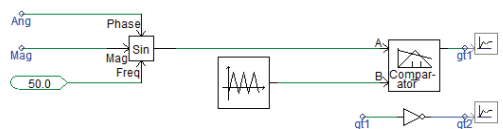

Fig. 5. Modelled circuit for PWM output

D. Proportional-Integral PI Controller

Proportional-Integral (PI) controller was chosen because of its ability to maintain exact set point. Usually, the proportional (P) controller is used to decrease the steady-state error of the system. Integral time constant used to ensure the voltage matched with reference voltage under steady state condition. Small value of integral time constant cause slow response to bring voltage towards reference voltage while large value of proportional gain cause oscillation around the reference voltage [5].

For this project, two separate PI controller was used to control the output active and reactive power from PV that will be used to produce PWM output. Proportional gain used for active power was set to 1.5 with integral time constant equal to 0.1 seconds. Since the active power used to control the angle of PWM output, the maximum and minimum limits of the output are set at the range of +360 and -360, in order to prevent the overmodulation occurred. Another PI controller is used for reactive power, which controlled the magnitude output of PWM. Proportional gain was set to 0.015 and the value for integral time constant is 10 seconds. Since it control the magnitude of PWM output, the maximum and minimum limits of the output are set at the range of +1 and -1, in order to prevent the overmodulation occurred. Fig. 6 below shows the configuration of PI controller.

Step for turning the value of proportional gain, K_p and integral time constant, T_i :-

a) Both of the PI controller was set with value of 0.026 and 10^6 seconds for proportional gain and integral time constant respectively.

b) The simulation to find the value of critical gain, K_c that are plotted at y-axis. The value of K_c is taken after the output of PI controller starts to oscillate constantly or sustainably.

c) Then, values of K_i and T_i are found for both PI controller using (2) and (3):-

$$K_i = \frac{V_{dc(per\ unit)}(K_c)}{P_c} \qquad (2)$$

$$T_i = \frac{1}{K_i} \qquad (3)$$

where;
P_c = oscillation period
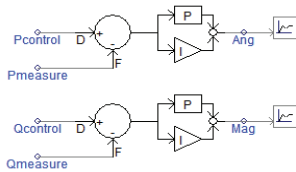V_{dc} = input of DC voltage in per unit

Fig. 6. The configuration of PI controller

E. Filter

The low-pass filter can be used because it allows only low frequency and block the frequency that is higher than cut-off frequency. The cut-off frequency, f_c for this type

of filter are shown in (4) below [6]-[7]. Fig. 7 shows the developed low-pass LC filter. This type of filter will eliminate high frequency which is classified as harmonics from the output signal of inverter. Using (4), the cut-off frequency, f_c was set to 100Hz and inductor (L) was set to 1.0mH. Value of capacitor used in the filter circuit can be obtained as stated in (5).

$$f_c = \frac{1}{2\pi\sqrt{LC}} \qquad (4)$$

$$C = \frac{1}{2\pi\sqrt{(1.0mH)(100Hz)}} = 2533.03\mu F \qquad (5)$$
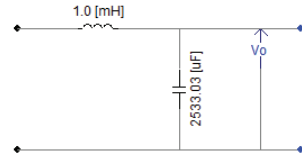
Fig. 7. Developed LCL filter circuit

F. Transformer

By using the PSCAD software, isolation transformer is needed to ensure the output voltage produced from designed PV model is close to 240V. This transformer turn ratio is 1:1 which consists of 0.24kV for primary and secondary winding. Fig. 8 shows the single-phase transformer that can be used.

Fig. 8. Single-Phase Transformer

G. Fixed Load

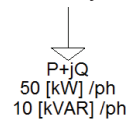Fixed load was used to model the load. Fig. 9 shows the fixed load in PSCAD library component.

Fig. 9. Fixed load

IV. Result and Analysis

The performance of the designed single-phase grid connected PV was tested under active power (P) and reactive power (Q) control. Firstly, the PV model was tested to make sure that the voltage and frequency from PV model are similar with the grid settings, which are 50Hz and 240V respectively. This is to ensure that the designed PV model was able to be synchronized with the grid network. Synchronization is important in order to avoid damage to the transmission line and load connected to the line. Fig. 10 shows the frequency and voltage produced by the PV model. From the result below, it shows that the designed PV model successfully meet the requirement for synchronization.

The PV model was then tested to make sure that it is able to produce output power that are exactly or almost equal to the reference power. Fig. 11 shows the reference power and output power produced by PV model. The model was tested with connection to utility grid system. From the result, it shows that the value of output power from PV model was almost equal with the reference power. The designed PV model can produce the output power that was similar with the reference power. This behaviour of PV model is important in controlling the power injection to grid or load demand. The output result was taken based on the root mean square (RMS) value.
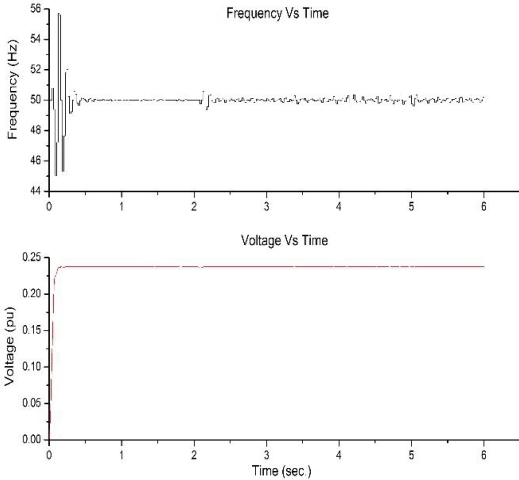

Fig. 10. Frequency and voltage produced by PV model
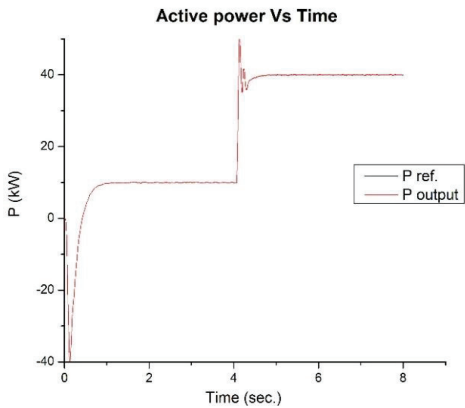

Fig. 11. Reference power same with output power produced by PV model

Lastly, the designed PV model was tested with 50kW and 10kVar load demand. Grid network will be disconnected with the PV model at 3 seconds and injected power for PV model will be increased starting from 10kW. Fig. 12 shows the output power produced by PV model with different injected power. From the result, it shows that the PV model only able to produce active power up to

90kW. The output power become unstable as the injected power exceed 90kW which can cause damage to equipment. The output result was taken based on the root mean square (RMS) value.
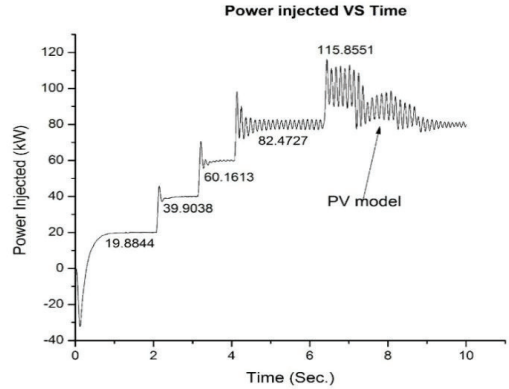

Fig. 12. Output active power that can be produced by PV model

V. Conclusion

As a conclusion, the designed PV model was able to fulfil the requirement for synchronization of network as it was able to produce 240V with 50Hz which are same with grid network. The PV model designed using PSCAD software meets the requirement as it is able to produce desired result from single-phase grid-connected PV system. Unfortunately, this PV model is only capable to assist the grid in supporting load demand which is not more than 90kW. Output power from PV model can be controlled by adjusting the injected power to PV model. In the future, this PV model could able to be used in analysing the impact of PV system towards distribution network.

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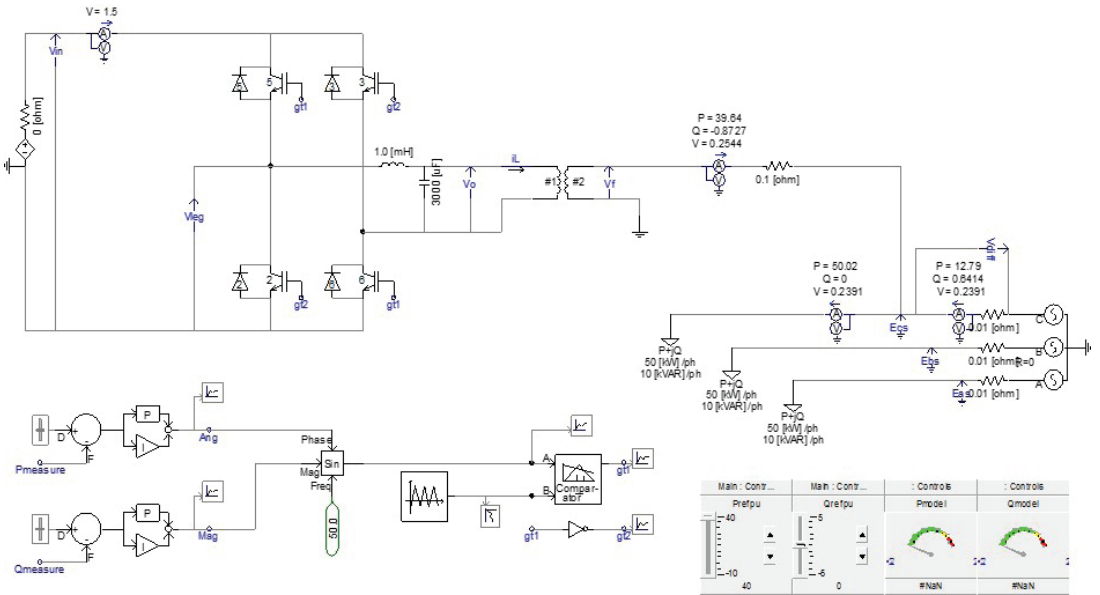
Fig. 13. The proposed single-phase PV system connected with grid network