Design and Modelling of a Three-Phase Grid-Connected Photovoltaic for Low Voltage Network using PSCAD Software

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Abstract— *This paper presents the design and modeling of a Three-Phase Grid-Connected Photovoltaic (PV) generator module in PSCAD/EMTDC. The model is useful for simulation studies of grid interface applications. The validity of the PV model developed has been verified using a set of case studies. The output power from the PV module can be controlled through the PI controller. All the simulation study has been done in the PSCAD/EMTDC simulation software. The simulation results show that the simulation models are robust with acceptable performance in terms of power sharing between the load and the grid.*

Keywords— *Three-phase grid-connected PV, distribution network, distributed generation, PSCAD software*

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I. Introduction

Solar energy is one of the cleanest renewable energy forms, as well as wind and hydro energy sources. Today, a large number of solar photovoltaic (PV) power plants are being installed all over the world. As the penetration of this PV plant rose, the interface with the grid may cause various of issues. For example, short fluctuation of irradiance, cloud cover and injected harmonic from the PV inverter will cause the power quality issue [1]. Furthermore, the stability of the PV interconnection is closely related on PV response to the system voltage and frequency. Also short circuit contribution from PV may have an effect on the protective devices such as relay settings, bus bar and circuit breakers rating [2]. Thus, the impact on the system voltage, power quality, faults and short circuit contribution needs to be well studied in order to achieve practically safe operation of PV power plants [3].

This paper deals with a modelling of a three phase grid connected PV solar system with active and reactive power control to analyse its performance on low voltage networks. All the simulation study has been done in the PSCAD/EMTDC simulation software.

II. Modelling of the PV Module

Three-phase PWM inverter is needed in order to convert the DC power generated by the PV panels into AC form. In order to obtain the desired performance and allow the system to operate in stable condition, proper controller through inverter needs to be implemented. 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 the three-phase system [4].

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 the inverter [5]. Three-phase inverter was required to convert the DC electricity produced into AC form before it is connected to the grid. Switching mechanism that was used in the inverter is Insulated-Gate Bipolar Transistor (IGBT). This is 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 [6]. Each phase from solar PV system is 240V with 50 Hz which will be connected to the three-phase grid network.

III. PV Control Design

Control system is designed in order to control the power generated from the PV system to the grid system. From the block diagram for three-phase grid-connected PV system shown in Fig. 1, the output voltage and current from the inverter is converted into DQ form by using ABC to DQ converter. Power controller is used to compare between the reference of 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 PI controller. Both of the current from ABC to DQ 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 is converted back to three-phase form using the DQ to ABC converter which are labelled as m_a, m_b and m_c. Output from the DQ0 to ABC converter is in sine wave. The output of DQ to ABC converter is compared with a triangular input to produce switching scheme for the IGBTs. Phase Locke Loop (PLL) is used to determine the angle of the voltage that will be used in the ABC to DQ0 converter.

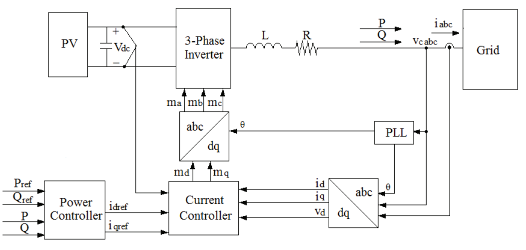

Fig. 1. Block diagram for three-phase grid-connected PV system

IV. PV Modelling in PSCAD

Three-phase PV system is modelled using the 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. The design of the three-phase grid-connected PV model using PSCAD software is as shown in Fig. 14.

A. PV Array

As PV array produced DC power, DC voltage source was used in the simulation circuit to replace the PV arrays. According to [6], 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 the DC source can be decided using formula stated in (3).

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

From (3), 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. Fig. 2 shows the DC supply used in the modelled circuit.

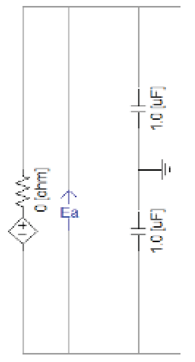

Fig. 2. Modelled DC power source

B. Three-Phase Inverter

This three-phase grid-connected PV system uses three-phase inverter to convert the DC output voltage into AC form. As discussed in [7], IGBT is used as it requires simple gate drives and it is suitable for application that requires high switching frequency. Each pair of power switches will be switched 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. Fig. 3 shows the three-phase inverter used for the system.

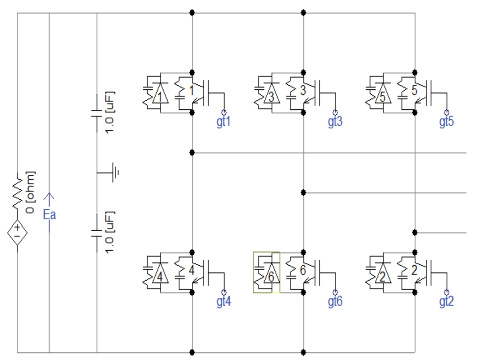

Fig. 3. Modelled three-phase inverter

C. Pulse-Width Modulation (PWM)

As mention in [8], PWM output is used as IGBT switching scheme as it has low harmonic distortion of line current and controllable power factor. Frequency of the modulating signal is set to 50 Hz while frequency of the carrier signal is set to 3.3 kHz with maximum output level equal to 1 and minimum output level set to -1. From information discussed in [9], frequency of carrier signal must be 21 times higher than frequency set for the 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. Level of comparator was set to 1 for reference signal higher than carrier signal while -1 for reference signal lower than carrier signal. Over modulation phenomenon will occur if the amplitude modulation of PWM exceeds 1. Output of the comparator is used as the gate signal for the IGBTs. Fig. 4 shows the modelled PWM output for inverter switching.

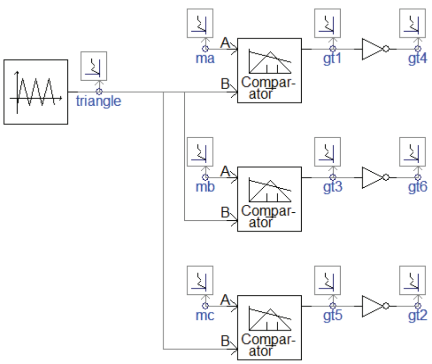

Fig. 4. Modelled PWM output for inverter switching

D. Phase Locked Loop (PLL)

Phase Locked Loop (PLL) is used in the modelled system to determine the angle to be used for ABC to DQ converter [10], [12]-[15]. From Fig. 5 shown below, the voltage from the filtered output of the inverter is used as the input of PLL. The angle output is then being compared with the angle from the carrier signal which is 90° before converted into ω in radian. The angle with label 'theta' will be used as transformation angle for ABC to DQ converter. The frequency of the PLL was set to 50Hz to be compatible with the whole three-phase system.

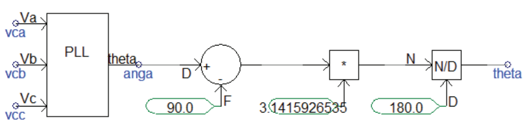

Fig. 5. Modelled PLL

E. PI Controller

According to [11], PI controller can produce an output from the combination of proportional and integral mode. The proportional controller amplifies 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.

For three-phase grid-connected PV system, PI controller is used to adjust the settling time of the system and produce zero steady-state error in the current control loop. The PI controller is also used for power controller to produce reference current in current controller model which are labelled as i_{dref} and i_{qref} as shown in Fig. 6.

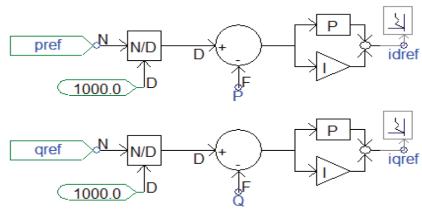

Fig. 6. Modelled circuit for power controller

The outputs are then used for comparison with the actual i_d and i_q from ABC to DQ converter as shown in Fig. 7. PI controller is used to produce d_d and d_q outputs from the output of the summing junction. Both of the outputs from current controller will produce m_d and m_q which are connected with DQ to ABC converter.

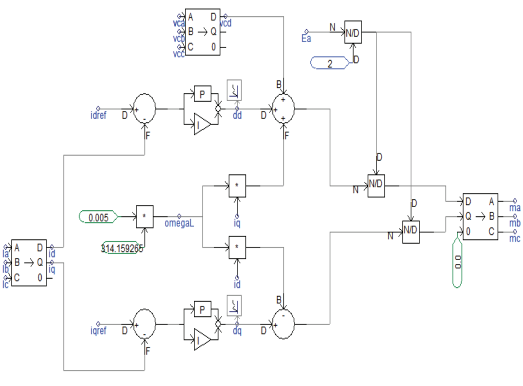

Fig. 7. Modelled circuit for current controller

As discussed in [12], zero steady-state error and fast response can be achieved when PI controller is used. From Fig. 8, (4) can be achieved.

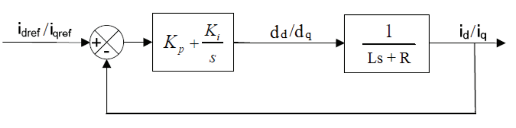

Fig. 8. Block diagram from current controller and power controller

$$\frac{i_d}{i_{dref}} = \frac{i_q}{i_{qref}} = \frac{K_p s + K_i s}{Ls^2 + (R + K_p)s + K_i} \tag{4}$$

F. ABC to DQ0 Converter

ABC to DQ0 converter is used to convert the filtered output current and voltage from the inverter to be used in power controller and current controller. The I_a, I_b and I_c

are converted into i_d and i_q form while v_{ca}, v_{cb} and v_{cc} are converted into v_{cd} output. DQ to ABC converter converts the output of current controller to produce a reference signals for the system which are labelled as ma, mb and mc as shown in Fig. 9. The Park Transformation formula was shown in (5) below. This formula transforms from three-phase (abc) reference frame to dq0 reference frame.

$$\begin{bmatrix} X_d \\ X_q \\ X_0 \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta & 0 \\ -\sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} X_\alpha \\ X_\beta \\ X_0 \end{bmatrix} \tag{5}$$

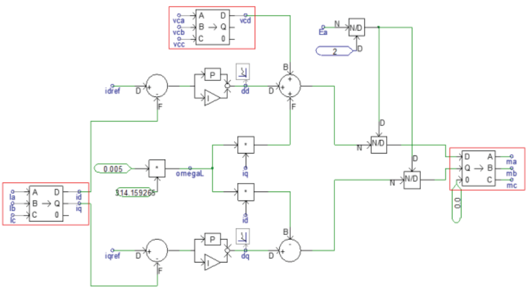

Fig. 9. ABC to DQ converter used in modelled circuit

From [10], value of P_{in} and P_{out} as shown in (6) and (7) can be achieved by using (5).

$$P = \frac{3}{2} v_d i_d \tag{6}$$

$$Q = -\frac{3}{2} v_d i_d \tag{7}$$

G. LCL Filter

Output parameter from the three-phase inverter is filtered using LCL filter. The value of capacitor needed in the filter circuit can be calculated using (8) with resonant frequency is set to 100Hz and both of the inductors are set to 1mH.

$$f_0 = \frac{1}{2\pi} \sqrt{\frac{L_1 + L_2}{L_1 L_2 C}} \tag{8}$$

$$C = 5.1\mu F \tag{9}$$

By using value of capacitor in (9), LCL filter is developed as shown in Fig. 10.

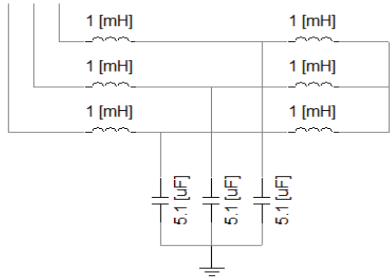

Fig. 10. Developed LCL filter circuit

V. Simulation results

The designed circuit is then tested to ensure that the PV system is able to connect with the grid network. The results are observed based on the value of voltage amplitude and frequency between PV model and grid network. To fulfil the requirement in synchronization of network, both voltage amplitude and frequency must be the same. The standard value of frequency and voltage at grid network is 0.24kV and 50Hz. Fig. 11 shows the result for synchronization between the PV model and the grid network.

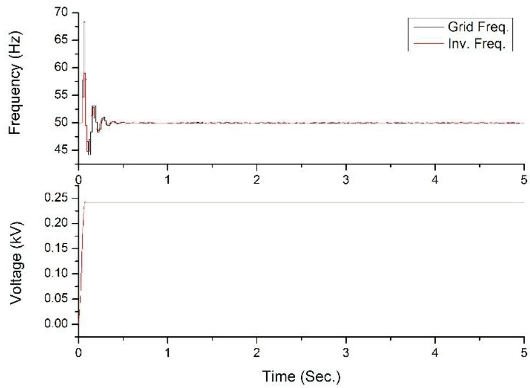

Fig. 11. Result for synchronization between PV model and grid network

The circuit is then tested to verify whether or not the output of the PV model able to achieve the reference power set to the PV system. For this test, the value of reference power for the PV system is changed from 40kW to 75kW. Fig. 12 shows the value of output power from the PV model and reference power set for PV system. The results show that the designed PV model is able to produce the output power that is identical with reference power set for the PV system.

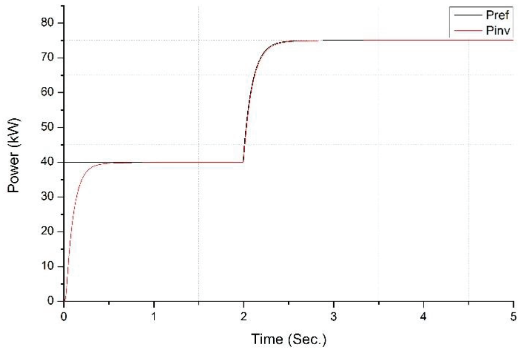

Fig. 12. Value of output power from PV model and reference power set for PV system

Basically, the designed PV model must able to assist the grid in supplying voltage to the load. The PV model should be able to fully supply the load if the loads capacity is beyond its ability. Fig. 13 shows the output power from the PV model, load and grid at phase A. The PV model is able to produce around 33.5054kW while the load only requires 30kW. From the result, it can be seen that power at grid have negative value which is -2.8256kW. This negative value indicates that the grid received power from PV model as there is surplus of power generated from the PV model. Therefore, it can be deduced that the designed PV model is able to fully support the load demand and fulfil its duty in aiding the grid network. Since the three-phase system is balanced, the power at each phase are the same.

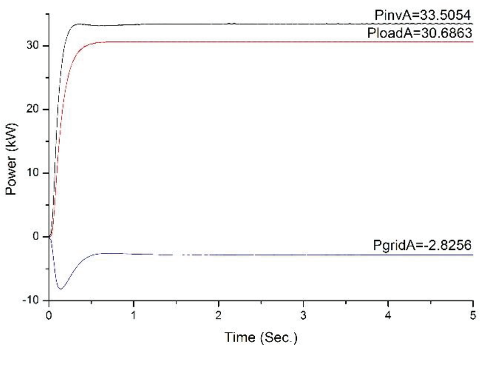

Fig. 13. Output power from PV model, load and grid at Phase A

VI. Conclusion

As a conclusion, the three-phase grid-connected PV model is able to produce the desired results for this project. Synchronization between PV model and grid network is important to avoid any damage that could happen in the network. By using this design, the requirement for synchronization is fulfilled. Besides that, the designed PV model able to produce required power as set for the PV system. The designed PV model using PSCAD software can fulfil its duty in helping the grid network by supplying sufficient power for the load demand.

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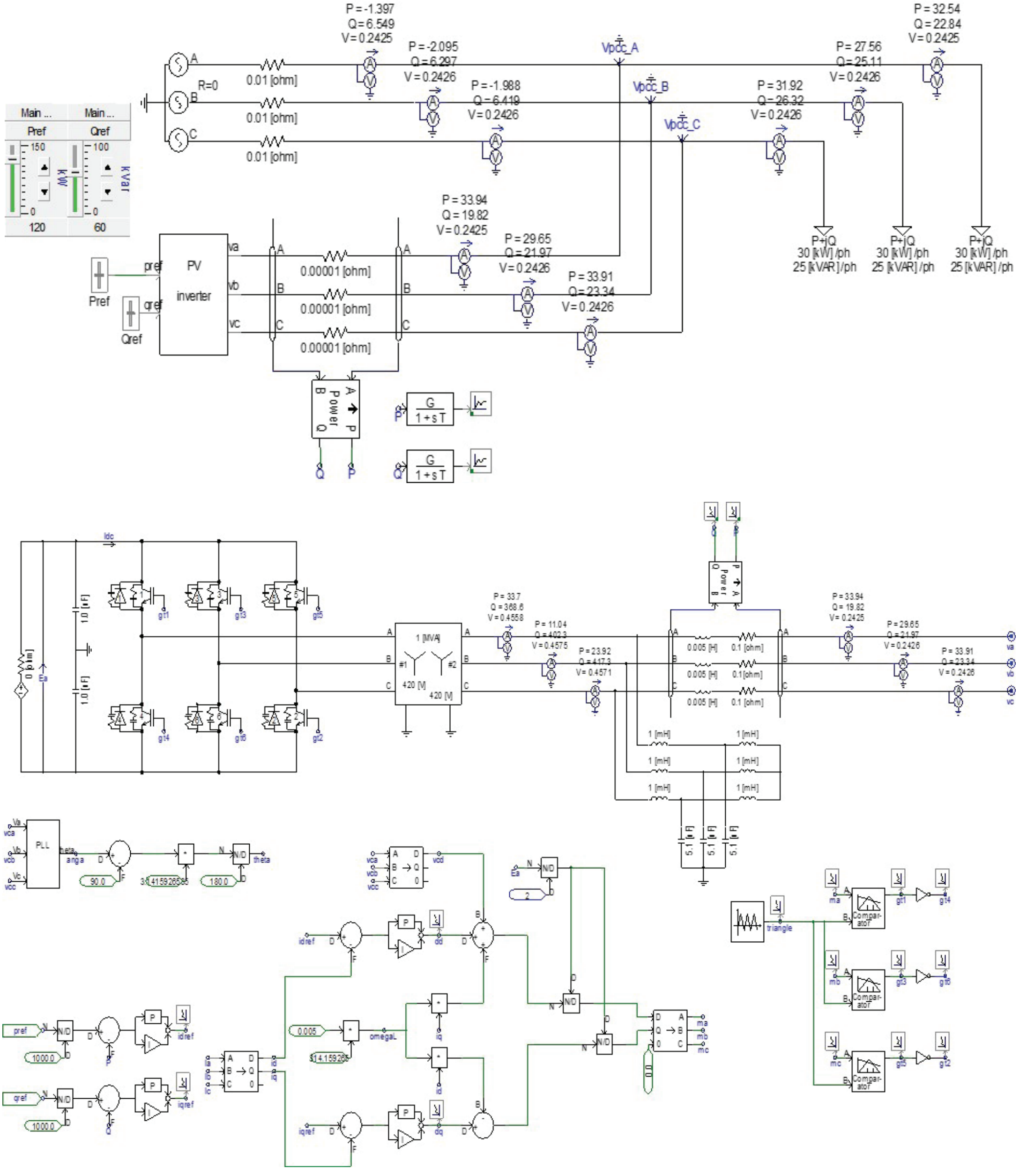

Fig. 14. Design of three-phase grid-connected PV system using PSCAD software