GRID-CONNECTED INVERTER MODEL AND CONTROL STRATEGIES FOR PHOTOVOLTAIC APPLICATION

Z A Ghani a,b, M A Hannan a, A Mohamed a

aDept. of Electrical, Electronic & Systems Engineering,  
Faculty of Engineering and Built Environment, Universiti Kebangsaan Malaysia, 43600 Bangi, Selangor, Malaysia  
bFaculty of Electronic and Computer Engineering,  
Universiti Teknikal Malaysia, Melaka, Malaysia

Abstract

This paper describes the three-phase grid-connected inverter model for photovoltaic application. The inverter system model and control strategies are carried in MATLAB/SIMULINK environment. Utilizing both proportional-integral controllers for the control loops, and the sinusoidal pulse-width modulation switching signals generation technique for the IGBTs, the inverter control system capable of converting dc power from PV to power up the ac load. Not only stabilize the output voltage and current, the inverter also feeds the excess PV power to the utility grid. The system is simulated with the PV simulator which facilitates the PV power to be fed to the inverter input stage. The control system produced 2.48% and 4.64% of output voltage and current total harmonic distortion, respectively. The simulation results such as the ac output voltages and currents, system power flow, and grid disturbances detection signals, proved the effectiveness of the developed control algorithm.

Keywords: Photovoltaic, three-phase inverter, grid, PI, SPWM

Nomenclature

A      ideality factor
G      irradiance
I_s    output current of the solar cell
I_o    diode reverse saturation current
I_{ph} light generated cell current
I_{pv} output current of the PV array
I_{sat} diode saturated current
K      Boltzman constant
N_p    modules number in parallel
N_s    modules number in series
P_{pv} output power of the PV array
q      electron charge
R_{sq} internal resistance of stack
T      stack temperature
T_c    cell temperature in Kelvin
T_{ref} reference stack temperature
α      current temperature coefficient
β      voltage temperature coefficient

1. Introduction

There is a need to find alternative energy resources for the future energy sustainability. Photovoltaic (PV) energy is one of the important renewable energy sources. With the aid of electronics power converters, mainly the dc boost converters and inverters, this kind of energy can be utilized and transported to the electric utility [1]. However, the inverter efficiency need to be improved further on in order to mitigate the effects of the self-consumption losses, unbalanced load on inverter output voltage, nonlinearity, PV low efficiency, electromagnetic interference and high level of harmonics content [2]-[4]. In addition, it is important that the inverter system acquires the capability to operate with high speed and frequency in generating the pulse-width modulation (PWM) signals [5]. Hence, the inverter controller which plays an important role in the improvement of the abovementioned issues, needs to be enhanced further to uplift the inverter performance in renewable energy applications, especially in PV. Analogue circuit controllers, microcomputers, digital circuit controllers, field programmable gate arrays (FPGAs) and digital signal processors (DSP), e.g. dSPACE, are among the controllers used in the inverter control system [6]-[9].

In this work, the inverter control system algorithm, strategies and modelling are developed and simulated in
structure as in equation (2) and (3). The power output of the PV array is the product of output current and output voltage of PV represented in equation (4) [12].

\[
I_c = I_{ph} - I_o = I_{ph} - I_{sat} \left[ e^{\left(\frac{q}{AKT}\left(V + IR_s\right)\right)} - 1 \right] \tag{1}
\]

\[
V_{PV} = N_S \times \left( V_{ref} - \beta \left( T - T_{ref}\right) - R_S \left( T - T_{ref}\right) \right) \tag{2}
\]

\[
I_{PV} = N_p \times \left[ I_{ref} + \alpha \left( \frac{G}{1000} \left( T - T_{ref}\right) + \left( \frac{G}{1000} \right) I_{sc} \right) \right] \tag{3}
\]

\[
P_{pv} = I_{pv} \times V_{pv} \tag{4}
\]

The PV array characteristics are (i) open circuit voltage, \( V_{oc} = 21.8 \) V, (ii) short circuit current, \( I_{sc} = 5 \) A, (iii) maximum power output voltage, \( V_{mp} = 17 \) V, and (iv) maximum power output current, \( I_{mp} = 4.7 \) A. The built-in dc-dc boost converter increases the voltage to 700 V for the inverter input stage. This enables the inverter to generate rms output line voltage of 415 V. The generated ac voltage and current contain undesired harmonics which can be reduced by the low pass filter. Consequently, the ac output waveform becomes almost sinusoidal. The generated ac power from the inverter is supplied to the ac load. Any available excess power is dispatched to the grid.

### 3. Inverter Control Strategy

The inverter control system operates in two modes, standalone and grid-connected. The system begins in a standalone mode, stabilizing the output voltage before gaining the grid synchronization. Once in synchronization, the system switches to a grid-connected mode. Figure 2 illustrates the control strategy structure for standalone mode, which utilizes PI controllers to regulate both the inverter input and output voltage.

![Fig.2. Standalone inverter voltage control scheme](image-url)
where \( V \) is the voltage magnitude and \( \omega \) is the angular frequency. It is governed by equation (8).

\[
\begin{bmatrix}
\psi_v \\
\psi_q \\
\psi_d
\end{bmatrix} =
\begin{bmatrix}
\cos \omega t & \cos \left( \omega - \frac{2\pi}{3} \right) & \cos \left( \omega + \frac{2\pi}{3} \right) \\
-\sin \omega t & -\sin \left( \omega - \frac{2\pi}{3} \right) & -\sin \left( \omega + \frac{2\pi}{3} \right) \\
1 & 1 & 1
\end{bmatrix}
\begin{bmatrix}
\psi_a \\
\psi_b \\
\psi_c
\end{bmatrix}
\]

(8)

Under balanced load, \( \psi_d \) in the \( \psi_{dq} \) coordinate can be neglected and left only \( \psi_v \) and \( \psi_q \). Thus, the PI controllers are able to keep track the reference voltage, which stabilizes the inverter output voltages. The PI control algorithm is shown in equation (9).

\[
u(t) = K_p e(t) + K_i \int_0^t e(t) dt
\]

(9)

where \( u(t) \) is the output of the PI controller, \( K_p \) and \( K_i \) are the controller proportional and integral gains respectively, and \( e(t) \) is the error signal as in equation (10), e.g. the difference between the reference voltage signal, \( r(t) \), and the measured one, \( y(t) \).

\[
e(t) = r(t) - y(t)
\]

(10)

The PI controller minimizes the inverter output voltage rise time, overshoot and steady-state error. The PI controller generates a control signal in such a way that the error signal is kept to a minimum value. Thus, the system is capable of tracking the reference voltage. Hence, the inverter output voltage can be controlled and stabilized as desired.

After stabilizing the voltage and frequency, the control system senses the grid voltage, frequency and phase for synchronization. It establishes the grid connection by the breaker closure. The inverter current is sensed and transformed to \( \psi_{dq} \) components. As in Figure 3, the current control scheme enables the PI controller to track the reference current based on the error between the actual current components, \( I_d \) and \( I_q \), and their reference current, \( I_{dref} \) and \( I_{qref} \) respectively.

![Fig.3. Grid-connected two-loop current control scheme](image)

These reference currents are generated from the dc voltage control scheme where the dc link voltage, \( V_{dc} \), is regulated by the PI to track the dc reference voltage of 700 V. For the system protection against the grid disturbances such as frequency and voltage changes, the system implemented the voltage and frequency disturbances detection algorithm. Upon detection of the parameters changes, a cut off signal is send to the breaker to isolate the inverter from the grid, leading to a standalone mode situation. In this situation, any event of overload condition, where the loads power demand exceeds the generation, the inverter will go into a power off mode. This is to ensure the protection of the PV inverter system.

**4. PWM Signal Generation**

At final stage of the control scheme, the algorithm utilizes the sinusoidal PWM (SPWM) technique, where the output of the PI controllers determines the switching signals. In producing these signals, the control signals which are the modulating signals are compared to the 15 kHz triangular wave. The SPWM is one the method to pulse-width modulate the inverter IGBTs in order to shape the output ac voltages to be as close to a sine wave as possible. The switches duty cycles are modulated by the control signals that is the desired inverter output fundamental frequency. This triangular wave frequency establishes the inverter switching frequency at which the inverter switches are switched.

The ac output voltage contains harmonics components which appear as sidebands, centered around the switching frequency and its multiple as in equation (11). These harmonic can be filtered by the LC type, and a nearly sinusoidal output waveform can be achieved. This filter acts as a high impedance for higher order harmonics and low impedance for lower order frequency.

\[
f_{\text{harmonic}} = k M_f f_{\text{control}}
\]

(11)

where \( k \) is an integer, \( f_{\text{control}} \) is the frequency of the control signal and \( M_f \) is the frequency modulation index as in equation (12).

\[
M_f = \frac{f_{\text{triangular}}}{f_{\text{control}}}
\]

(12)

The PV input voltage is controlled at a certain voltage reference which resulted in the regulation of ac output voltage as in equation (13).
\[ V_{\text{line, rms}} = 0.612 M_a V_{dc} \]  \hspace{1cm} (13)

where, \( V_{dc} \) is the dc input voltage and \( M_a \) is the amplitude modulation index. It is the ratio of the amplitude of control signal, \( V_{\text{control}} \) to the amplitude of triangular wave signal e.g. carrier signal, \( V_c \) as shown in equation (14).

\[ M_a = \frac{A_{\text{control}}}{A_c} \]  \hspace{1cm} (14)

This parameter determines the value of the inverter fundamental rms output line voltage. It should be maintained in the range of 0.9 so that no over-modulation occurs, which causes more harmonics appear in the output waveform and this condition should be avoided.

5. Simulation Model

A simulation was conducted for 0.16 seconds in MATLAB/SIMULINK to validate the effectiveness of the control system. It is shown in Figure 4.

The inverter is evaluated with three load profiles:

(i) 5.8 kW (equal to PV capacity)
(ii) 3.0 kW (less than PV capacity)
(iii) 8.8 kW (higher than PV capacity)

The inverter output waveform must be nearly sinusoidal with a unity power factor and below 5% of total harmonic distortion (THD) \[13\]. In addition, the inverter behavior is assessed during the grid voltage and frequency disturbances, e.g. over voltage, under voltage, over frequency and under frequency conditions.

6. Result and Discussion

In this section, the simulation results are presented to validate the effectiveness of the inverter control system. Figure 5 presents the filtered three phase inverter output voltage waveforms, \( v_a, v_b \) and \( v_c \).
power drawn or dispatched to the grid and this is shown by 0 kW on the grid contribution profile. Then the load power is increased to 8.8 kW (0.05 to 0.1 sec), which is equivalent to an increase of 3kW of power. Apparently, the additional power is drawn from the grid which is indicated by -3kW on the grid contribution profile. A scenario where the load demands less power from the PV is depicted in 0.1 to 0.16 second. In other words, the load power is reduced to 3kW, causing the excess power of approximately 2.8kW being fed to the grid as can be seen on the grid contribution profile.

The above result of system power flow analysis implies the effectiveness of the control system algorithm in both standalone and grid-connected operation.

Figure 8 and 9 show the THD of the phase voltage and current waveforms. They are 2.48% and 4.64% respectively, which are below 5% of the IEEE standard. These results exhibit the effectiveness of the implementation of developed voltage and current-controlled algorithms, SPWM technique and filter as well.

Figure 10 shows the over-frequency scenario, where the grid frequency is increased to 51 Hz. The inverter connects to the grid at 0.03 second. After the disturbance detection (0.06 to 0.09 second), the inverter isolated from the grid, and then shut down at 0.118 second. The inverter switching-off. As a result, no grid current flowing through and the inverter terminal voltage became zero as illustrated in Figure 13.

The under-frequency situation of the grid frequency reduced to 49Hz is shown in Figure 11. The inverter connects to the grid at 0.03 second. It detected the disturbance which occurred at 0.065 second, turned off and isolated from the grid at 0.118 second. The inverter shutting down and isolating process took approximately 2.65 cycles which is within the range of the IEEE requirement. This can be seen from the figure after 0.118 second, whereby both the inverter voltage and grid current are zero, resulted from the occurrence of inverter shutting down and grid-isolating process.

The response of the inverter algorithm towards the grid disturbances are illustrated in the following figures. Figure 10 shows the over-frequency scenario, where the grid frequency is increased to 51 Hz. The inverter connects to the grid at 0.03 second. After the disturbance detection (0.06 to 0.09 second), the inverter isolated from the grid, and then shut down at 0.113 second. The system disconnection period, which is the time of the disturbance occurrence to the time of grid disconnection, is approximately 2.65 cycles, which comply with the IEEE requirement. It can be seen that after 0.113 second, the inverter voltage is zero and no current flowing, indicating the process of inverter shutting-down and isolating from the grid. This is the safety feature of the inverter system.
Fig. 12. Detecting signal for grid voltage of 264 V

Fig. 13. Inverter voltage and grid current for grid voltage of 264 V

The inverter behavior when the grid voltage dropped to 211 V is shown in Figure 14. In the grid-connected mode, upon detection of the disturbance which occurs at 0.065, the control system generates the 'low' level detecting signal, isolating from the grid and at then switches off. No grid current flowing through and the inverter terminal voltage become zero as illustrated in Figure 15.

Fig. 14. Inverter voltage and grid current for grid voltage of 211 V

Fig. 15. Inverter voltage and grid current for grid voltage of 211 V

Conclusion

The investigation of the grid-connected three-phase inverter for the PV applications has been presented. The developed inverter control system modeling is carried out in MATLAB/SIMULINK environment with different load power demands and grid voltage and frequency disturbance scenarios. The presented results showed that the inverter control algorithm is successful in converting PV dc power to ac power with acceptable THD level for supplying power to the load and grid as well. In addition, the system manages to regulate the 50Hz sinusoidal output voltage and response to the grid voltage and frequency disturbances effectively. Overall, this investigation has proved the good performance of the developed inverter control system and protection algorithm.

References


