TELKOMNIKA Indonesian Journal of Electrical Engineering
Vol. 14, No. 1, April 2015, pp. 62 ~ 71
DOI: 10.11591/telkomnika.v14i1.7646

Capacitor Bank Voltage Equilibrium for MPPT in Single-Phase Single-Stage Five-Level Inverter for PV-Grid Application

L. Heru Pratomo*[1], F. Danang Wijaya[2], Eka Firmansyah[3]
[1,2,3]Department of Electrical Engineering and Information Technology, Gadjah Mada University
[1]Department of Electrical Engineering, Soegijapranata Catholic University,
Jl. Grafika No 2. Kampus UGM, Yogyakarta, 55281, Indonesia, Telp/Fax: (0274) 547506, 51098
*Corresponding author, e-mail: heru.s3te12@mail.ugm.ac.id

Abstract

Single-phase single-stage PV-Grid system using a five-level inverter has been investigated. Some of integration systems used two-stage converters, while others used single-stage converter. However, two-stage converters had a very complicated problem. The first converter acted as a maximum power point tracker to maximize power generated by sunlight energy to electric power, implemented by PV. The second stage was used as an interface to the grid. In single stage-converter was very simple in which an inverter was used for a maximum power point tracker and interface to the grid. This paper is designed to develop a single-stage PV-Grid system using a single-phase voltage source five-level inverter. The voltage equilibrium on capacitor was to make PV generate maximum power; hence, the equilibrium voltage between PV and five-level inverter output was proposed to deliver that maximum power generated by PV to the grid. Here, an analysis and a simulation were performed to demonstrate the design effectiveness.

Keywords*: PV-Grid, five-level inverter, power equilibrium, capacitor*

1. Introduction

In response to the very rapidly growing need for energy, the use of a solar energy grows very rapidly. Such energy development, however, also emerges some environmental problems. In this case, Photovoltaic (PV), solar energy conversion equipment directly into electrical energy, has been widely used. PV has a nonlinear characteristic curve; therefore, when loaded directly, PV would make the power generated by the PV not maximal, for this, improving the system is a must [1]. The device called Maximum Power Point Tracker (MPPT) has been used to enable the PV to operate at maximum power point. This device must be used in many of applications such as PV for battery charger application, or PV-Grid system.

The utilization of independent PV requires a greater demand in which this system is mostly applied in some areas inaccessible by power lines. This system is called stand-alone PV systems. The other one is called grid-connected systems in that PV and grid have been integrated. The PV-grid system is a very interesting topic, making this technique growing very rapidly and widely studied by many researchers. In PV-grid integration, it must be ascertained that the PV operates at maximum power point. PV-grid systems that use a two-stage conversion consist of a DC-DC converter functioning as a maximum power point tracker to maximize power generated by PV and inverter acting as an interface to the grid. This system would be more complex, requiring complicated control; hence, it might be costly in its implementation [2-5].

In single-stage PV-Grid system using an inverter, the system would be more attractive in view of the use of the inverter both as the maximum power point tracker and as an interface to the grid. In this way, the power generated by PV would be delivered to the grid. A three-phase inverter has been used to improve stability in the PV-Grid system. That system is implemented by means of DSP hardware [6] and control using a PI regulator [7]. A single-stage three phase for the solar PV system with energy capture improvement based on voltage control to solve fast changing irradiation problem is proposed. This structure is used along with a DC link voltage control loop and a current control loop [8]. For a better performance, the authors [9]

Received December 27, 2014; Revised Mach 3, 2015; Accepted March 16, 2015

has used fuzzy logic to control this one and the others using Double-Linear-Approximation MPPT [10]. A photovoltaic grid-connected simulation platform for digital/physical hybrid real-time simulation in which RTDS uses a digital-to-analog interface to communicate with external DSP devices were feasibility and effective [11]. An implementation using DSP hardware is commonly rather complex in algorithm and must have a good performance. Though single-phase single-stage PV-grid system using hill-climbing control or P & O has a good performance [4], [12-14], the hill-climbing algorithm based on ∆ V and ∆ P has some oscillations at maximum power point. If ∆ V and ∆ P are large, the system will be faster to achieve maximum power, but the system would produce greater oscillation. In contrast, if ∆ V and ∆ P are getting smaller, achieving the maximum power point would be slower, but with a relatively small oscillation. Capacitor control is used as an MPPT for boost DC-DC converter. This system has been integrated with a single phase inverter to deliver power generated by PV to the grid. In other words, for using a two-stage conversion system, the system was relatively complex [15].

In turn, this paper proposes a capacitor bank equilibrium control for MPPT in a single-phase single-stage PV-Grid system, the implementation of which was by using a five-level inverter. A control based on the energy has been stored in a capacitor bank to be detected by the voltage censor on the capacitor. It was by controlling the voltage on the capacitor to see whether it was equal to the power control on the capacitor. This capacitor mounted as capacitor banks located between the PV modules and five-level inverter. This control scheme purposely was to achieve power equilibrium between instantaneous and average power. This strategy in turn would force the average power of five-level inverter to have the same value as the maximum power generated by PV modules. The five-level inverter was used for good performance in power quality output. Finally, it was continued by performing analysis and simulation to demonstrate the design effectiveness.

2. Research Method

The first step was to recognize the proposed PV-Grid system by describing a theoretical analysis about voltage equilibrium on capacitor bank and PV. Based on Figure 1, the P-V characteristic of PV was nonlinear. Maximum power point (P_{MPP}) would be generated by voltage (V_{MPP}). These values of power would be various under the different condition of irradiance and temperature.

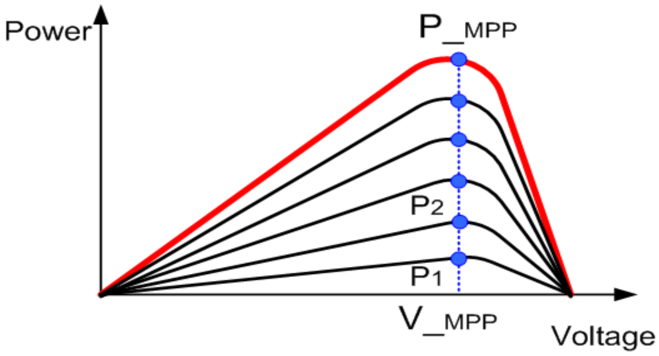

Figure 1. Characteristic P-V curve of PV

It is revealed that, to keep the voltage capacitor constant, the PV should be installed. Thus, it was possible to control the output voltage of the PV via the voltage across the capacitor bank. In fact, the voltage across the capacitor had a relationship with power, indicating that by controlling the voltage on the capacitor bank, the power could also be controlled. The drop of the voltage across the capacitor at the DC voltage indicates the real power given to the five-level inverter, while, if the capacitor voltage rose; the absorption power of PV would occur. To ensure the increase and decrease in power, the capacitor voltage must be kept constant, Figure 2.

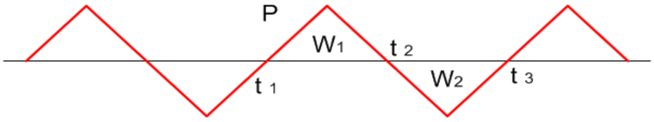

Figure 2. Control power to the capacitor bank with a voltage

The first condition: at interval of $t_1 - t_2$, the capacitor transmitted power to five-level inverter, thus making the capacitor voltage down. For this, the amount of energy is expressed by the equation:

$$W_1 = \int_{t_1}^{t_2} P(t)dt \tag{1}$$

The second condition: at interval of $t_2 - t_3$, the capacitor absorbed power from the PV, thus raising the capacitor voltage. Thus, the amount of energy is expressed by the equation below:

$$W_2 = \int_{t_2}^{t_3} P(t)dt \tag{2}$$

Since solar modules used the voltage on the capacitor detection system, the energy absorption can be derived as follows:

$$W = W_1 = W_2 \tag{3}$$

At interval condition t_1 would produce a voltage across the capacitor: V_{cap1}

At interval condition t_2 would produce a voltage across the capacitor: V_{cap2}

At interval condition t_3 would produce a voltage across the capacitor: V_{cap3}

Thus, the capacitor voltage can be expressed as follows:

$$\begin{aligned} &V_{cap\,1} < V_{cap\,2}\,, \\ &V_{cap\,3} < V_{cap\,2}\,, \\ &V_{cap\,1} = V_{cap\,3}\,. \end{aligned} \tag{4}$$

The delivery process and energy absorption would cause voltage fluctuations in the capacitor bank at:

$$\Delta V = V_{cap\,2} - V_{cap\,1} \tag{5}$$

The capacitor bank was capable of storing energy absorbed from the PV and then sent energy to the grid. The amount of energy stored in the capacitor bank was defined by the equation:

$$\begin{aligned} W &= \frac{1}{2}C(\Delta V)^2 \\ W &= \frac{1}{2}C(V_{cap2} - V_{cap1})^2 \end{aligned} \tag{6}$$

Thus, the value of the capacitor bank could be expressed in an equation:

$$C = \frac{2\int_{t_1}^{t_2} P_C(t)\,dt}{\left(V_{cap\ 2} - V_{cap\ 1}\right)^2} \tag{7}$$

The capacitor bank voltage would fluctuate in value of ΔV. The power supplied or absorbed by the capacitor bank was expressed as follows:

$$P_C = C\,V(t)\frac{d(V)}{dt} \tag{8}$$

By maintaining a constant voltage value on the circumstances, the power could also be maintained. Based on the above description, the control scheme can be derived as seen in Figure 3.

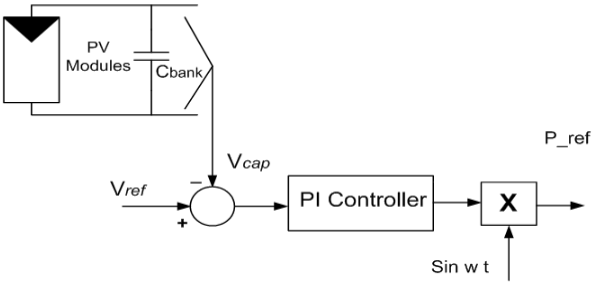

Figure 3. Power control scheme based on the capacitor bank voltage

The output of PV modules was DC voltage in which an inverter was needed to convert DC voltage into AC voltage. Some parallel connections between PV in the grid must consider several parameters, one of which was that the output voltage of the inverter must be synchronized with the grid voltage. If the inverter was used based on current control, the output of the inverter would automatically lock to the grid voltage. Figure 4 shows the block system PV modules, inverter, and the grid.

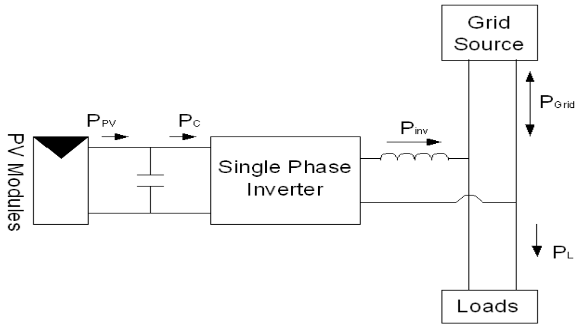

Figure 4. Block system: PV modules, inverter, and the grid

If the grid voltage V_{Grid} and output current inverter I_{inv}, the instantaneous power was injected into the grid, as expressed below:

$$p_{inv}(t) = v_{Grid}(t) \cdot i_{inv}(t) \tag{9}$$

Thus, the average power could be found at:

$$P_{inv} = \int_0^T p_{inv}(t)dt \tag{10}$$

When current and voltage were in phase, the average power could be calculated by using the RMS value of current and voltage (Figure 5). Thus,

$$P_{inv} = V_{grid} \cdot I_{inv} \tag{11}$$

In ideal condition, the average power of injected power had the same value of PV power.

$$\begin{aligned} P_{PV} &= P_C = P_{inv} \\ P_C &= V_{Grid} \cdot I_{inv} \end{aligned} \tag{12}$$

For these conditions, the inverter output current could be expressed as:

$$I_{inv} = \frac{P_C}{V_{Grid}} \tag{13}$$

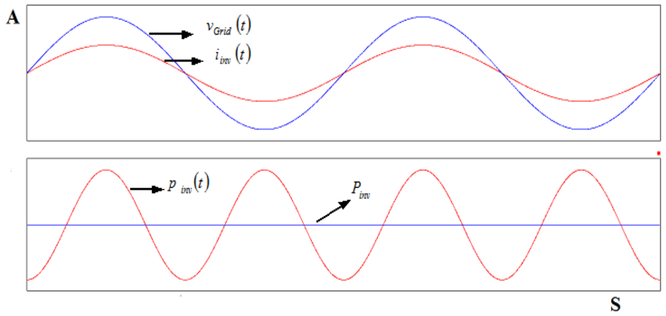

Figure 5. Instantaneous values of voltage, current and power

The important one that must be considered was inverter. Inverter with high performance known as the five-level inverter has been investigated [16]. If the five-level inverter made a generalization of the switching function would have the following equation:

$$\frac{d\,i(t)}{dt} = \frac{[S_{sw}]V_s - V_o}{L} \tag{14}$$

Equation (14) shows that the five-level inverter could be used as a controlled current source strategy to transmit power, Figure 6.

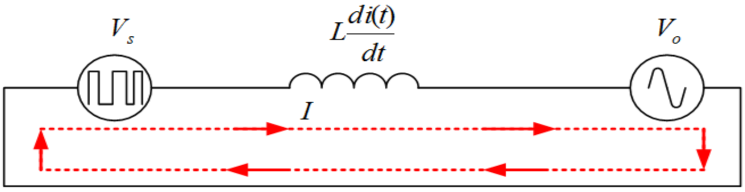

Figure 6. Equivalent circuit of a five-level inverter pulse width modulation as a controlled current source

The influence of the switch on the current conditions and the actual reference could be illustrated in Figure 7. Thus, the function of the output current of the switching function was obtained as follows:

$$i(t) = \int \frac{[S_{sw}]V_s - V_o}{L} dt + i_o \tag{15}$$

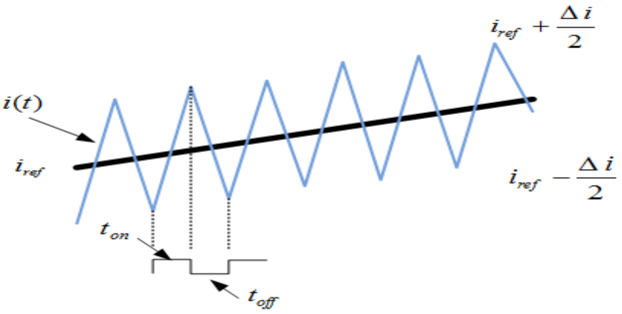

Figure 7. Influence of the switch to the current conditions of the reference and the actual current

In the implementation of the actual current will fluctuate around the current ΔI of reference, as seen in Figure 8.

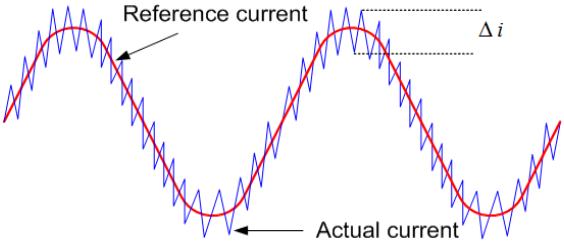

Figure 8. Actual current fluctuations around current reference

Thus, the reference current and the actual current could be written as follows:

$$\frac{\Delta I}{2} = i^*(t) - i(t) \tag{16}$$

$$i(t) = i^*(t) - \frac{\Delta i}{2} \tag{17}$$

Then the magnitude of the output voltage was obtained as follows:

$$V_S(t) = L \frac{i^*(t) - \frac{\Delta i}{2}}{dt} + V_o(t) \tag{18}$$

Equation (18) shows that the five-level inverter output voltage was required to follow the output current ΔI reference to fluctuations in the instantaneous voltage. The voltage source was added to the inductor. Five-level inverter output voltage of V_d was the average voltage pulse width modulation. A current controller would try to make ΔI as small as possible and the actual current magnitude must be ensured equal to the reference value by adding a control system. The proposed scheme of single-phase single-stage PV-Grid system using five-level inverter based capacitor bank voltage equilibrium control is shown in Figure 9.

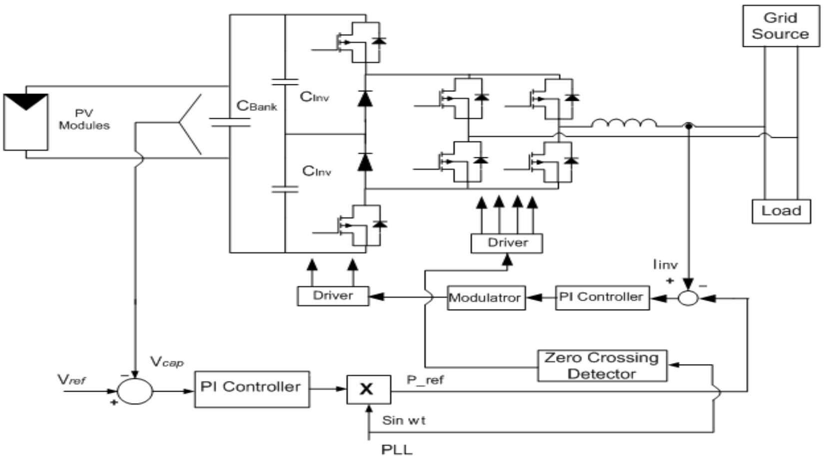

Figure 9. The proposed scheme

3. Results and Analysis

Once the analysis has been conducted, its verification was performed through a simulation. The simulation works were based on Power Simulator software using the scheme as depicted in Figure 9. Table 1 presents the parameter used in the simulation. The power line system contains a number of resistive loads used as a grid where the PV and five-level inverter were connected to the grid. Furthermore, four conditions for the simulation were taken the solar irradiance under 1000W/m^2 with resistive load of 50 Ohm and 10 Ohm, then the solar irradiance under 500W/m^2 with resistive load of 50 Ohm and 100 Ohm. Under 1000W/m^2 with resistive load of 50 Ohm, it was considered that the power absorbed by a resistive load (50 Ohm) was less than the power generated by PV; therefore, the amount of power would be delivered to the grid. Hence, the grid current's phase angle was 180^0 with respect to the grid voltage and current load and inverter output current would be in phase, Figure 10.

Table 1. The simulation parameter value

Parameters	Value
PV module max Power	50.45 Wp
PV Module Voltage at max Power	14.20 V DC
PV Module Current at max Power	3.55A
Number of modules in array	16
Modules connection	Series
Voltage Grid	220V AC
Load	10, 50, 100 Ohm
Inductor	3mH
Capacitor Bank	470uF
Capacitor on Inverter	220uF
Switching Frequency	10KHz

Since the inverter output current and voltage were sinusoidal and in phase, the instantaneous power would fluctuate from zero to maximum value whose average power was equal to the power generated by PV. Capacitor bank played a significant role to keep power equilibrium power delivered PV and five-level inverter, an Equation (7).

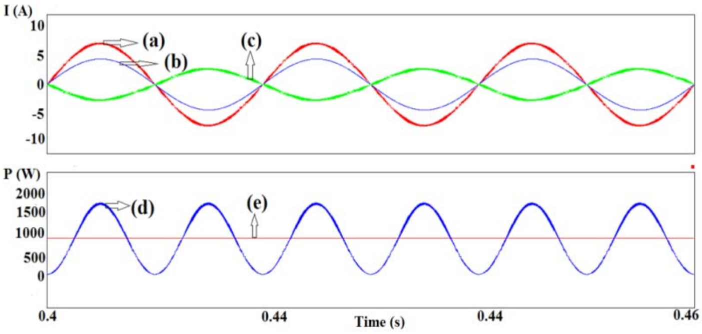

Figure 10. Simulated waveforms under 1000W/m^2 with resistive load 50 Ohm (a) Inverter output current, (b) Load current, (c) Grid current, (d) PV maximum power, (e) Inverter output power

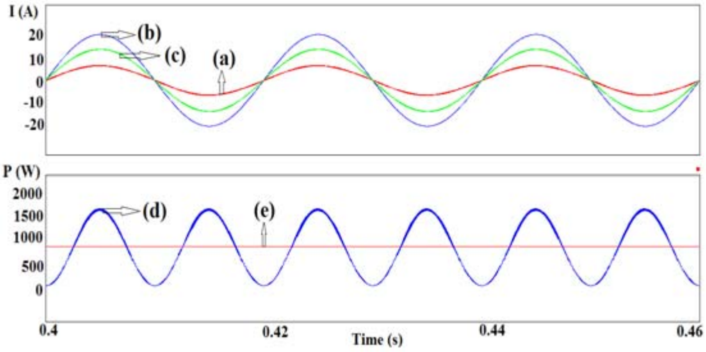

Figure 11. Simulated waveforms under 1000W/m^2 with resistive load 10 Ohm (a) Inverter output current, (b) Load current, (c) Grid current, (d) PV maximum power, (e) Inverter output power

When the solar irradiance was at 1000W/m^2 with resistive load 10 Ohm, the power generated by PV would be fixed. This condition would influence the power delivered by grid source. For the load's power greater than the power produced, the amount of power would be supplied by grid source. For this condition, all of the current would be in phase with respect to the grid voltage, Figure 11.

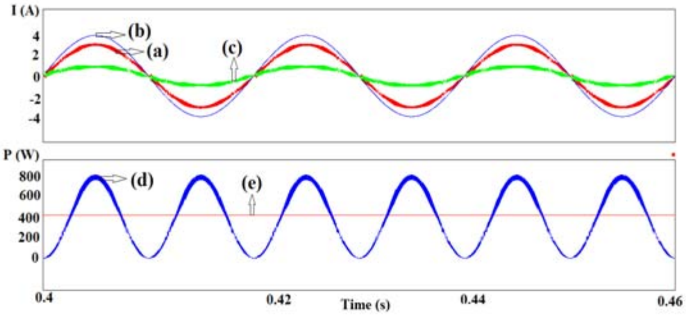

Figure 12. Simulated waveforms under 500W/m^2 with resistive load 50 Ohm (a) Inverter output current, (b) Load current, (c) Grid current, (d) PV maximum power, (e) Inverter output power

When the solar irradiance dropped until 500W/m^2 with resistive load of 50 Ohm, the power generated by PV would be decreased. This condition would influence the power delivered by grid source. For the load's power greater than the power produced, the amount of power would be supplied by grid source. For this condition, all of the current would be in phase with respect to the grid voltage, Figure 12.

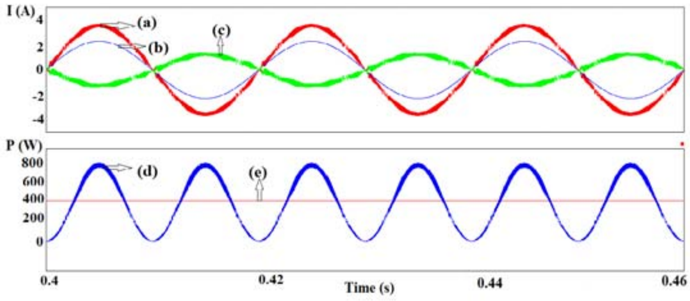

Figure 13. Simulated waveforms under 500W/m^2 with resistive load 100 Ohm (a) Inverter output current, (b) Load current, (c) Grid current, (d) PV maximum power, (e) Inverter output power

When the solar irradiance dropped until 500W/m^2 with resistive load change to 100 Ohm, the power generated by PV would be decreased. This condition would influence the power delivered by the grid source. For the load's power lower than the power produced, the amount of power would be absorbed by grid source. For this condition, the grid current's phase angle was 180^0 with respect to the grid voltage and current load and inverter output current would be in phase all of the current would be in phase with respect to the grid voltage, Figure 13.

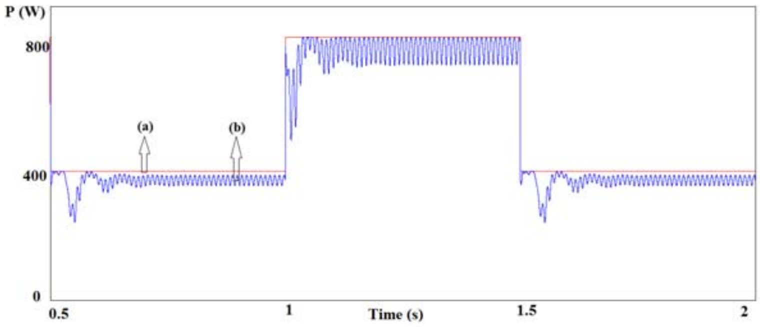

Figure 14. Simulated power waveforms under 500 – 1000 W/m^2 (a) power on nameplate, (b) power output PV

The analysis on the power conversion using voltage detection on capacitor method was shown in Figure 14. The magnitude of the energy conversion efficiency of this method was approximately 93.76%. Five-level inverter used in the simulation could be run well, as many as five levels, Figure 15.

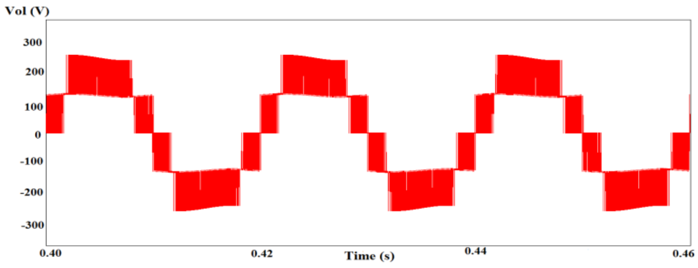

Figure 15. Inverter output voltage

4. Conclusion

Based on the analysis about single-stage PV-Grid system using five-level inverter based on capacitor bank voltage equilibrium control, it is revealed that a capacitor bank voltage control to obtain equilibrium power on PV was very simple. This control scheme for five-level inverter to maximize the power generated by PV and to deliver power to the grid was derived. In this case, the proposed control was good to achieve the required functions. The simulated result shows that under maximum irradiance (1000W/m^2) and when the solar irradiance dropped until 500 W/m^2, maximum power can still be produced. When the maximum power produced by PV, the five-level inverter is still good to transmit all power generated by PV to the grid. In the use of voltage detection on capacitor method in single-stage PV-Grid system had efficiency at approximately 93.76%.

References

[1] Fu Qiang, Tong Nan. A Strategy Research on MPPT Technique in Photovoltaic Power Generation System. *TELKOMNIKA Indonesian Journal of Electrical Engineering*. 2013; 11(12): 7627-7633.

[2] YK Lo, et al. Grid-Connected Photovoltaic System with Power Factor Correction. *IEEE Transactions on Industrial Electronics.* 2008; 55: 2224-2227.

[3] Jia Min Shen, et al. Five-Level Inverter for Renewable Power Generation System. *IEEE Transactions on Energy Convert ion*. 2013; 28(2): 257-266.

[4] Slamet Riyadi. dsPIC33 Based Control for PV-Grid System with a Buck-Boost MPPT. *TELKOMNIKA.* 2014; 12(7): 5137-5143.

[5] Jia Min Shen, et al. Five-Level Inverter for Renewable Power Generation System. *IEEE Transactions on Energy Conversion*. 2013; 28(2): page 257-266.

[6] W Libo, et al. A Single-Stage Three-Phase Grid-Connected Photovoltaic System with Modified MPPT Method and Reactive Power Compensation. *IEEE Transactions on Energy Conversion*. 2007; 22: 881-886.

[7] S Kranthi Kiran, et al. Photovoltaic Grid – connected Inverter Based MPPT Using PI Regulator. *International Journal of Engineering Research and Development.* 2012; 4(1): 68-80.

[8] K Prasada Rao, et al. Development of A Grid Connected Inverter for Solar PV Systems with Energy Capture Improvement Based On Current Control Strategy. *International Journal of Scientific and Research Publications*. 2013; 3(4):1-6.

[9] B Nagaraju. A Fuzzy Logic MPPT Three-Phase Grid-Connected Inverter for Photovoltaic Applications. *International Journal of Engineering Research and Applications (IJERA)*. 2012; 2(1): 104-107.

[10] Chih-Lung Shen, Jye-Chau Su. Grid-Connection Single-Stage Photovoltaic Inverter System with Double-Linear-Approximation MPPT. *Applied Mathematics & Information Sciences An International Journal.* 2015; 9(1): 205-211.

[11] Lin FENG, et al. Hardware-in-the-loop Simulation Platform of Photovoltaic Grid-Connected System. *TELKOMNIKA Indonesian Journal of Electrical Engineering*. 2014; 12(4): 2465-2473.

[12] WANG Yu-xin, ZHANG Feng-ge, LI Lin-lin. Research on Single-Variable Current Perturbation Tracking Method for Maximal Power Tracking Control Method of the Solar Power Generation System. *TELKOMNIKA Indonesian Journal of Electrical Engineering*. 2014; 12(2): 899-904.

[13] MM Marimuthu. Optimized Control in Grid Connected Photovoltaic System based on Single-Stage Voltage Source Inverter. *International Journal of Advance Research in Computer Science and Management Studies*. 2014; 2(3):136-142.

[14] Slamet Riyadi. Single-Phase Single-Statge PV-Grid System using VSI Based on Simple Control Circuit. *International Journal of Power Electronics and Drive Systems (IJPEDS).* 2013; 3(1): 9-16.

[15] Wen-Jung Chiang, et al. *Maximum Power Point Tracking Method for the Voltage-Mode Grid-Connected Inverter of Photovoltaic Generation System*. International Conference on Substancial Enviromental Technologies. Singapore. 2008: 1-6.

[16] Leonardus Heru Pratomo, et al. A Simple Strategy of Controlling a Balanced Voltage Capacitor in Single Phase Five-Level Inverter. *International Journal of Power Electronics and Drive Systems (IJPEDS).* 2015; 6(1): 160-167.