International Journal of Power Electronics and Drive System (IJPEDS)
Vol. 6, No. 3, September 2015, pp. 449~458
ISSN: 2088-8694

A Single-Phase Dual-Stage PV-Grid System with Active Filtering

Slamet Riyadi*, Yanuarsyah Haroen**
* Department of Electrical Engineering, Soegijapranata Catholic University, Semarang, Indonesia
** School of Electrical Engineering and Informatics, Bandung Institute of Technology, Bandung, Indonesia

Article Info

Article history:

Received Apr 15, 2015
Revised Jul 28, 2015
Accepted Aug 10, 2015

Keyword:

Active filtering
Inverter
Maximum power point tracker
PV-grid system
Shunt active power filter

ABSTRACT

Integrating photovoltaic based electricity into the grid and power quality improvement have become two major issues in electrical system. Formerly, these can be solved by using two converter systems separately, a PV-Grid System and an active power filter. But recent technology uses only a converter system to do both function. An existed shunt active power filter (SAPF) can be modified to form a dual-stage PV-Grid with active filtering capability. In this paper, a PV-Grid System that is capable to transfer all power generated by PV modules and reduce harmonic contents is proposed. The system was formed by connecting a boost chopper as a Maximum Power Point Tracker and PV modules to the DC-link capacitor of a single-phase SAPF. It just needed a current transducer and also required simpler control circuits. A voltage controller was needed to achieve power equilibrium while a current controller was needed to make the grid current sinusoidal with unity power factor. To verify the analysis, simulations and experiments were done.

Corresponding Author:

Slamet Riyadi,
Department of Electrical Engineering,
Soegijapranata Catholic University,
Pawiyatan Luhur IV-1 Bendan Duwur Semarang 50234, Indonesia
Email: s_riyadi672003@yahoo.com

1. INTRODUCTION

Photovoltaic (PV) is becoming an alternative solution to overcome the fossil based energy crisis. Unlimited supports of solar energy on earth makes PV is more interested. Some PV based power plants have been built in some countries. Due to the PV characteristic [1], a maximum power point tracker (MPPT) is required to maximize the power generated. Many MPPT methods have been developed to improve the performance of PV systems [2]-[4]. Integrating PV panels and grids offer some advantages. Some of them use dual-stage converter system and the others only require single-stage converter [5]-[7]. Some PV-Grid Systems are aimed to transmit all power generated by PV modules into the grid, they are also functioned as active filtering.

Recently, nonlinear loads are widely used in residential, office building and industry applications. They include static converters, computers, fluorescent lamps, etc and cause non-sinusoidal currents due to the harmonic contents in the system. They result in power quality degradation and contribute serious problems in the system. Active power filtering is capable to mitigate the harmonic contents by injecting currents/voltage to the system [8]-[10]. In the conventional systems, PV-Grid Systems and active power filters are used separately so the systems are more expansive. By developing the control schemes of PV-Grid Systems, active filtering function can also be done. A dual-stage PV system using zero-voltage switching half-bridge converter was operated to transfer real power with active filtering so the topology is more complex [11]. Another dual-stage PV system with active filtering for three-phase system was designed by using parallel four-leg inverter, an LCL filter was also inserted into the output of the inverter. The dq0-coordinates based control circuit is used so it had more complexity [12]. A single-phase PV-Grid system with standard topology inverter was developed by using utility-current command calculation based control, it consisted of more number of calculations [13].

In this paper, a single-phase dual-stage PV-Grid system with active filtering capability is proposed. It was constructed from the existed SAPF by connecting an MPPT to the capacitor dc-link. It required a current transducer in the inverter stage and used simple control circuits. The Voltage Source Inverter (VSI) was operated as a controlled current source with no synchronization was needed.

2. RESEARCH METHOD

One of main problems appears in power system is power quality degradation caused by harmonic contents. A shunt active power filtering (SAPF) has become an effective solution to mitigate harmonics. The core of a SAPF is an inverter with a capacitor connected to its dc-link. The absence of DC source at its dc-link, so the SAPF is only capable to inject harmonic and reactive power.

PV-Grid Systems are commonly used to transfer power generated by PV modules into the grid. They deliver real power power to the grid under linear loads; this is represented by sinusoidal current with unity power factor (Figure 1a). The different situation will arise under nonlinear loads, the grid distorted current will flow (Figure 1b). Recently the function of a PV-Grid System can be expanded to do active filtering.

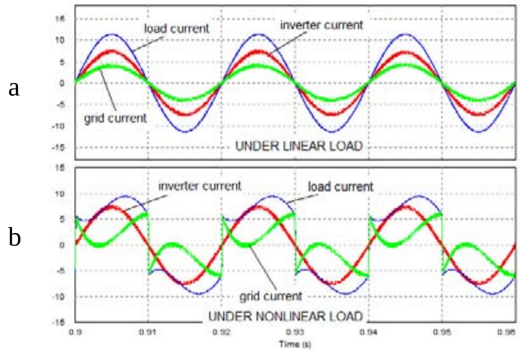

Figure 1. Currents of the PV-Grid System under linear loads and nonlinear loads

A PV module is capable to convert solar energy into electric energy in the form of DC voltage/current. Due to its characteristic curve, the operating point must be at its maximum power point or MPP (Figure 2). Direct connection of a PV module to loads results in the location of its operating point depending on the load resistance. By using an MPPT, the load resistance seen from the PV side will be a variable value. If it equals to the PV resistance under its MPP (R_{MPP}), the maximum power will be generated (Figure 3).

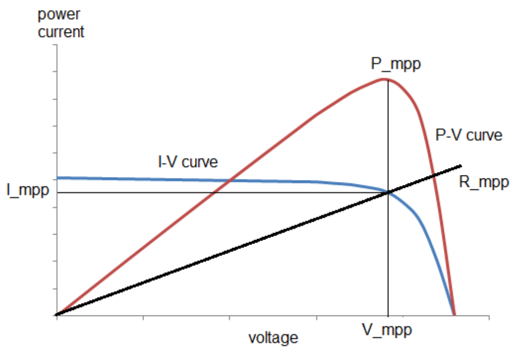

Figure 2. Photovoltaic characteristic curve

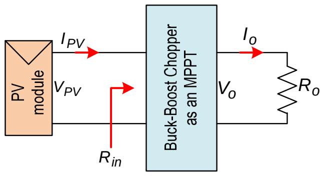

Figure 3. Connection of a PV module and loads via an MPPT

PV-Grid Systems integrate the electric energy generated by PV modules and a grid. For a dual-stages PV-Grid System, the first stage converter is operated as an MPPT to force PV modules generated maximum power and the second one is an inverter as an interface to the grid. But for a single-stage PV-Grid System, the converter is an inverter with dual functions (Figure 4). An inverter takes significant role in PV-Grid Systems. It must be capable to transmit all power generated and synchronize to the grid voltage.

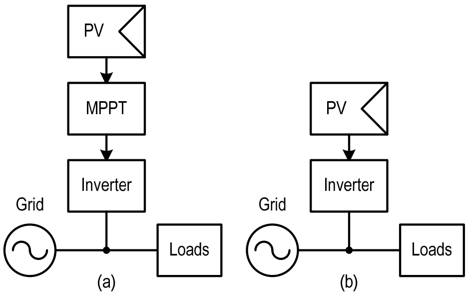

Figure 4. Block diagram of PV-Grid Systems (a) with dual converters (b) with single converter

The PV-Grid System consisting of a boost chopper and an inverter is proposed. The system is constructed by connecting PV-MPPT to the dc-link capacitor of the existed SAPF (Figure 5). It can transfer the maximum power generated by PV modules and is also capable to do active filtering. The inverter is implemented by a VSI and operated as a controlled current source (CCS) so the complexity related to the synchronization can be reduce. The CCS output voltage is automatically locked to the grid voltage. To control the MPPT, voltage and current detections on PV are required. Based on these detections, duty cycle *d* of the boost chopper as the MPPT is controlled. Then the input current of the MPPT will change closer to the PV current at its MPP (I_{MPP}). The flow diagram of the proposed control is depicted in Figure 6.

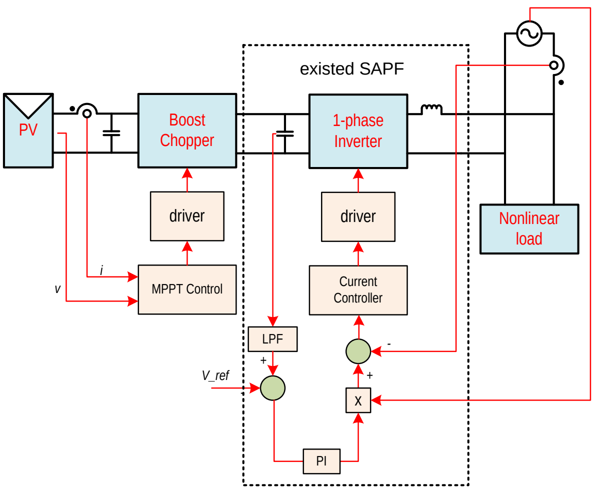

Figure 5. The proposed PV-Grid System

The single-phase inverter acts as an interface between the MPPT and the grid therefore the output voltage will be locked to the grid voltage. All power flowing from the MPPT must be transmitted into the grid hence the inverter requires power flow detection. By sensing the DC-link voltage v_{cap}, the power equilibrium can be known. The voltage controller is needed to keep the DC-link voltage constant that represents no average power absorbed/released by the inverter. To reduce the harmonic contents caused by nonlinear loads, the grid current must be sinusoidal with unity power factor. This can be achieved by a current controller.

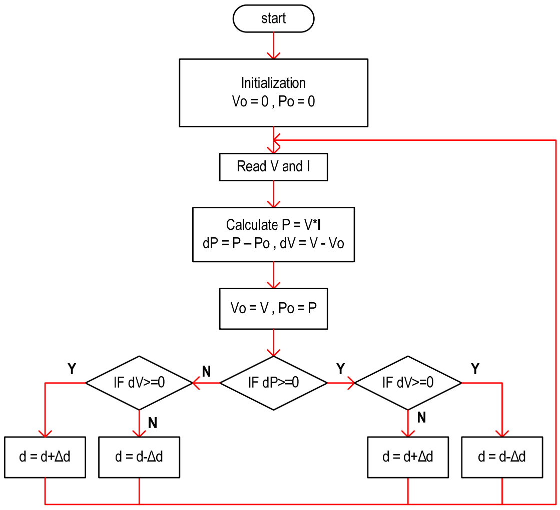

Figure 6. Flow diagram of the MPPT control

A current template i_{temp} taken from the grid voltage is required, then its value is modulated by the output signal of a voltage controller, it is named as the reference source current $i_{S\text{-}ref}$. When V_{ref} is the reference voltage of the DC-link of the inverter (this must be greater than the peak value of the grid voltage), the error signal of the voltage controller e_v can be obtained by

$$e_v = V_{ref} - v_{cap} \tag{1}$$

If the modulated factor is k then by using the Proportional-Integral controller we have

$$k(s) = \left(K_p + \frac{K_i}{s} \right) e_v(s) \tag{2}$$

Where K_p and K_i are the proportional and integral constants, the source or grid current reference can be calculated as

$$i_{S-ref} = k.i_{temp} \tag{3}$$

The current controller requires two input, $i_{S\text{-}ref}$ and the actual grid current i_S. If the controller runs well, then

$$i_S \cong i_{S-ref} \tag{4}$$

Based on the above analysis, the power flow is derived. The instantaneous value of the output power of the MPPT can be determined by multiplying the instantaneous values of the capacitor voltage v_{cap} and the MPPT output current i_{MPPT} . If the MPPT is assumed ideal so the average value of the MPPT output power P_{MPPT} equals to the maximum power generated by PV modules

$$p_{MPPT} = v_{cap}\, i_{MPPT}$$

$$P_{MPPT} = \int p_{MPPT}.dt = V_{MPP} I_{MPP} \quad (5)$$

Power equilibrium can be analyzed by using the relationship among the instantaneous power of the DC-link capacitor p_{cap}, the MPPT p_{MPPT} and the inverter p_{inv} as the following

$$p_{cap} = p_{MPPT} - p_{inv} \quad (6)$$

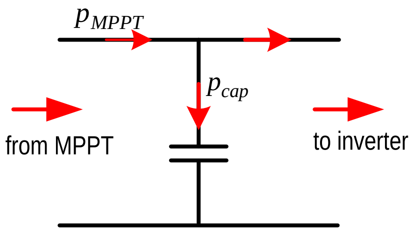

Figure 7. Power flow in the DC-link capacitor

For the instant time, when p_{MPPT} is greater than p_{inv} then the capacitor voltage (DC-link voltage) will increase while the vice versa condition will cause the capacitor voltage decreases. The voltage controller must be capable to keep this voltage nearly constant so the average power of the capacitor P_{cap} will be null.

$$P_{cap} = \int p_{cap} dt \cong 0 \quad (7)$$

The average value of inverter output power P_{inv} is

$$P_{inv} = \int p_{inv} dt \cong P_{MPPT} \quad (8)$$

Equation (8) indicates that the inverter output current is sinusoidal and in phase with respect to the grid voltage. If V_S is the RMS value of the grid voltage, its instantaneous value is stated as

$$v_S = \sqrt{2} V_S \sin(\omega t + \varphi) \quad (9)$$

then

$$P_{inv} = V_S I_{inv-p} \cos(0) \text{ and } I_{inv-p} = \frac{P_{inv}}{V_S} \cong \frac{P_{MPPT}}{V_S}$$

$$i_{inv-p} = \sqrt{2} I_{inv-p} \sin(\omega t + \varphi) \quad (10)$$

Where i_{inv-p} is the inverter output current that contributes to the real power and I_{inv-p} is the RMS value of the inverter output current.

If the nonlinear loads are connected to the grid, the load current i_L will consist of fundamental i_{Lf} and harmonic components i_{Lh}. The fundamental component contains the active current i_{Lfp} and reactive current i_{Lfq}.

$$i_L = i_{Lf} + i_{Lh} = (i_{Lfp} + i_{Lfq}) + i_{Lh} \quad (11)$$

$$i_{Lfp} = \sqrt{2} I_{Lf} \cos(\varphi - \theta) \sin(\omega t + \varphi) \quad (12)$$

$$i_{Lfq} = \sqrt{2} I_{Lf} \sin(\varphi - \theta) \sin\left(\omega t + \varphi - \frac{\pi}{2}\right) \quad (13)$$

$$i_{Lh} = \sum_{h=2}^{\sim} \sqrt{2} I_{Lh} \, sin(\varphi - \theta_h) \quad (14)$$

When the grid voltage is assumed ideal as stated in (9), then the real power absorbed by the nonlinear load can be calculated as

$$P_L = V_S I_{Lf} \, cos(\varphi - \theta) \quad (15)$$

The reactive and harmonic power at the load side are

$$Q_L \cong V_S I_{Lf} \, sin(\varphi - \theta) \quad (16)$$

$$D_L \cong V_S \sqrt{\sum_{h=2}^{\sim} I_{Lh}^2} \quad (17)$$

where I_{Lf} is the RMS value of fundamental load current.

Apparent power will consist of real power P, reactive power Q and harmonic power D. Under an ideal grid voltage, P and Q are related to the sinusoidal current that in phase (i_{Lfp}) and 90 degree displaced (i_{Lfq}) with respect to the grid voltage while D is related to the harmonic current (i_{Lh}). When the PV-Grid System is functioned as active filtering, the grid current only consists of active current.

$$i_S = i_{Lfp} \quad (18)$$

Then current components of i_{Lfq} and i_{Lh} are supplied by the inverter.

$$i_{inv} = i_{inv-p} + i_{Lfq} + i_{Lh} \quad (19)$$

It must be noted that i_{Lfq} and i_{Lh} contribute no real power so the equation (8) is still valid.

3. RESULTS AND DISCUSSION

To support the above analysis, simulation works were developed. The first simulations were done to prove the capability of the MPPT control method as shown in Figure 6. This works were based on the PV module equivalent circuit depicted in Figure 8 [13]. The voltage E, R_{LIM} and R_E are voltage corresponds to the solar irradiance, series resistance that limits the output current and resistance for open-circuit condition, while R_{B1} and R_p are the resistance that control the BJT_1 and parallel resistance.

The simulation results under different irradiance level is shown in Figure 9, the voltage of the PV module will decrease significantly under lower irradiance level while the PV current is slightly different. The operating points of the MPPT under two different irradiance level are depicted in Figure 10, where the two operating points are near the knee of the I-V characteristic curve. Under time based curve, the power generated (by multiplying I_{PV} and V_{PV}) will fluctuates near the maximum power (80 Wp). Based on the simulation works, the MPPT efficiency is 94%.

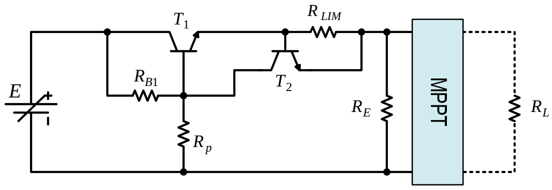

Figure 8. Equivalent circuit of a PV module [13]

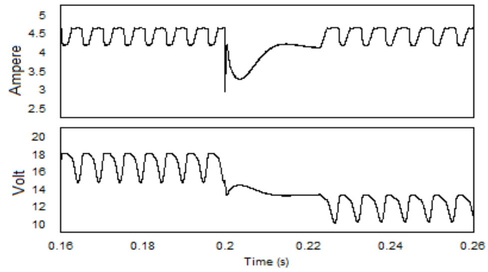

Figure 9. Simulation results for the PV module under irradiance level variation from G =1000 W/m^2 to G =800 W/m^2 (a) current (b) voltage

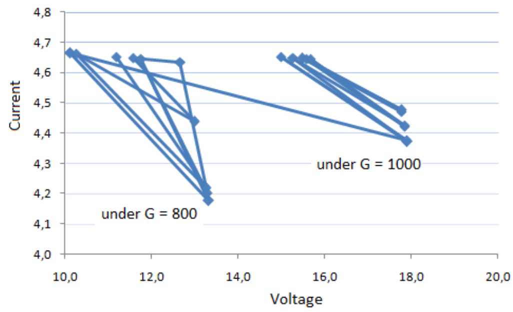

Figure 10. The operating point of the MPPT under different irradiance level (from G =1000 W/m^2 to G =800 W/m^2)

The second works of simulation are based on Figure 5. Six PV modules were series connected and then a diode rectifier with highly inductive load is used as the nonlinear load for the grid. The parameters used is represented in Table 1.

Table 1. Parameters for simulation works

Photovoltaic	6 pcs 80Wp PV modules (series) V_{MPP} = 17.3 V, I_{MPP} = 4.6 A
DC-link Voltage	120 V
Grid Voltage	80 V(peak)

The current waveforms under condition when the load power (p_L) is greater than the power generated by the PV modules (P_{PV}) is depicted in Figure 11. The non-sinusoidal load current indicates that it contains harmonic components. The grid current is sinusoidal and in phase with respect to the grid voltage. This means that the grid delivers real power to the load without harmonic contents. Parts of the load power is supplied by the inverter. The average value of the inverter output power equals to the power generated by the PV modules (Figure 12). While for p_L is less than P_{PV}, part of P_{PV} will flow into the grid so the grid current is sinusoidal with opposite polarity with respect to the grid voltage (Figure 13).

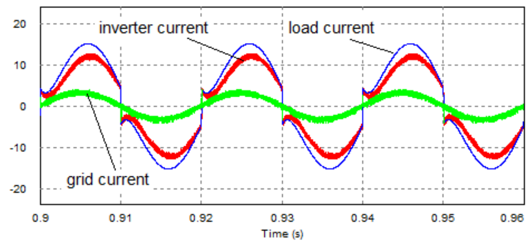

Figure 11. Simulation results when the load power is greater than the PV power

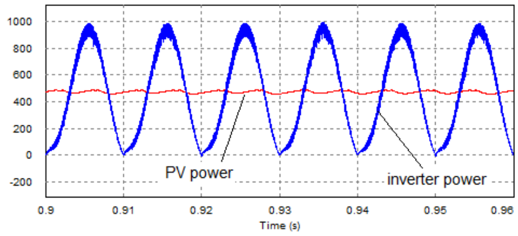

Figure 12. Simulation results of the power comparison

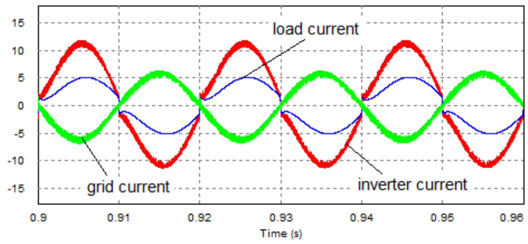

Figure 13. Simulation results when the load power is less than the PV power

Finally, to verify the simulation results, the experimental works were done based on the prototype depicted in Figure 14 and parameters shown in Table 2. The works depict the comparison of the load current, inverter current and grid current, they also show the phase displacement between the grid voltage and current (Figure 15 and Figure 16). The inverter currents injected into the grid are non-sinusoidal because parts of the currents represent real power transmitted and the other for harmonic compensation. The different phase of the grid currents means that the grid delivers power (Figure 15) and absorbs power (Figure 16). When the nonlinear load is implemented by a diode rectifier with inductive load, there is no reactive power Q. the load power just consists of P and D.

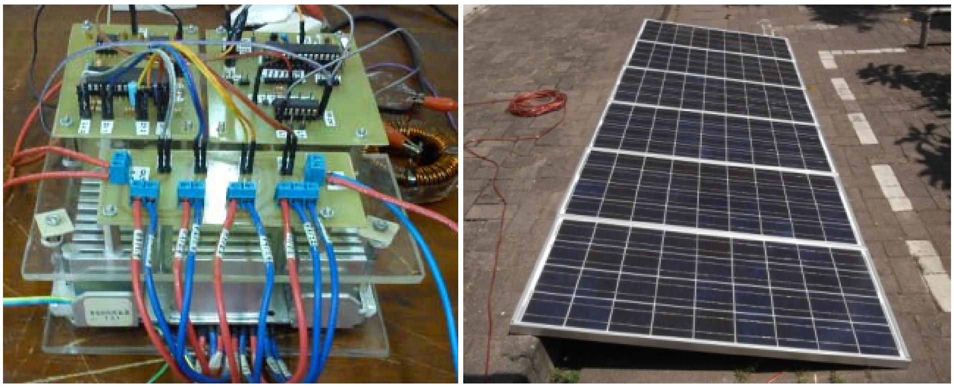

Figure 14. The prototype used for experimental works

Table 2. Parameters for experimental works

Photovoltaic	6 pcs 80Wp PV modules (series)
	V_{MPP} = 17.3 V, I_{MPP} = 4.6 A (datasheet)
DC-link Voltage	120 V
Grid Voltage	70 V(rms)

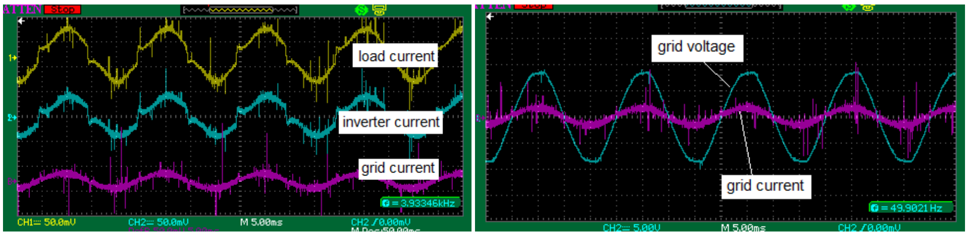

Figure 15. Experimental results when the load power is greater than the PV power [7A/div- 50V/div – 5ms/div]

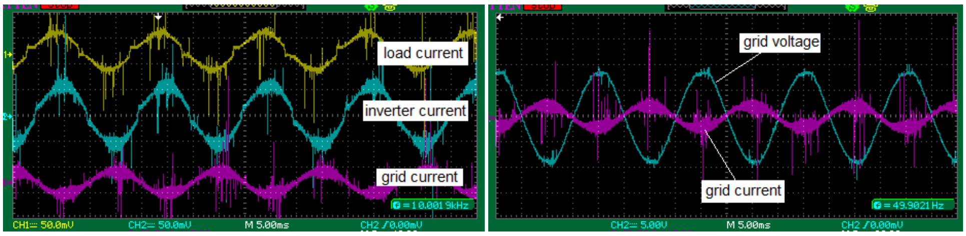

Figure 16. Experimental results when the load power is less than the PV power [7A/div- 50V/div – 5ms/div]

4. CONCLUSION

A single-phase dual-stage PV-Grid System that is capable to transfer power and to do active filtering has been analyzed, simulated and implemented. With the simple control schemes used in MPPT and inverter stages, the system can deliver all the maximum power generated by the PV modules and make grid current sinusoidal with unity power factor under nonlinear loads. Detecting the grid current can reduce the amount of current transducer required by the inverter. The system can also be constructed from the existed SAPF by connecting an MPPT to the capacitor dc-link of the SAPF.

ACKNOWLEDGEMENTS

This work was supported by The Directorate General of Higher Education, The Ministry of National Education, Republic of Indonesia

REFERENCES

[1] E. Koutroulis, *et al.*, "Development of a Microcontroller-Based Photovoltaic Maximum Power Point Tracking Control System", *IEEE Trans. on Power Electronics*, Vol. 16, No. 1, pp. 46-54, Jan. 2001.
[2] B. Alsayid and J. Jallad, "Modeling and Simulation of Photovoltaic Cells/Modules/Arrays", *International Journal of Research and Reviews in Computer Science (IJRRCS)*, Vol. 2, No. 6, pp 1327-1331, Dec. 2011
[3] C Liu, *et al.*, "Advanced Algorithm for MPPT Control of Photovoltaic Systems," *in Proceedings of Canadian Solar Buildings Conference*, Montreal, Canada, August. 2004.
[4] M A G de Brito, *et al.*, "Evaluation of the Main MPPT Techniques for Photovoltaic Applications", *IEEE Trans.on Industrial Electronics*, Vol. 60, No. 3, pp. 1156-1167, March. 2013.
[5] S Jain and V. Agarwal, "A Single-Stage Grid Connected Inverter Topology for Solar PV Systems with Maximum Power Point Tracking", *IEEE Trans.on Power Electronics*, Vol. 22, No. 5, pp. 1928-1940, Sept. 2007.
[6] R. Gonzales, *et al.*, "Transformerless Inverter for Single-Phase Photovoltaic Systems", *IEEE Trans.on Power Electronics*, Vol. 22, No. 2, pp. 693-697, March. 2007.
[7] S. B, Kjaer, *et al.*, "Review of Single-Phase Grid-Connected Inverters for Photovoltaic Modules", *IEEE Trans.on Industry Applications*, Vol. 41, No. 5, pp. 1292-1306, Sept/Oct. 2005.
[8] H. Akagi, "Trends in Active Power Line Conditioners", *IEEE Trans.on Power Electronics*, Vol. 9, No. 3, pp. 263-268, May. 1994.
[9] S. Kim and P. N. Enjeti, "A New Hybrid Active Power Filter (APF) Topology", *IEEE Trans.on Power Electronics*, Vol. 17, No. 1, pp. 48-54, Jan. 2002.
[10] S Riyadi, *et al.*, "Functioning a Shunt APF as a Power or Current Compensator", *European Journal of Electrical Engineering*, Vol. 12, No. 1, pp. 57-76, 2009.
[11] D. C. Martins and K. C. A. de Souza, "A Single-Phase Grid-Connected PV System With Active Power Filter", *International Journal of Circuits, Systems and Signal Processing*, Vol. 2, No. 1, pp. 50-55, 2008.

[12] X. Wang, *et al.*, "Modeling and Control of Dual-Stage High-Power Multifunctional PV System in *d–q–o* Coordinate", *IEEE Trans.on Industrial Electronics,* Vol. 60, No. 4, pp. 1556-1570, April. 2013.
[13] T. F. Wu, *et al.*, "A Single-Phase Inverter System for PV Power Injection and Active Power Filtering with Nonlinear Inductor Consideration", *IEEE Trans.on Industry Application,* Vol. 41, No. 4, pp. 1075-1083, Jul/August. 2005.

BIBLIOGRAPHIES OF AUTHORS

Slamet Riyadi was born in Semarang-Indonesia, in 1967. He received B.S. degree from Diponegoro University, Semarang in 1991 and M.Eng. degree from Bandung Institute of Technology, Bandung-Indonesia in 1997. In 2006, he received Ph.D degree in Electrical Engineering from Bandung Institute of Technology with Partial Research done in ENSEEIHT-INPT Toulouse, France. Currently, he is with the Departement of Electrical Engineering, Soegijapranata Catholic University, Semarang-Indonesia as a lecturer and researcher. His current research is focused on power factor correction techniques, active power filtering and PV-Grid Systems. Some of his researches were supported by, ASEM duo-France, The Ministry of Research and Technology- Indonesia, The Directorate Generale of Higher Education-Ministry of National Education-Indonesia, etc. He is also an IEEE member.

Yanuarsyah Haroen received B.S. degree from Bandung Institute of Technology – Bandung Indonesia in 1976, Dipl. Ing. From ENSEEIHT, Toulouse-France in 1980, DEA and Ph.D degree from INPT, Toulouse-France in 1981 and 1983. He is currently a Professor in electrical engineering departement, Bandung Institute of Technology. His research interests are power electronics and drives. He is also an IEEE senior member.