Development of A Hybrid Method to Control the Grid-Connected PV Converter

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***Abstract*—Grid-connected photovoltaic (PV) systems are considered as the best options for home solar electric system applications. Compared to other alternatives, grid-connected PV systems offer the least expensive and lowest-maintenance choice for residential usage. The PV systems are constructed using some solar cells to extract the energy from sun radiations and power converters to convert the output DC voltage into AC one. In the present study a hybrid scheme is suggested to control the grid-connected PV converters. The developed scheme is able to inject the power created by solar arrays into the network. Also, it can rectify the problems associated with the reactive power and load harmonics in the system. Moreover, the suggested technique can secure the load active and reactive power during the network failure conditions. One of the contributions of the proposed method is that it can manage the power of solar arrays to supply the load, filter the harmonics and compensate the reactive power in a situation where the power produced by solar arrays is less than the power of converters. In this condition, the proposed technique can make the current drawn from the grid completely sine at unity power factor.**

***Index Terms*—Photovoltaic, Instantaneous Reactive Power Theory, PV Converter, Load Harmonics, Reactive Power**

I. INTRODUCTION

A. Motivation and Literature Review

Solar photovoltaic (PV) technology is a renewable and clean source of energy production with low influence on the environment [1]. Generally, the reasons why PVs have attracted a lot of attentions of researchers can be summarized as follows [2]:

1) PV processes are totally solid state and independent.
2) There are no moving parts and no materials devoured or discharged.
3) They can be joined with other power sources to build framework dependability.
4) They can be upgradeable to higher demand of energy quickly and easily.

PV systems can be utilized in different modes, among which the grid-connected mode is a more attractive option [3]. Fig. 1 shows the general structure of such systems. As shown in this figure, if the PV system is absent, it is evident that the total load active and reactive power (ARP) consumption will be provided by the grid. Moreover, in the situation that PV only produce the active power for the network, the active power absorbed from the main grid will be decreased while the reactive power experience no fluctuations. In this condition, power factor of the grid will decrease which is not desirable [4]. To deal with this problem, different control methods have been proposed in last recent years [5]. These methods can be separated into two vital categories as follows:

- Maximum power point (MPP) controller [6]–[8]. In these methods the main goal is to extract the MPP out of the PV system.
- Converter controller [9], [10]. In these techniques, generated ARP by the grid are controlled to guarantee the high quality of the injected power and grid synchronization.

Hereby in the present study, the second controller is discussed. In the control methods of this category, the control scheme utilized in the PV generates maximum output power. In this situation, PV can be operated as a reactive power compensator [11]. Commonly, the method should be able to activate the PV to produce the reactive power. If the PV system produces the exact required load reactive power, the grid power

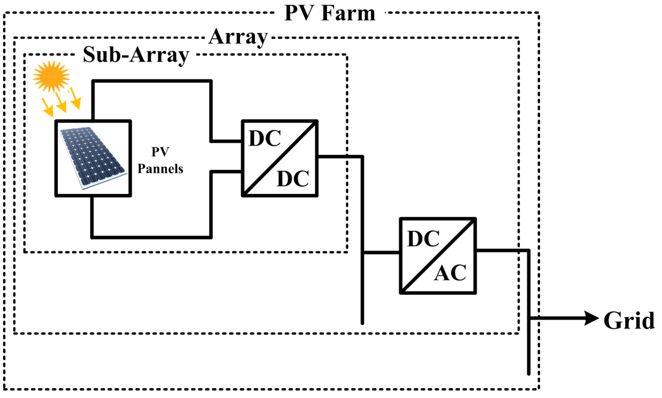

Fig. 1. General structure of PV systems

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factor will remain identical [12].

For instance, a nonlinear control based approach is proposed in [13] to control the PV converter. In this approach, the error estimation parameters are selected form instantaneous ARPs. Generally, the drawbacks of this technique can be related to high calculation complexity and dead-time effects. In [14], a PI-based controller is developed to control the PV system under disturbances. Although this method is simple and easy to implement practically, its performance is not robust in different possible conditions. The proportional-resonant based controller has been developed in [15]. This controller has the ability to suppress the selected harmonics. Model predictive control is the basis of the method presented in [16]. In this paper, the method optimized the switching signal using a proper cost function which is based on lowering the total harmonic distortion. A robust current control based on uncertainty and disturbance estimator is presented in [17]. This reference stated that the method is effective in loweing the resonance damping and following the performance in grid disturbances. The ref. [18] proposed a sliding mode control based technique for the grid-connected PV system. The method is capable to support the dc-link voltage fluctuations and ARP during grid fault. In the technique suggested in [19], a cascaded loops based controller is utilized to manage the ARP utilizing the voltage and currents of the network as well as the DC link. In [20], a novel control method based on feedback linearizing is developed using the sequences of the grid voltages.

B. Aim and Contribution

In the present study, a novel hybrid control scheme for the grid-connected PV system is developed. In this technique, the power produced by solar arrays is injected into the grid by the PV system. In addition, the problem of reactive power as well as load harmonics are rectified by the proposed method. The load harmonics compensation through this control method leads to a completely sine grid current and prevention of entry of load harmonics into the grid. In this control method, if the produced power by solar arrays is less than the power of inverters, the remaining capacity can be utilized to eliminate the shortcomings regarding the reactive power as well as the load harmonics. Another characteristic of the developed method is that if the main grid fails, the PV system could supply the required load power. In this case, the system will work as uninterruptible power supply (UPS).

C. Paper Organization

The rest of the paper is organized as follow. In Section II, a detailed explanation of the functional principles of grid-connected PV systems is given. Section III presents the proposed control strategy and mathematical formulas. Section IV describes the different simulations and shows the results. Finally, conclusions are presented in Section VI.

II. FUNCTIONAL PRINCIPLES OF THE UTILIZED GRID-CONNECTED PV SYSTEM

Compare with stand-alone systems, grid-connected PV systems contribute to higher than 99% of the PV installed capacity. Fig. 2 represents a grid-connected PV system schematic in more details. In this system, the solar arrays are connected to the grid through a voltage source inverter (VSI). To connect VSI to grid, a series inductance is utilized which enables the control of inverter output power. Considering the fact that the solar arrays generally behave as a current source [16], a dc capacitor will be used at the inverter's input. From the grid's viewpoint and based on the control method, VSI might be regarded as an AC source, load resistor, inductor and capacitors, all with identical apparent power. In normal conditions, the PV system injects the power produced by solar arrays into the grid and generates load currents harmonics along with load reactive power consumption. In this situation, the current drawn from or injected into the grid is completely sine and of similar phase with voltage (i.e. grid power factor is almost equal to 1). The employed topology in this paper is a VSI-based PV system, in which the input voltage of the inverter is almost constant, utilizing proper controllers. One of the appropriate methods for controlling VSIs is to control their output current flow. In this paper, this type of control is deliberated. Application of current-control based method for grid-connected PV systems is more suitable than other types because of the following reasons:

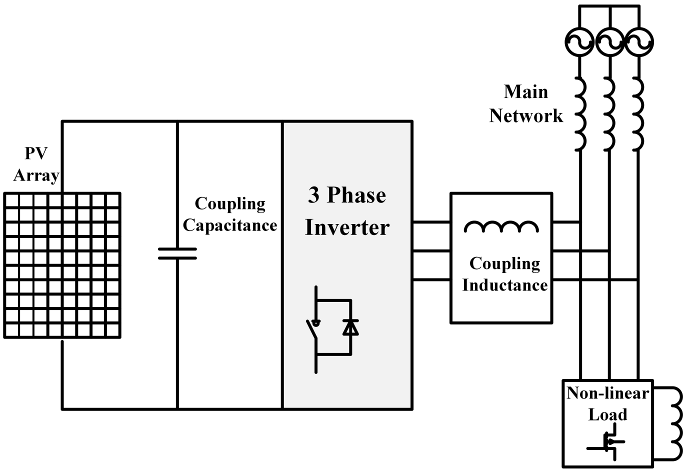


Fig. 2. The structure of grid-connected PV systems

1) The power shared between VSI and the grid can be relegated to control the current which is passing through VSI to grid and vice-versa, considering the fact that the grid is an almost a constant voltage source.
2) Even a small error in the output phase voltage of the inverter can lead to an excessive current passing through the system if the voltage control method is implemented to connect the PV system to the grid, while the systems based on current control methods do not face such problems.

In the present paper, hysteresis method is used for inverter current control [12]. In the proposed method, the PV system controller determines the reference current of inverter based on three parameters of the produced power of solar array, harmonic currents, and load reactive power and then, delivers it to hysteresis controller. The hysteresis controller issues the inverter switching command in a way that the inverter's output current is equal with the reference current. The functioning of grid-connected PV systems is directly dependent upon selected control strategy for VSI. In general, the control strategy of these systems should have the following capabilities:

1) Waveform generation of reference current for three phases
2) Stabilization of the input dc capacitor voltage

III. PROPOSED CONTROL METHOD

In this paper, the instantaneous reactive power (IRP) theory introduced by Agaki for controlling active filters is employed for determining reference currents of inverter [15-18]. In this theory, reference currents are calculated in the way that in the circumstances of being produced by inverter, the produced power by solar arrays is entered to the grid and the inverter compensates the harmonic of load currents and remove the reactive power problems. The IRP theory is based on transferring voltage and current variables into $\alpha\beta$ coordinates. The instantaneous values of voltage and current variables in $\alpha\beta$ coordinates can be calculated through equation (1):

$$\begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} = \begin{bmatrix} A \end{bmatrix} \times \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix}, \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = [A] \times \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \quad (1)$$

In the above expression, [A] is the transfer matrix which is as follows:

$$[A] = \sqrt{\frac{2}{3}} \times \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \quad (2)$$

The above transform functions are correct if $\mathrm{v_a}+\mathrm{v_b}+\mathrm{v_c} = 0$ and $\mathrm{v_a}$, $\mathrm{v_b}$ and $\mathrm{v_c}$ are sine and balanced. In this situation, the instantaneous ARP in $\alpha\beta$ coordinates are as follows:

$$\begin{aligned} p(t) &= v_\alpha(t)i_\alpha(t) + v_\beta(t)i_\beta(t) \\ q(t) &= -v_\alpha(t)i_\beta(t) + v_\beta(t)i_\alpha(t) \end{aligned} \quad (3)$$

Considering equation (3), i_α and i_β can be written based on the instantaneous powers as shown in the following equation:

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \frac{1}{v_\alpha^2 + v_\beta^2} \begin{bmatrix} v_\alpha & v_\beta \\ v_\beta & -v_\alpha \end{bmatrix} \begin{bmatrix} p \\ q \end{bmatrix} \quad (4)$$

In equations (3) and (4), p and $-q$ values can be considered as the sum of their dc and ac elements.

$$\begin{aligned} p &= \bar{p} + \tilde{p} \\ q &= \bar{q} + \tilde{q} \end{aligned} \quad (5)$$

In equation (5), $\bar{p}$ and $\tilde{p}$ represent the dc and the ac element of the instantaneous power p, respectively. Also, $\bar{p}$ is related to the main element of active current and $\tilde{p}$ is related to the type of harmonic currents produced by the active part of p. Simultaneously, $\bar{q}$ refers to the dc element of p which is related to reactive power produced by main elements of voltage and current, and $\tilde{q}$ is the ac element of p which is related to the type of harmonic currents that are produced by reactive part of the instantaneous power. In order to enable the PV system to produce reactive power as well as harmonic currents produced by non-linear loads, its reference current should include $\tilde{p}$, $\bar{q}$ and $\tilde{q}$ values. The advantage of applying the above theory is regarding the fact that the ARP corresponding to the main elements of current and voltage are dc and can be eliminated if it is necessary.

In grid-connected PV systems, the VSI control method have the following goals: 1) Eliminating the reactive power problems), 2) Filtering the load harmonics), 3) Injecting the power into the grid.

$$\int_{-\infty}^{t} \left(V_c i_{PV} - P_{active}\right) d\lambda = \frac{1}{2} C V_c^2 \quad (6)$$

In equation (6), $\mathrm{V_c}$ is the instantaneous voltage of the input capacitor of the inverter, $\mathrm{i_{PV}}$ is the instantaneous current taken from solar arrays and P_{active} is the instantaneous power injected to grid by the inverter. If the power produced by solar arrays is not injected into the grid, considering the fact that solar arrays act as a current supply, the capacitor voltage will increase linearly. The controller should monitor the active power injected to the grid in a way that the voltage of capacitor remains constant. Therefore, the equation for evaluating active power injected from solar cells into the grid can be written in the following equation:

$$P_{active} = K_p \left(V_c^* - V_c\right) + K_I \int \left(V_c^* - V\right) dt \quad (7)$$

In the equation (7), V_c^* is the reference voltage of capacitor, V_c is the instantaneous voltage of capacitor, and $\mathrm{K_p}$ and $\mathrm{K_I}$ are respectively the proportional and integral coefficients of the PI controller. The selection of these coefficients is based on a compromise between steady-state and dynamic function of the system. If $\mathrm{K_p}$ and $\mathrm{K_I}$ are considered to be high, the steady-state error of the response will decrease. On the other hand, if $\mathrm{K_p}$ and $\mathrm{K_I}$ are low, the dynamic function of the system will be better in contrast with solar radiation variance. Considering equation 4, the reference currents in $\alpha\beta$ coordinates which can produce reactive power and harmonic currents of the load and to inject power produced by solar arrays into the grid, can be represented in the following equation:

$$\begin{bmatrix} i_\alpha^* \\ i_\beta^* \end{bmatrix} = \frac{1}{v_\alpha^2 + v_\beta^2} \begin{bmatrix} v_\alpha & v_\beta \\ v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} \tilde{p}_L + P_{active} \\ \bar{q}_L + \tilde{q}_L \end{bmatrix} \quad (8)$$

In equation (8), v_α and v_β are load voltage, i_α^* and i_β^* are reference currents of the PV system, and p_L and q_L refer to the instantaneous load power in $\alpha\beta$ coordinates. In equation 8, P_{active} represents the output of the input dc capacitor voltage controller. The reference currents in abc coordinates can be written in the following equation:

$$\begin{bmatrix} i_a^* \\ i_b^* \\ i_c^* \end{bmatrix} = \sqrt{\frac{2}{3}} \times \begin{bmatrix} 1 & 0 \\ -1/2 & \sqrt{3}/2 \\ -1/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} i_\alpha^* \\ i_\beta^* \end{bmatrix} \quad (9)$$

If the inverter's output current is equal to i_a^*, i_b^*, and i_c^*, the power produced by PV system is entered to the grid in a way that the voltage of the input dc capacitor remains constant.

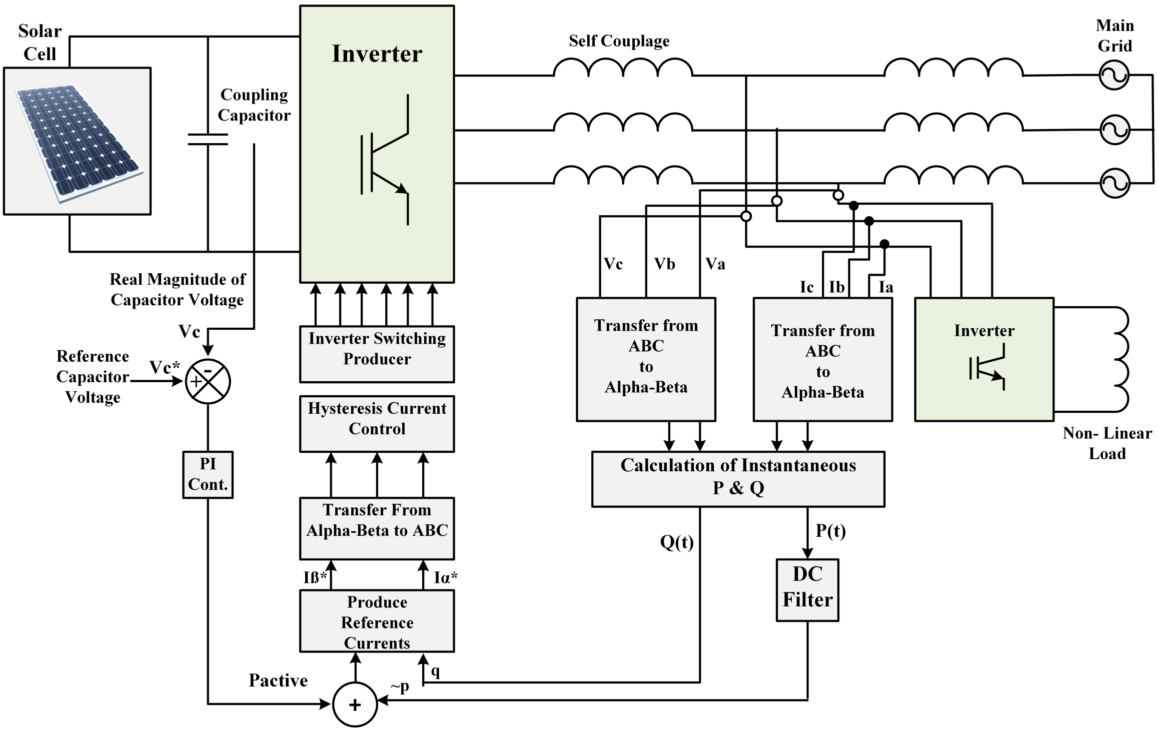
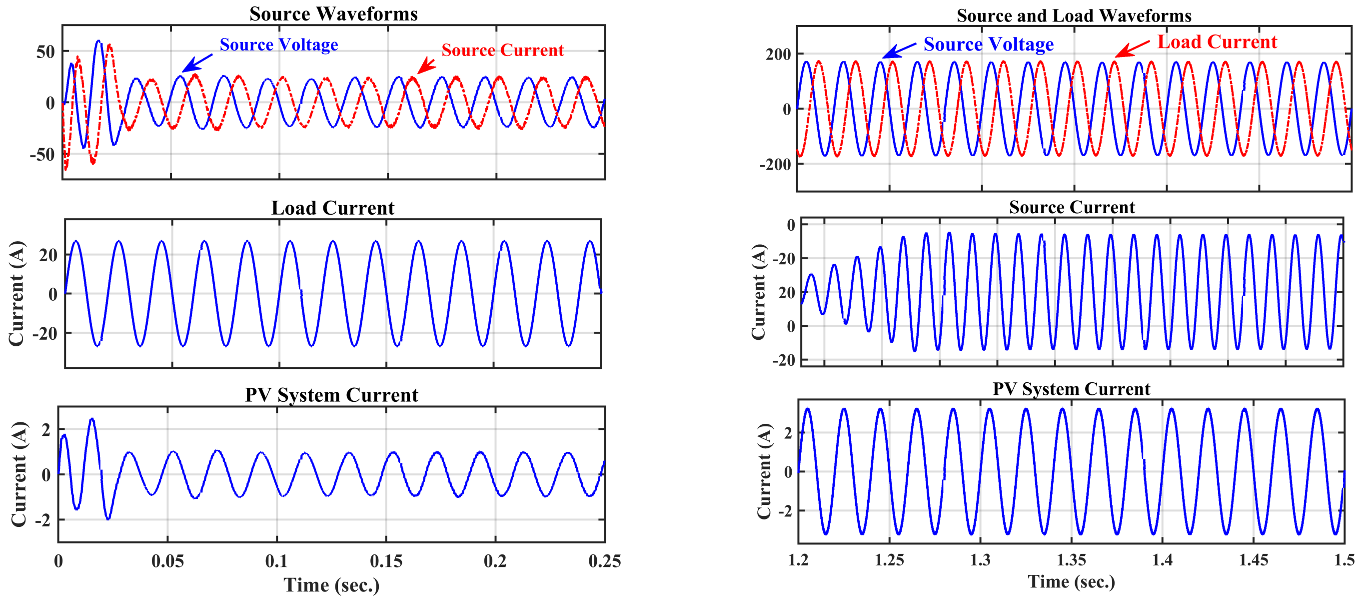


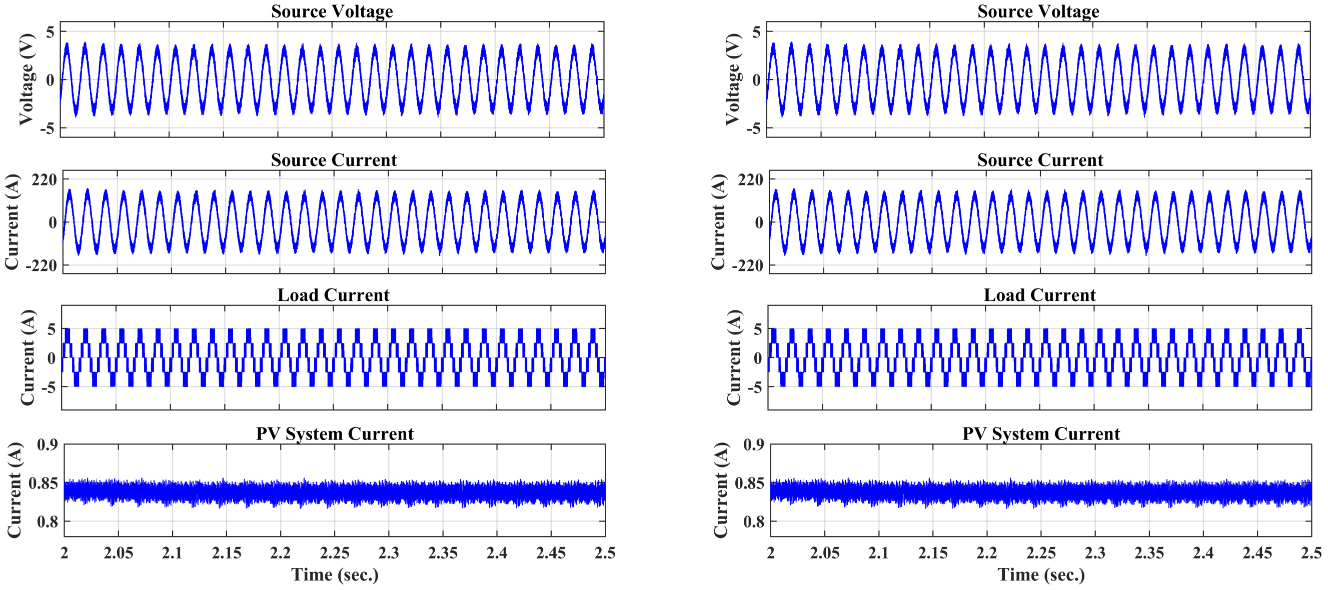
Fig. 3. Proposed control strategy of grid-connected PV system



(a) (b)

Fig. 4. Simulation results with the RL load: (a) Solar array power is lower than the required load power; (b) Solar array power is more than the required load power

The harmonic currents and the load reactive power is produced by the inverter in a way that the grid power factor is almost equal to 1, and harmonic current is not inserted into the grid. If the produced power by solar arrays is low, the controller of capacitor voltage can absorb some active power of the grid, so as to inhibit the reduction of capacitor voltage in the case of inverter losses. In this case, the photovoltaic system can supply active power and harmonic currents of load. Fig. 3 demonstrates the scheme of the proposed control strategy of grid-connected PV system.



(a) (b)

Fig. 5. Simulation results with three-phase diode full-bridge rectifier as a non-linear load: (a) Voltage and current drawn from grid; (b) Voltage and current injected to grid

IV. SIMULATION AND RESULTS

In this section, the accuracy of suggested method is verified through simulation of grid-connected PV systems with MATLAB software according to the control strategy proposed in Section III. The simulation parameters include:

- Phase to neutral grid voltage = 220 v
- Reference voltage of the input dc capacitor = 800 v
- Capacity of the input capacitor = 1 mF
- Grid connection inductance = 500 mH

In controlling the inverter current through hysteresis method, the switching frequency of each cycle will be variable if the bandwidth of hysteresis is fixed. To deal with this problem in the present paper, the hysteresis bandwidth was set in a way that the switching frequency was always fixed on 10 kHz. Initially, one RL load was used as reactive power consumer. The results of simulation based on the developed model are shown in Fig. 4. In Fig. 4 (a), the generated power by solar arrays is assumed to be low and grid-connected PV system solely generates load reactive power. Under this circumstance, the active power consumption of the load is absorbed from the main grid. In Fig. 4 (b), the generated power by solar arrays is hypothesized to be higher than the required load power. In this case, it is observed that the PV system feeds the APR of the load and injects active power into the main grid.

To review the compensation of load harmonics by the system, a three-phase diode full-bridge rectifier is used as a non-linear load (Fig. 5). The simulation results demonstrate that despite the nature of the load current, which include harmonics, and the consumption of reactive power by the load, the current drawn from grid, as shown in Fig. 5 (a), and the current which is injected into the grid, as shown in Fig. 5 (b), are almost sine and of similar phase with the line voltage. As Fig. 5 (a) shows, the PV system only compensates harmonic currents and active load power. In this case, this system acts as an active filter. One of the advantages of introduced control method is that if the grid voltage system is disconnected, this system can supply the required load power in an independent manner from grid. In this case, the PV system works as a UPS.

V. CONCLUSION

Solar energy is among the important sources of renewable energy to supply the residential demands. PV systems and technologies are largely utilized in different voltage levels of home applications. So it is necessary to study the details of each part with more effort and suggest different methodologies to enhance its efficiency. Grid-connected PV systems utilize the solar cells to capture the energy of the sun and power converters for network interfacing. In this paper, the focus was to enhance the performance of the power converters for efficient integration of PV systems into the network. To do so, a hybrid control method has been proposed based on IRP theory. To evaluate the performance of the proposed scheme, a simulation based test bench is considered in MATLAB software where the simulation results indicate the high level performance of the suggested technique. Also, the simulation results show that the system has the ability to compensate active power and harmonic currents of the load up to the power level of inverters regardless of power produced by PV arrays. In addition, the inverters can feed the load without delay in the case of grid disconnection.

REFERENCES

[1] S. Kouro, J. I. Leon, D. Vinnikov, and L. G. Franquelo, “Grid-connected photovoltaic systems: An overview of recent research and emerging pv converter technology,” *IEEE Industrial Electronics Magazine*, vol. 9, no. 1, pp. 47–61, 2015.

[2] M. A. Jarrahi, A. Jafari, F. Roozitalab, and S. Bazyari, “Novel voltage control method in distribution networks with dg resources,” in *2015 2nd International Conference on Knowledge-Based Engineering and Innovation (KBEI)*. IEEE, Conference Proceedings, pp. 462–467.

[3] L. Hassaine, E. OLias, J. Quintero, and V. Salas, “Overview of power inverter topologies and control structures for grid connected photovoltaic systems,” *Renewable and Sustainable Energy Reviews*, vol. 30, pp. 796–807, 2014.

[4] M. Obi and R. Bass, “Trends and challenges of grid-connected photovoltaic systems–a review,” *Renewable and Sustainable Energy Reviews*, vol. 58, pp. 1082–1094, 2016.

[5] O. P. Mahela and A. G. Shaik, “Comprehensive overview of grid interfaced solar photovoltaic systems,” *Renewable and Sustainable Energy Reviews*, vol. 68, pp. 316–332, 2017.

[6] H. El-helw, M. Hassanien, and H. A. Ashour, “Maximum power point tracking for irregular irradiance of a photovoltaic array,” in *2013 12th International Conference on Environment and Electrical Engineering*. IEEE, Conference Proceedings, pp. 52–57.

[7] S. Romero-Camacho, V. Gonzalez-Diaz, R. Ambrosio-Lazaro, G. Mino-Aguilar, E. Bonizzoni, and F. Maloberti, “An improved analog maximum power point tracking circuit for solar cells suitable for abrupt variations in irradiation levels,” in *2017 IEEE International Conference on Environment and Electrical Engineering and 2017 IEEE Industrial and Commercial Power Systems Europe (EEEIC/I&CPS Europe)*. IEEE, Conference Proceedings, pp. 1–6.

[8] N. S. Shah and H. H. Patel, “Enhancing output power of pv array operating under non-uniform conditions,” in *2016 IEEE 16th International Conference on Environment and Electrical Engineering (EEEIC)*. IEEE, Conference Proceedings, pp. 1–6.

[9] A. Momeneh, M. Castilla, J. Miret, P. Martí, and M. Velasco, “Comparative study of reactive power control methods for photovoltaic inverters in low-voltage grids,” *IET Renewable Power Generation*, vol. 10, no. 3, pp. 310–318, 2016.

[10] G. R. Walker and P. C. Sernia, “Cascaded dc-dc converter connection of photovoltaic modules,” *IEEE transactions on power electronics*, vol. 19, no. 4, pp. 1130–1139, 2004.

[11] L. Collins and J. Ward, “Real and reactive power control of distributed pv inverters for overvoltage prevention and increased renewable generation hosting capacity,” *Renewable Energy*, vol. 81, pp. 464–471, 2015.

[12] I. Kim and R. G. Harley, “The transient-state effect of the reactive power control of photovoltaic systems on a distribution network,” *International Journal of Electrical Power & Energy Systems*, vol. 99, pp. 630–637, 2018.

[13] M. Aourir, A. Abouloifa, I. Lachkar, C. Aouadi, F. Giri, and J. M. Guerrero, “Nonlinear control and stability analysis of single stage grid-connected photovoltaic systems,” *International Journal of Electrical Power & Energy Systems*, vol. 115, p. 105439, 2020.

[14] J. Selvaraj and N. A. Rahim, “Multilevel inverter for grid-connected pv system employing digital pi controller,” *IEEE transactions on industrial electronics*, vol. 56, no. 1, pp. 149–158, 2008.

[15] N. Kumar, T. K. Saha, and J. Dey, “Control, implementation, and analysis of a dual two-level photovoltaic inverter based on modified proportional–resonant controller,” *IET Renewable Power Generation*, vol. 12, no. 5, pp. 598–604, 2018.

[16] R. Errouissi, S. Muyeen, A. Al-Durra, and S. Leng, “Experimental validation of a robust continuous nonlinear model predictive control based grid-interlinked photovoltaic inverter,” *IEEE Transactions on Industrial Electronics*, vol. 63, no. 7, pp. 4495–4505, 2015.

[17] B. Wang, Y. Xu, Z. Shen, J. Zou, C. Li, and H. Liu, “Current control of grid-connected inverter with lcl filter based on extended-state observer estimations using single sensor and achieving improved robust observation dynamics,” *IEEE Transactions on Industrial Electronics*, vol. 64, no. 7, pp. 5428–5439, 2017.

[18] A. Merabet, L. Labib, A. M. Ghias, A. Aldurra, and M. Debbouza, “Dual-mode operation based second-order sliding mode control for grid-connected solar photovoltaic energy system,” *International Journal of Electrical Power & Energy Systems*, vol. 111, pp. 459–474, 2019.

[19] N. Hamrouni, M. Jraidi, A. Dhouib, and A. Cherif, “Design of a command scheme for grid connected pv systems using classical controllers,” *Electric Power Systems Research*, vol. 143, pp. 503–512, 2017.

[20] A. Merabet, L. Labib, A. M. Ghias, C. Ghenai, and T. Salameh, “Robust feedback linearizing control with sliding mode compensation for a grid-connected photovoltaic inverter system under unbalanced grid voltages,” *IEEE Journal of Photovoltaics*, vol. 7, no. 3, pp. 828–838, 2017.