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An efficient hybrid photovoltaic battery power system-based grid-connected applications

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ABSTRACT

Power management systems for grid-tied photovoltaic-battery power systems are the focus of this research. Solar photovoltaic (PV) panels, lithium-ion batteries, and a voltage source inverter (VSC) are all part of the system. By employing the fuzzy logic (FL) technique, a PV system's power output can be maximized in a variety of weather circumstances. In addition, the state-of-charge-based power management system (PMS) was investigated to manage power sharing between sources and the grid and then manages the battery module's charge/discharge process. Active-reactive (PQ) control was used on the VSC converter while it was synced with the grid and regulated. In order to model and simulate the suggested system under various solar irradiances, Matlab/Simulink was employed. In contrast to the standard grid-connected inverter, which operates without batteries, the simulation results showed that adding the battery energy storage system BESS increased the system's performance. A grid-connected inverter that makes use of BESS can prevent the absence of PV energy or shading of the arrays. To explain why PMS is so effective, the simulations show that the injected grid current is more stable and has less total harmonic distortion (THD).

Keywords: Grid-connected inverter, Fuzzy logic, Hybrid photovoltaic-battery system, PQ control method, Power management system.

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1. Introduction

Solar photovoltaic (PV) systems considers the major renewable energy sources that available along the year [1, 2]. The PV system generates the required power for electricity by photo effect process [3]. The scheme of the PV systems is categorized into three individual parts: PV modules, which are connected together to form a PV array that converts sunlight power into direct current (DC) electrical power and electrical power conversion, which consists of DC-DC converters or DC-AC converters [4-8]. Inverters, which are DC-AC converters, are important components of any PV system. The improvements of PV power system usually depend on the technical developments on the three parts individually [9-11]. The inverter circuit schemes, which are connected with PV module, are of these types: one stage inverters, two inverters, and multi stage inverters as seen in Fig.1 [12-15]. In single stage inverter scheme, only direct-alternating (DC/AC) single stage with a PV module was connected to obtain a AC output power feeds to the gird. This scheme is the standard choice for low power PV applications as a result of its simplicity. Furthermore, the total power of PV modules is sometimes decreased remarkably when problems occur in a few PV modules, thereby decreasing the current generated from PV modules. Thus, the total efficiency for system is low due to it needs a suitable transformer in grid side [16-20]. A two stages inverter scheme, considers a compromise between a grid and central PV system. This scheme consists of different string of modules, and then string is connected through a D/DC converter to implement MPPT controller to build larger PV system that connected to a grid. For this reason, the efficiency of this scheme is high than single stage due to it does not need the transformer [21-23].

On other the hand, several DC/DC or DC/AC converters may be used to implement the grid connected inverter. This type is more cost than the other topologies. For this reason, in this study, a dual stage grid connected inverter was used. Many advantages of this scheme over other technologies such as low cost, high reliability, and more efficient for low power applications [24, 25, 15, 26, 27].

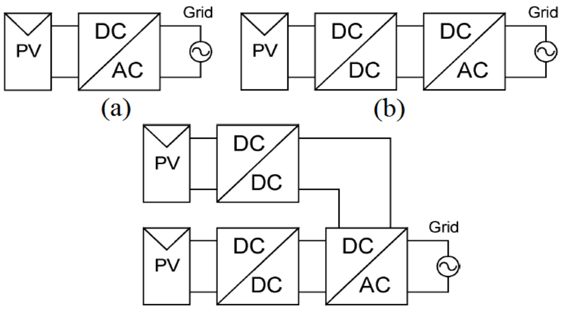

Figure 1. PV inverter architectures-based power stage unit (a) single stage inverter (b) two stage inverter (c) Multi stage inverter

1.1. Foremost contributions for this research

The central goal of this research is to design and develop a hybrid PV-battery inverter without using transformer in its circuit for grid-connected PV mode. A suggested inverter is presented to inject alternating current to the utility grid with minimum values of THD and unity power factor (P.F). The objectives of this work include the following highlights:

i. Modeling and simulation of PV system with a better performance using artificial intelligent MPPT technique of FL to increase to the tracking speed and get the peak PV power.
ii. Suggest PMS strategy to stabilize the DC bus voltage and manage the real power among a grid and sources.
iii. Improve the performance of the grid connected inverter by including BESS.

2. State of art

Grid-connected microinverters for photovoltaic systems have been the subject of numerous published studies in the last few years. Thus, this section presents an overview of PV grid-connected inverters, including their advantages and downsides. The one stage flyback inverter described in [28-30] was designed and implemented by the authors. The MPPT concept was implemented utilizing a direct digital synthesis method based on a dsPIC microcontroller. A 120W prototype setup was used to get the results. It was a wise decision to use this inverter with AC PV modules. Grid-connected inverter based on interleaved two-stage flyback converter demonstrated in reference [31]. As a result, this inverter was outfitted with two flyback converters linked in parallel. To synchronize this inverter with the grid, we used two different open loop phase synchronization approaches. To show the inverter's performance, the simulations were run on a 200 W experimental prototype. Using a DC/DC conversion stage and a grid-frequency push-pull converter, B. D. Reddy et al. [32] devised a two-stage single-phase inverter. Using three semiconductor switches, one at a high switching frequency and two at the grid frequency, this inverter was built. The gate sequences for the switches were constructed using analog devices. In both stand-alone and grid-connected modes, the proposed inverter was evaluated. Another PV micro-inverter type using a mixed MPPT technique was published by researchers [33]. P&O and fractional short circuit current were combined in this inverter's DC/DC converter to achieve hybrid MPPT. Co-simulation between Simulink and power simulation (PSIM) software was used to simulate this MPPT approach. A one-stage PV micro-inverter was demonstrated by M. Khalilian et al. [34]. Snubbers have been added to the primary switch in order to reduce the amount of time it takes to turn it off. Switching state of the primary converter switch is required for the proposed converter to work. In addition, we looked into the inverter's theory of operation, principle of operation, and design circuit. The proposed inverter was tested in a simulated environment. In 2016, J. Liao et al. [35] suggested a solar single-phase grid-connected inverter. It relied on a new decoupling power design that included an active and a passive circuit to eliminate ripple in its output power that was sent to the grid. An inverter with a multi-port converter was demonstrated in [36]. This inverter is suitable for both grid-connected and stand-alone PV power applications. The proposed inverter topology provides galvanic isolation between the PV module, battery, and the load through a single step DC/AC conversion. This resulted in an increase in battery life, as well as a reduction in output power ripple. Through Matlab/Simulink, the suggested inverter was simulated. A grid-connected single-stage flyback inverter was proposed by M. Kalilian and P. Guglilmi [37]. Zero-current switching (ZCS) for the main flyback inverter switch was demonstrated in this inverter. When it was time to turn the power off, the primary switch was shielded from a surge in voltage. PSIM was used to get the simulation results for the proposed inverter. A two-stage grid-connected micro inverter was presented by the authors in [38]. The push-pull DC-DC converter was used to build the first stage, and the DC-AC full bridge inverter with sinusoidal pulse width modulation (SPWM) current management was used to build the second stage. The second stage. With the suggested inverter, the PV module delivers MPPT in sync with the utility grid. In order to demonstrate the micro-stability inverters and transient responsiveness under varied weather circumstances, the micro-inverter was simulated with different solar irradiation levels and ambient temperatures. An MPPT micro-inverter with a two-stage PV converter has been developed by S. Sukatjasakul and S. P. Ngam [39]. Adjusting the PV module voltage was all that was required to use the MPPT approach when the solar irradiation changed. The phase locked loop (PLL) synchronization approach was used to build the proposed inverter to provide sinusoidal current with minimal total harmonic distortions (THD). The proposed inverter was tested and found to be correct.

H. Watanabe and J. Itoh [40] demonstrated a grid-connected inverter for photovoltaic (PV) applications that uses high power density. Designing an inverter with two stages, a DC-DC converter and an inverter with a current source were two steps of the suggested design (CSI).

Instead of a huge capacitor or a large inductor, an inductor was used to reduce the input voltage ripple. The high-quality factor was created in accordance with the modeling experimental results in order to offer a stable resonance current. Using an interleaved flyback type microinverter with a model-based approach to current sharing, Dong et al. [41] suggested a grid-connected device. The suggested inverter circuit has an accurate fourth-order model.

Because of the mismatch and coupling between the two flyback circuits, a continuous time sliding mode current controller might be developed using this technique. As a result, simulation results show that the current sharing is better than the typical strategy for interleaved flyback inverters.

3. Proposed grid-tied pv-battery inverter structure

Hybrid PV-Battery power systems for on grid solar applications were examined in this paper to improve the mains grid with AC current that contains the lowest possible harmonics. A diagram of the system's basic structure is depicted in Figure 2. Using fuzzy logic MPPT, the PV system was able to raise its output power and then improve its performance in a variety of weather circumstances. A lithium battery-based energy storage system was also included to reduce power surges when the PV system was obstructed by trees or another obstruction.
The Li-ion battery was managed using PI controller to achieve a stable DC bus voltage under simulation. Also, a DC/AC inverter was used to provide the stable voltage and linked the PV-battery system with the utility grid. This VSC was controlled by PQ control method which is design in next sections.

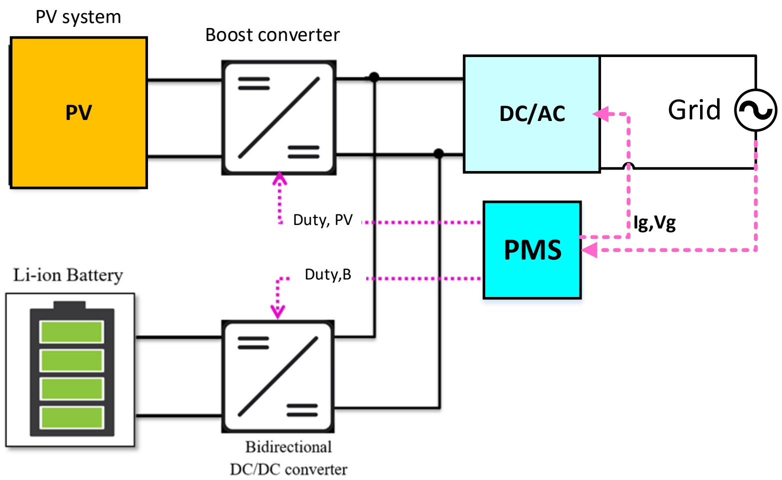

Figure 3. Proposed PV-battery grid connected inverter

3.1. Two-diode PV panel modeling

When using a one-diode model, losses in the depletion area are ignored. Furthermore, it is impossible to model precisely the large loss [2, 3]. Figure 3 shows that a PV cell has two diodes and that this model best reflects PV cell physics. This recombination loss was taken into account to improve the model's accuracy. Recombination loss is taken into consideration by adding another diode to one of the two diodes that focus on diffusion current.

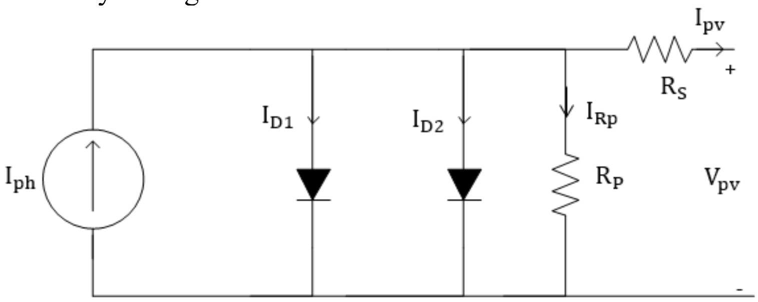

Figure 3. Two-diode PV cell model

The resultant current for PV module I_{pv} in dual-diode model is described as [3].

$$I_{pv} = I_{ph} - I_{D1} - I_{D2} - \left[\frac{V_{pv} + I_{pv}R_S}{R_P}\right] \tag{1}$$

$$I_{D1} = I_{01}\left[\exp\left(\frac{V_{pv} + I_{pv}R_S}{\alpha_1 V_{T1}}\right) - 1\right] \tag{2}$$

$$I_{D2} = I_{02}\left[\exp\left(\frac{V_{pv} + I_{pv}R_S}{\alpha_2 V_{T2}}\right) - 1\right] \tag{3}$$

Where I_{ph} denotes the photocurrent source, $I_{D1}$is the first diode current, I_{D2} represents the second diode current, V_{pv} stands for a terminal voltage of the panel, R_S is the series resistance, R_P stands for a parallel resistance, a saturation currents for the both didoes are denoted by I_{01} and I_{02}, respectively, $\alpha_1$and α_2 represent the ideality factors of the diodes, and the thermal voltage for the diodes are given by V_{T1} and V_{T1}. As stated before, more exact model is feasibly realized by means of two-diode instead of conventional one diode model.
Therefore, in this study, the PV panel was modeled using this accurate model based on the main electrical parameters at STC conditions as seen in Table 1.

Table 1. KC200GT PV panel parameters at STC conditions

Parameter	Value
Maximum power, P_{max}	$200W\ V$
Maximum voltage V_{max}	$17.4V$
Maximum current I_{max}	$7.41A$
Voltage at open circuit case V_{oc}	$32.9V$
Current at short circuit case I_{sc}	$8.21A$
Constant voltage coefficient , K_v	$-0.123V/K$
Constant current coefficient, K_i	$0.0032\ A/K$
Number of cells N_s	54

3.2. MPPT design

The I-V besides P-V characteristics of PV module or cell have been influenced by atmosphere conditions. For this reason, the output power of the PV module must be tracked [10-14]. Most of the conventional MPPT techniques are applied to the PV system used in VSC converter and are usually implemented by regulating input voltage or the duty ratio [4, 11, 23]. Because the main principle action of suggested inverter is operated as a sinusoidal current-source inverter synchronized with a grid voltage, and the input voltage cannot be directly controlled, which depends on PV module characteristics. For this reason, in this work, the FL MPPT method is used and realized by adjusting a duty cycle for a boost converter. A basic algorithm for this method is shown in Figure 4. The FL algorithm is based on the error and the change in the error,($\Delta error$) of the equation below [42]:

$$error = \frac{\Delta P}{\Delta V} = \frac{P(n) - P(n-1)}{V(n) - V(n-1)} \quad (4)$$

$$\Delta error = error(n) - error(n-1) \quad (5)$$

Here, $P(n)$ and $V(n)$ stand for the PV power and PV voltage, respectively. Moreover, based on the above equation, the membership functions of the FL MPPT have been designed in this study as seen in Figure 5

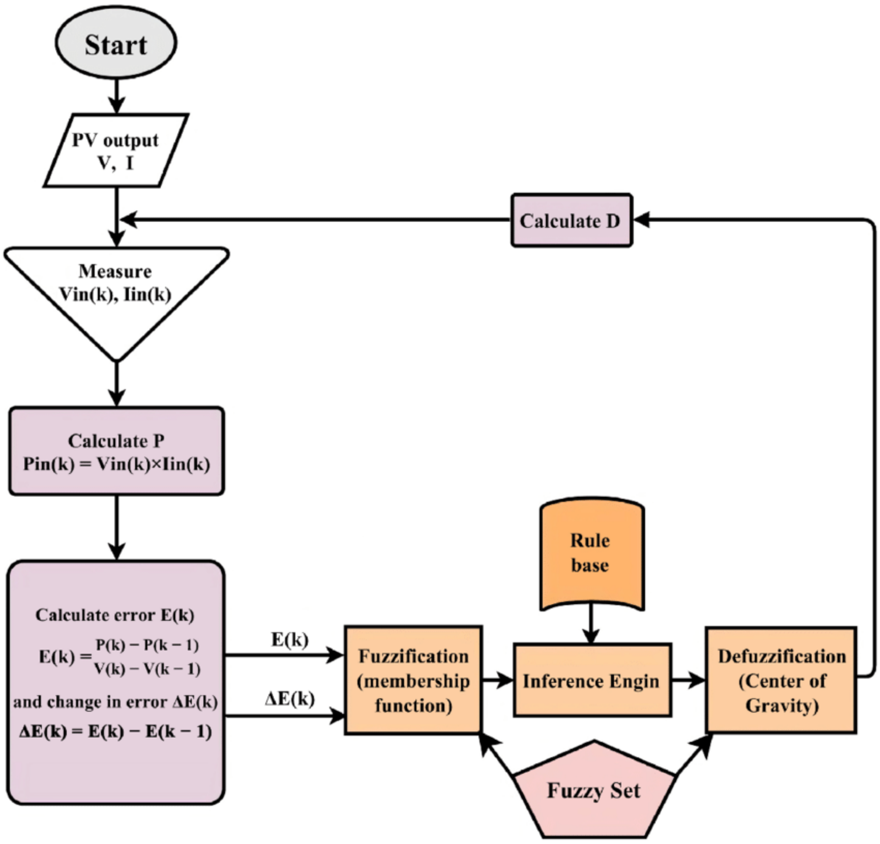

Figure 4. The FL algorithm based MPPT

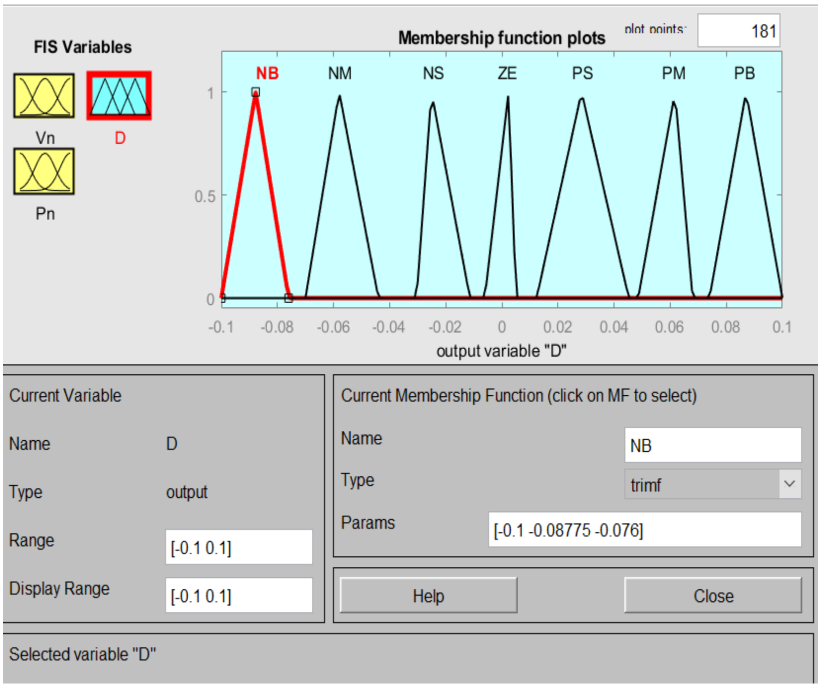

Figure 5. MFs of the presented FL algorithm

In addition, a DC/DC boost converter was employed in this architecture to implement the FL algorithm. This converter has additional benefits, such as cumulative input voltage for the PV to a utility grid level, increasing the power of the PV module by varying its switch duty cycle, and allowing the PV panel to reach the MPP in a short response time with low ripple content in the DC bus output voltage [3, 30]. Fig.6 reports the electrical circuit of the boost converter-based PV system with MPPT controller.

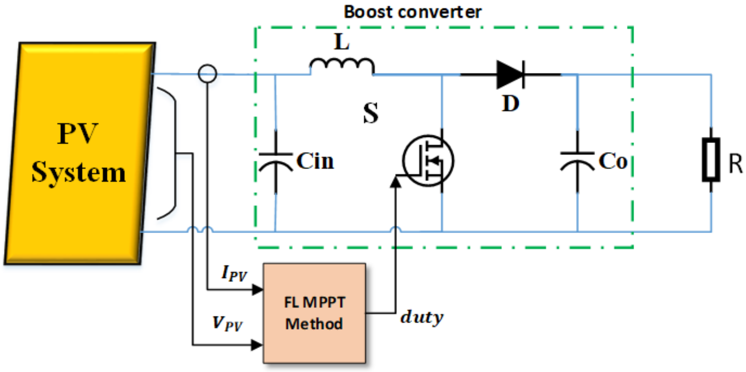

Figure 6. FL MPPT controller with boost converter circuit

3.3. PV-Battery management system

In this system, a PV-battery-based grid-connected inverter was evaluated and developed for a low-voltage application that feeds electricity to the utility grid. Every unit in a projected power system was controlled using the local control technique to share the optimal power between the grid, source, and storage devices, and they were later managed in the power management system (PMS) block diagram. When compared to typical grid-connected inverters, the battery ESS was added to the system to stabilize the system voltage and boost the dependability of the utility grid. In addition, the BESS removes the requirement for a dump load and improves grid operation. The proposed BESS was attached to a bidirectional converter, which managed the supplying and absorbing power from the battery and subsequently extended the battery's lifespan by providing the optimal operating. Furthermore, BESS ensures supply continuity under varied grid operation situations. The FL technique is used to generate steady, maximum, and continuous electricity from a PV system. The suggested PMS is based on estimating the battery's state of charge (SOC) and then comparing the power for the grid, PV, and battery to determine the appropriate duty cycles for the DC/DC converter during the PI controller as seen in Figure 7.

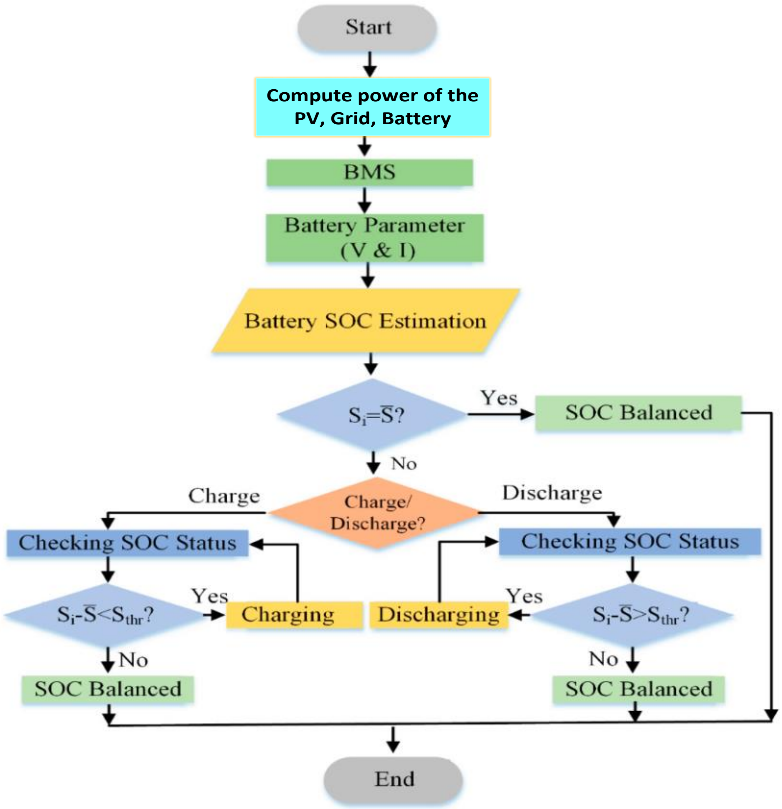

Figure 7. It proposed PMS algorithm of the hybrid PV-battery inverter

3.4. PQ Control Method for VSC converter

In this paper, PQ control method has been employed to control and synchronize the projected PV-battery system with the grid. This technique was used in several studies instead of the conventional techniques due to it has several advantages [43]. The PV-battery inverter may manage its active and reactive power production by adjusting the generator phase angle. An internal PQ controller can handle this issue. In order to provide PQ controllability to the simulation model of the individual PV systems, a typical PQ control scheme as seen in Fig. 8 was investigated. As stated in equations 6 and 7, the representation of active P and reactive power Q in a dq reference frame may therefore be reduced further. The real PQ control is then done by adjusting Id and Iq to match the reference values Idref and Iqref (inverter current control). A static reactive power supply technique or a dynamic approach is used to set Idref and Iqref [43].

$$P = V_{gd}\, I_d \tag{6}$$

$$Q = -V_{gd}\, I_q \tag{7}$$

Furthermore, the details model of the PQ control is illustrated in Fig.9. By producing the references current for the direct and quadrature axis during the PI control, the second stage then is the computing the reference voltage which are employed for generating the proper PWM signals for the VSC inverter.

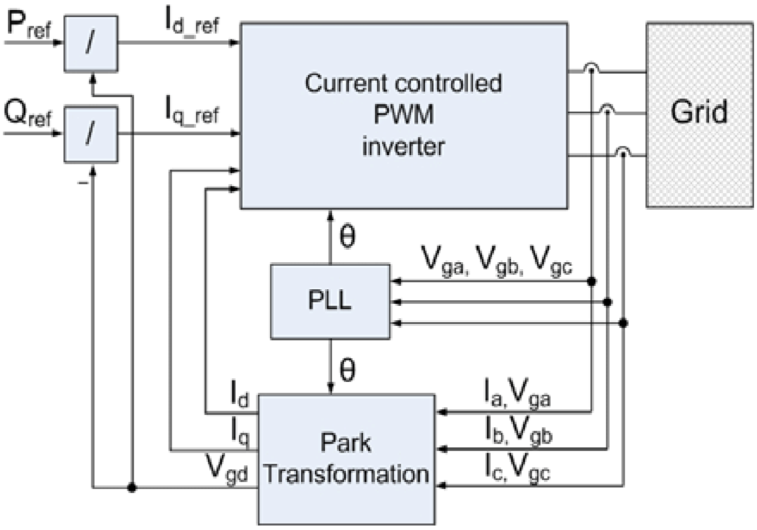

Figure 8. PQ control method for VSC inverter

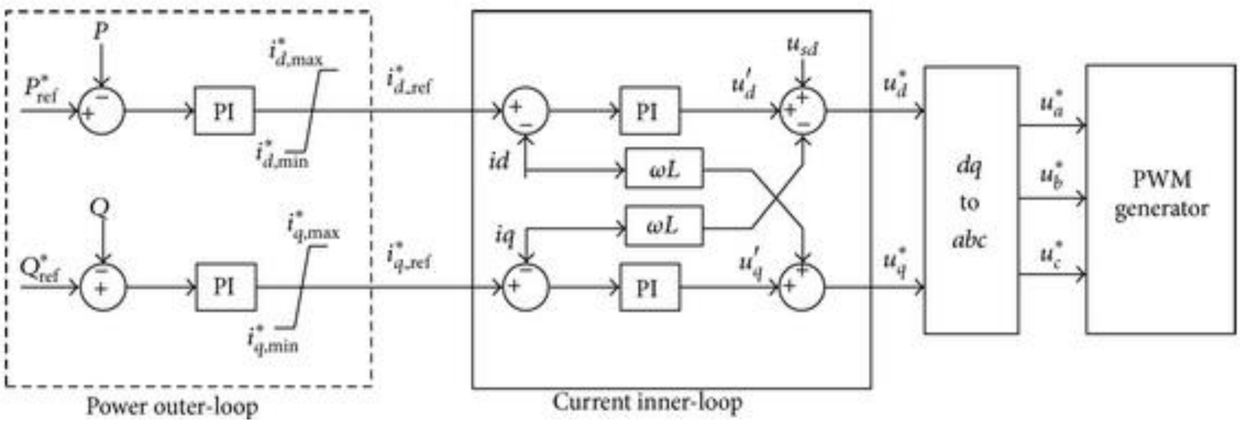

Figure 9. detailed model control of the PQ technique

4. Simulation results and discussion

To prove the suggested PV inverter, Matlab/ Simulink was used. The entire system parameters are listed in Table 2. These parameters including the grid voltage value$V_{g,rms}$, grid frequency f, filter inductor L, filter capaciotr C, boost converter inductance L_{boost}, and switching frequency f_s. With the intention of testing a performance for the proposed inverter, the real changes in solar irradiation were adopted as illustrated in Figure 10.

Table 2. Simulation parameters of the suggested inverter circuit

Item	**Value**
$V_{g,rms}$	$220\ V$
f	$50Hz$
L	$4mH$
C	$1\mu F$
$L_{boost},$	$1mH$
f_s	$5000Hz$

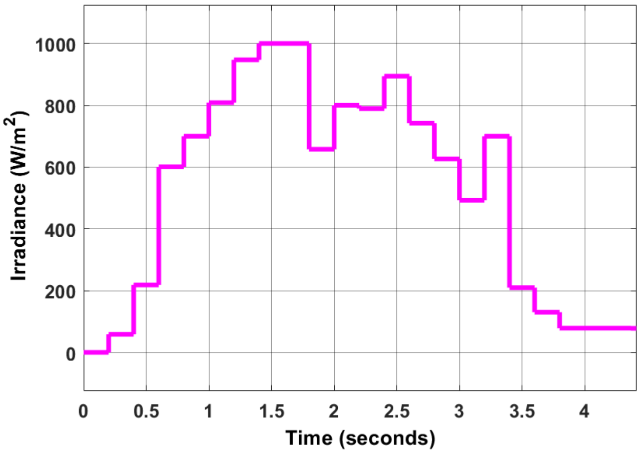

Figure 10. The suggested irradiance profile

Figure 11 reports obtained results of the PV system. As seen, the proposed FL technique success in obtaining the maximum power with minimum oscillation rate around the maximum power point (MPP). It has been clear that a voltage, current and power of the PV system are varied with an irradiance level if the temperature fixed with 25C. Figure 12 shows the bus voltage result. As seen, the presented PMS stabilizes the voltage of the DC bus against the high step in the solar irradiance. As a result, the voltage ripple in the bus voltage is decreased by means of suggested optimal updating PMS. Figure 13 presents the graphs of the real active power for the battery, PV and grid. As shown in this figure, when the PV power is less than the required grid power, the battery supplied the utility grid with required power and according to its SOC limits. Therefore, the results obtained in these figures prove the ability of the suggested PMS to meet the delivered power to the grid with BESS and PV arrays with good power quality.

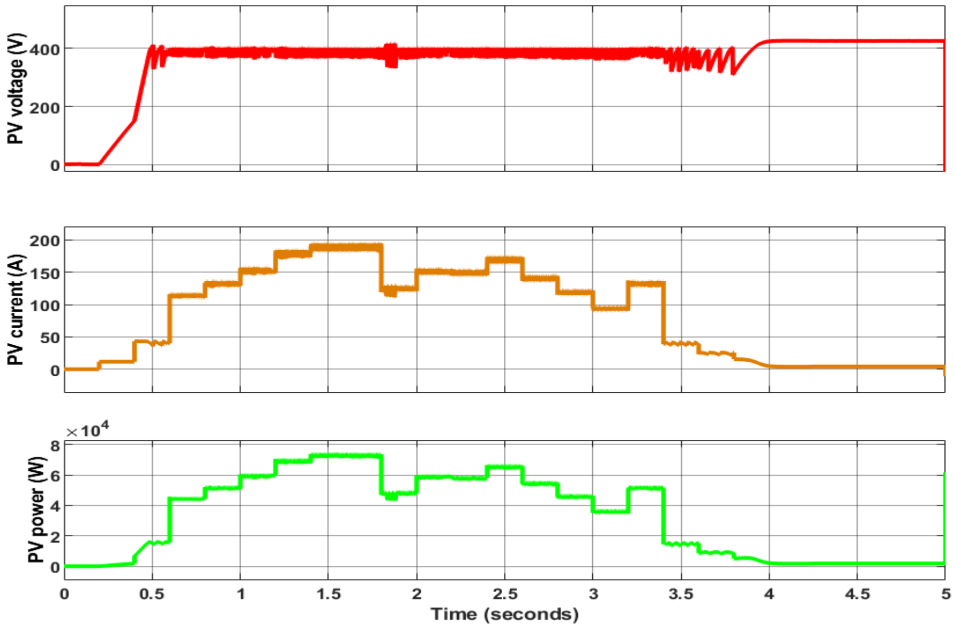

Figure 11. Results of the PV system from top to bottom: voltage, current and power

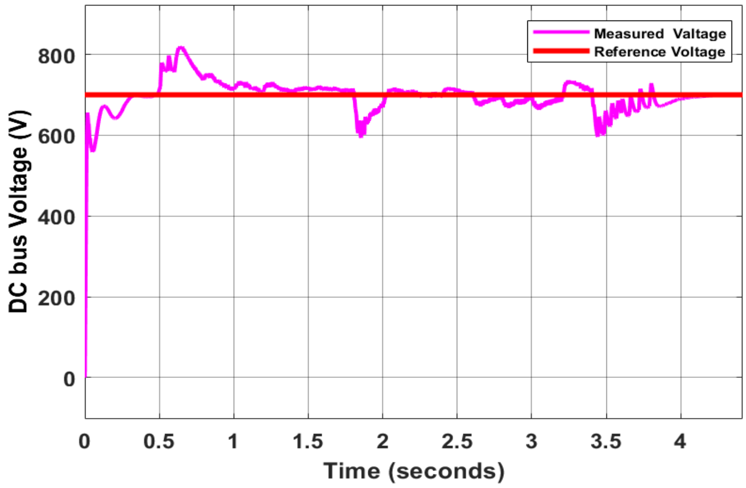

Figure 12. DC bus voltage result

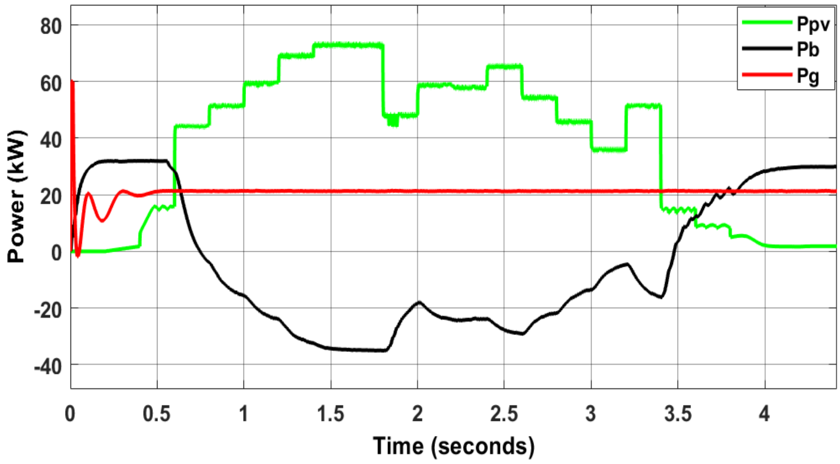

Figure 13. Power curves of the battery, PV and grid at varied solar irradiation case

The current, voltage and SOC of the battery are shown in Figure 14. As seen, with using SOC of 95% at initial stage, the battery will supply the grid when the PV power is not available or minimum, so the SOC of the battery at this case will decreased (discharge). On other the hand, if the level of irradiance increases the power of the PV will raise and it will supply the grid while the battery absorbs the exceed power (charge mode).

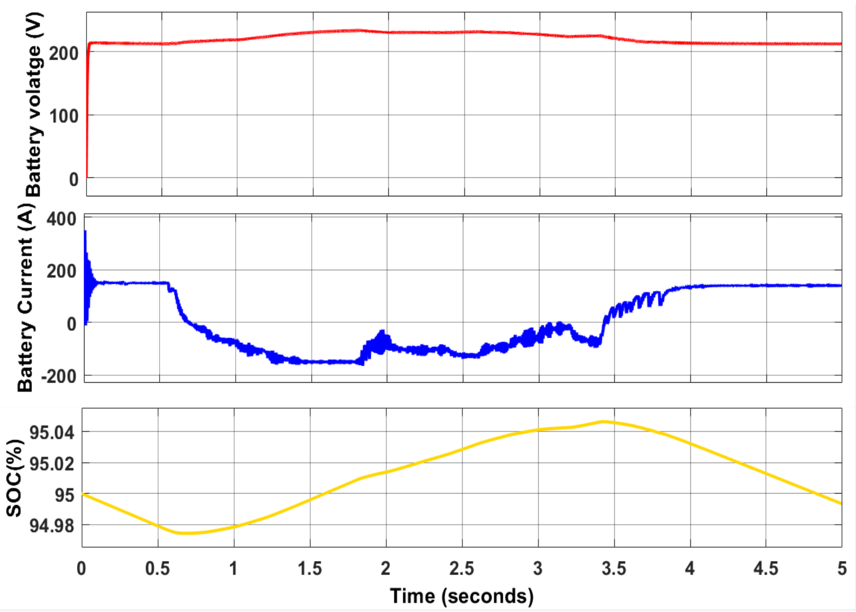

Figure 14. The voltage, current and SOC results of the battery

Figure 15 shows the three-phase grid voltage and current at steady state conditions. Also, an injected current with the grid current can be seen in Figure 16. As shown, the injected current almost in same phase with the voltage grid which means the proposed inverter delivers the active power to a grid with keeps a reactive power is zero. A harmonic content in the current is little and it has near unity power factor.

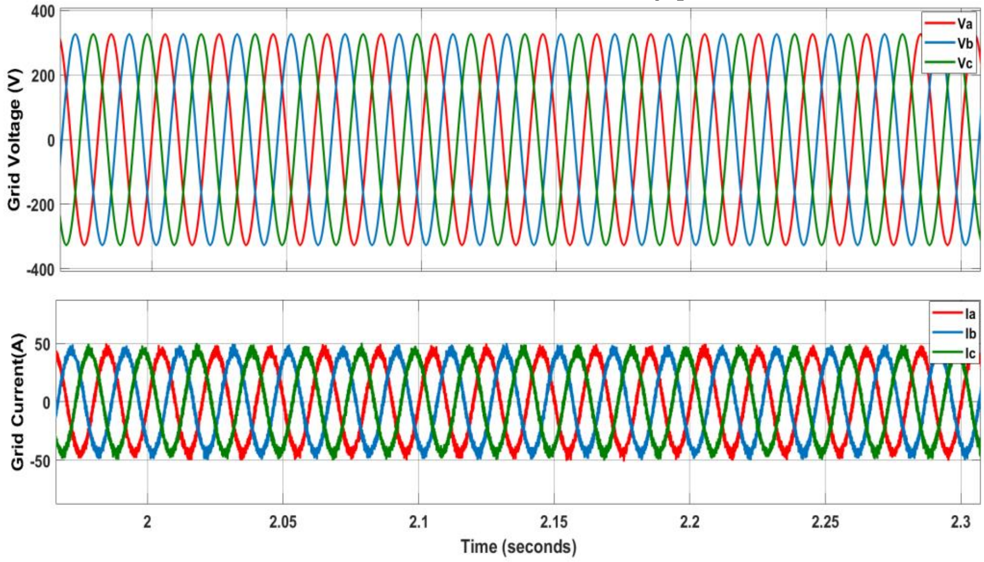

Figure 15. Three phase voltage and current of the utility grid

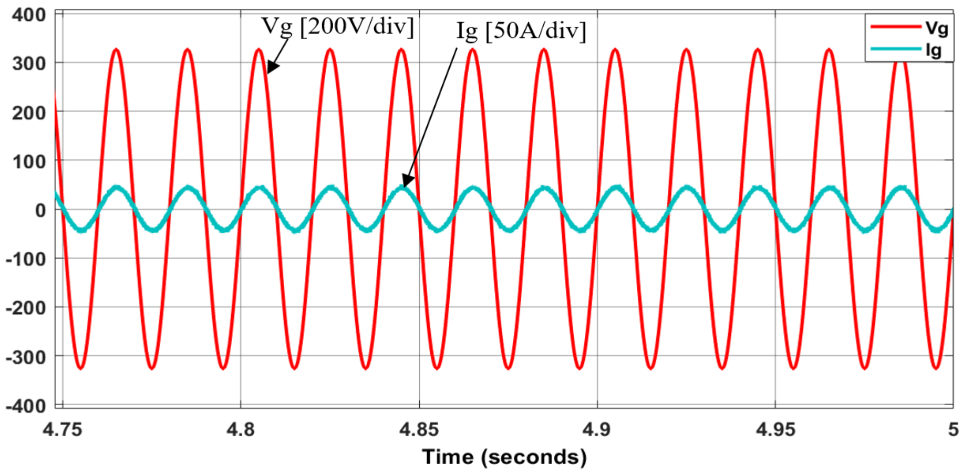

Figure 16. The results of the injected current to the grid with grid voltage

5. Conclusion

A hybrid photovoltaic/battery power system-based grid connected inverter with optimal power management system (PMS) was presented in this paper. The goal of the suggested PMS is to control the bus voltage and sharing the power between the sources and the grid with optimal strategy based on the SOC of the battery and the solar irradiance level. The proposed inverter system consists of PV system with 74KW, and battery size of 35KWh which are integrated through DC bus and linked with the grid by two level VSC inverter. as a result, the proposed PMS was tested in simulation for real irradiance profile and the suggested system show good performance under this condition. Moreover, the proposed PMS offers a stable DC bus voltage with minimum over shoots rate and less ripple content. The maximum value of the AC injected current was with lower THD content.

Declaration of competing interest

There are no financial or non-financial conflicting interests in any of the content discussed here.

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