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Highlights

- The study focuses on distributed generation using a photovoltaic (PV) system with battery storage.
- Power exchange with the grid is regulated based on the battery’s state of charge (SOC).
- The system aims to maximize PV power extraction under varying temperature and irradiation conditions.
- A converter with proper switching control enables efficient energy management.
- With well-designed controllers, the proposed structure ensures optimal and reliable power management in distributed systems.

Graphical Abstract

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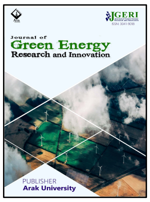

Modeling and Optimization of the Photovoltaic System Connected to the Grid

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ABSTRACT

In recent years, distributed generation as a source of local loads and continuous economic operation has gathered attention. In this thread, this study focuses on distributed generation using a photovoltaic package with batteries, so that the power drawn from the distributed generation system for injection into the main grid or receiving it is adjusted based on the battery charge status. The goal is to absorb the maximum power received from the photovoltaic system at any temperature and hypothetical radiation. If the battery charge is not optimal, part of this power is applied to the battery for charging. By presenting a suitable structure, a photovoltaic system with a battery package is presented as a distributed generation source with the design of appropriate controllers. The results show that at any temperature and radiation, the maximum power received from the photovoltaic system can be estimated. By controlling a converter switching the required amount of energy can be obtained from the photovoltaic system. It can be concluded that such a structure, as a desirable distributed generation source, is realized. With the proper design of the necessary controllers, optimal management can be done for power management.

1. Introduction

Distributed generation as a source of local loads, as well as continuous and economic operation, has been considered by researchers in recent years. For this reason, different structures and several control algorithms have been presented in most different research [1-3]. In some research, the issue of islanding and the recognition of the necessity of islanding to continuously feed the local load has been considered [4-6] in which the islanding problem is investigated when the main grid is shut down and islanding the dis-tributed generation system is intelligently designed by terminal voltage and network frequency to detect transient errors from the total blackout of the system [7,8]. In the IEEE 929-2000 standard, the islanding conditions of the distributed generation system are described from the main grid, but the main issue in observing this standard is the detection of transient errors and disturbances caused by local load changes from the main grid blackout [9-11]. A control technique has been introduced to determine the necessity of islanding, in which only local and available parameters are measured and remote signals are excluded [12,13]. Also, without the use of telecommunication signals, the connection of the distributed system and the main grid is designed using a hybrid technique based on multi-inverter performance [14,15]. In addition, in [16,17] a method for safe detection of islanding based on reactive power flowing under normal conditions and its investigation during sudden changes is presented, and the same method has been car-ried out in [18] taking into account the power factor and its sudden changes, in which after deciding to islanding, the disconnection order is sent to the switch.

In [19, 20], considering the moment of a sharp drop in active and reactive power, the islanding problem was analyzed. Ref. 2022 [21] presented a collaborative optimization of PV greenhouses and clean energy systems in rural areas. The combined coordination model of agriculture and energy networks is established, and the combined model involves carbon, electrical energy, and thermal energy. Fu et al. [22] have done modeling with the purpose of stochastic optimal planning of distribution networks considering a dynamic correlation and dimension reduction. Fu et al. [23] presented a statistical machine-learning model for capacitor planning considering uncertainties in photovoltaic (PV) power. The results verify that the proposed model greatly improves planning performance while meeting accuracy requirements. The case study also considers a realistic power distribution system operating under stressed conditions.

This paper discusses the use of distributed generation with a PV system and batteries. The power from this system is adjusted based on the battery charge status when it is either being injected into the main grid or received. The goal is to maximize the power received from the PV system regardless of temperature and radiation levels. If the battery charge is not optimal, some of this power is used to charge the battery. The paper first describes the PV system model, then designs the necessary controllers. Finally, simulation results are presented to demonstrate the effectiveness of the proposed structure.

2. Materials and Methods

2.1. *Structure description*

The structure introduced in this paper consists of a PV system connected to a DC/DC converter whose output is connected to a battery package with the appropriate voltage, shown in Figure 1. The output of the converter is connected to a two-level inverter and after connecting to a transformer and a harmonic filter, the local load is fed through a distributed generation system and main grid. The distributed generation system is connected to the main grid through a distribution transformer, and the local load is combined through the distributed generation system and the main grid. In this structure, two separate controllers are designed as follows:

A. Power controller of a PV system, which absorbs reference and determines power from the PV system at any given temperature and radiation. This will be done by adjusting the pulse switching of the DC/DC converter, and in fact, the pulse switching controller of the mentioned converter adjusts the power received from the PV system to its reference value.

B. The power controller is exchanged between the distributed generation system and the main grid, which is done by adjusting the pulse switching of the inverter connected to the DC/DC converter and adjusting the transmission power of the PV/battery set to the reference value. It is obvious that when the power transferred from the distributed generation system is less than the power generated by the PV system, the rest of the absorbed power from the PV system is applied to the batteries and sets them in charging conditions. When the transmission power is higher, the batteries will supply the rest of the power and will be in a discharged state.

2.2. *Modeling the PV system*

A PV system consists of several series/parallel cells, as shown in Figure 2, as described in [12, 24-26] on how they are modeled. In modeling the system, a current source whose value depends on the sun's radiation is used, and the relationships governing the voltage and current of this system are per Equation (1) to (4).

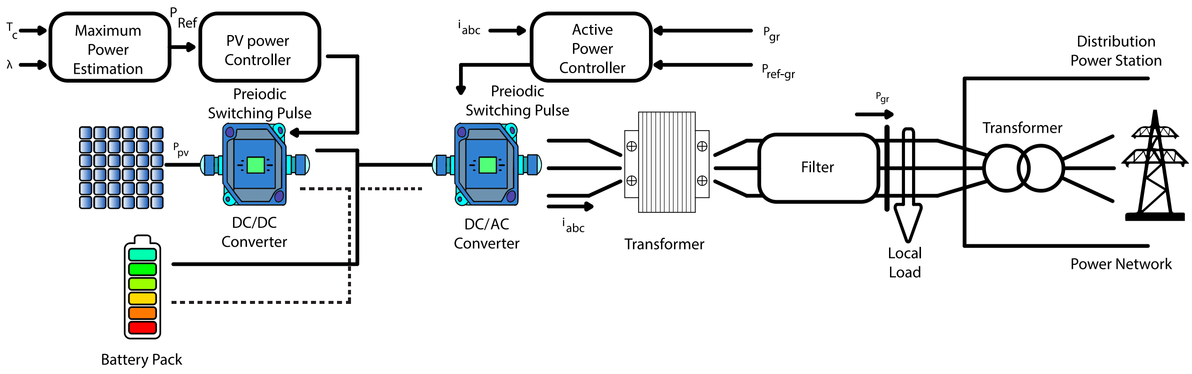


Figure 1. Power generation system with battery storage connected to the grid.

According to the above equations, voltage, current, and therefore the power of the system will depend on the temperature and radiation of the environment. In Figure 3, the sample curves of a PV system whose parameters are described in Table 1 are drawn from Equations (1) to (4).

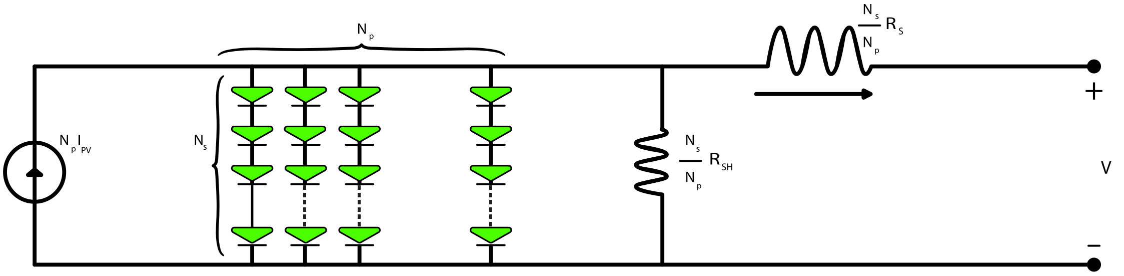


Figure 2. Model of the PV system consisting of series/parallel cells [12].

$$I_{PV} = \left[I_{sc} + K_l\left(T_{PV} - T_{ref}\right)\right], \lambda \tag{1}$$

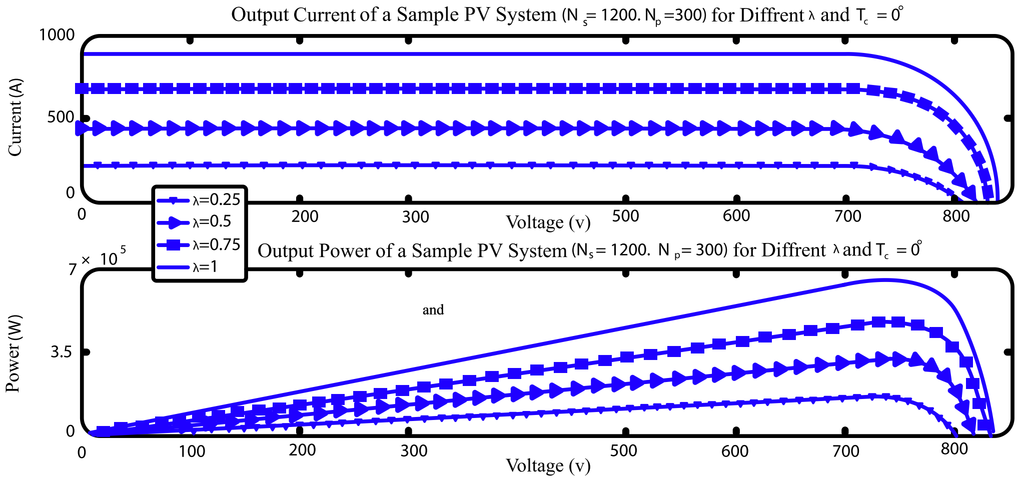
$$I_{RS} = \frac{I_{sc}}{e^{\frac{q, V_{ec}}{N_S, k, A, T_{PV}}} - 1} \tag{2}$$

$$I_S = I_{RS}\left(\frac{T_{PV}}{T_{ref}}\right)^3 \cdot e^{\frac{q, G, \left(\frac{1}{T_{ref}\ T_{PV}}\right)}{k, A}} \tag{3}$$

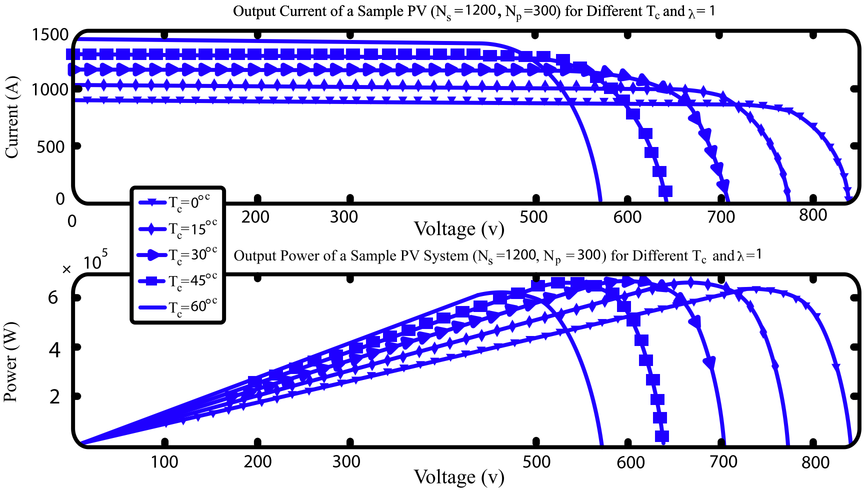
$$I = N_P, I_{PV} - N_P, I_s\left[e^{\frac{q\left(\frac{V}{N_S +} \cdot \frac{R_S . I)}{N_p}\right)}{k, T_{PV} \cdot A}} - 1\right] - \frac{\frac{N_p V}{N_s} + R_s, I}{R_{sh}} \tag{4}$$

Table 1. Parameters of a PV system.

Parameter	Rate
N_s	1000
N_p	250
K_i	0.025
V_{oc}	1200 × 0.6 = 720
I_{sc}	300 × 3.6 = 1090
T_{ref}	25°C
R_{sH}	10000 Ω
R_s	10 μΩ
A	3.3

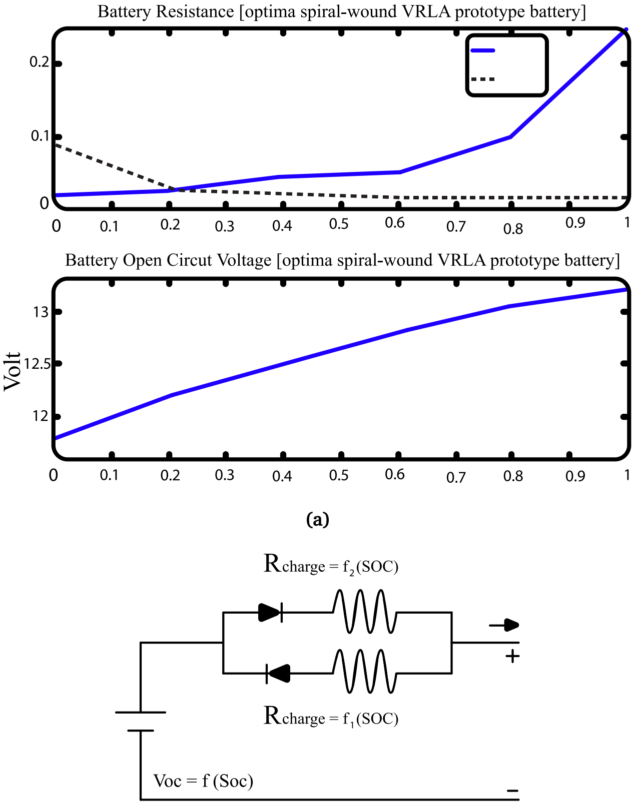


(a)



(b)

Figure 3. Voltage-current curve and power voltage of a sample PV package at (a) certain temperatures and different radiations, and (b) at different temperatures and certain radiations.



(a)

(b)

Figure 4. (a) Open-circuit voltage and internal resistance of a sample battery, (b) internal resistance model of the battery.

2.3. Battery modeling

A well-known battery model is the built-in resistance model [7,8,27,28], where the battery's internal resistance is modeled in charging and discharging modes and fits the charging status. Open-circuit voltage is also defined according to the charging state. This model is illustrated, and Figure 4 also shows the internal resistance and open-circuit voltage for a sample battery.

Battery charging mode, which is one of the most important control parameters of the system discussed in this paper, can be calculated from Equation (5) to (7) [7-9]:

$$\mathrm{SoC} = \frac{\mathrm{A,h} - \mathrm{Ah_{seed}}}{\mathrm{A.h}} \tag{5}$$

$$Ah_{\mathrm{used}} = \mathrm{Ah} \times \left(1 - SoC_{(0)}\right) + \int \frac{I_b}{3600} dt \tag{6}$$

$$I_b = \frac{V_{\mathrm{oc}} - \sqrt{4R_{\mathrm{int}} \cdot P_{\mathrm{el}}}}{2R_{\mathrm{int}}} \tag{7}$$

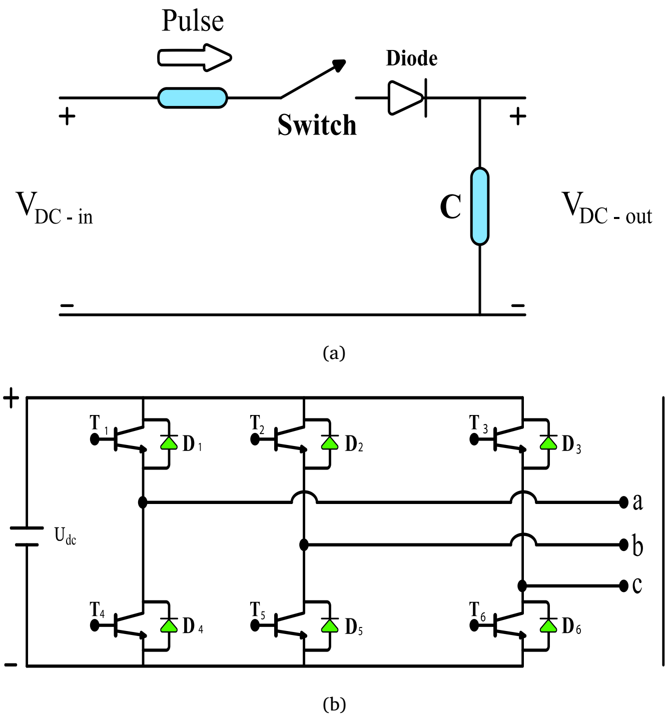
where Ah and $\mathrm{Ah_{seed}}$ are the instantaneous battery ampere-hour and ampere-hour consumed battery, respectively.

2.4. DC/DC and DC/AC inverters

According to the proposed structure of this paper, which is shown in Figure 1, a DC/DC converter is applied to control the absorbed power of the PV system, which is used through the switching pulse width of this model at a specified switching frequency. Figure 5(a) shows this incremental converter. In Figure 5(b), a two-level inverter used in the structure is shown, and its output power will be controlled by switching pulses.

2.5. Estimation of the maximum absorbable power from a PV system

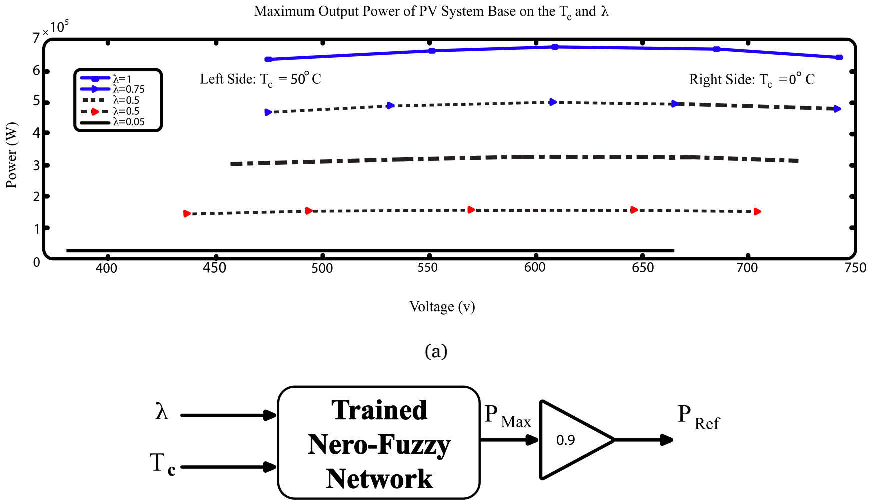
According to the previous explanations, the maximum absorbable power from the PV system depends linearly on two parameters: temperature and ambient radiation. Therefore, it is necessary to estimate the maximum receivable power for each PV system with specific parameters. According to the parameters given in Table 1 used for the PV system in this paper, the maximum power received is obtained according to Figure 6(a). To estimate the maximum absorbable power, Figure 6(a), data have been applied to a form-matching neural fuzzy network, given in Figure 6(b). The membership functions of this network are considered by dividing radiation and temperature values into five different intervals according to Figure 12 and after network training, its fuzzy surface is formed according to Figure 11. To prevent damage to the PV system, after estimating the maximum power absorbed by the fuzzy neural network, 90% of this power is used as reference power and is applied to the absorbed power controller of the PV system.



(a)

(b)

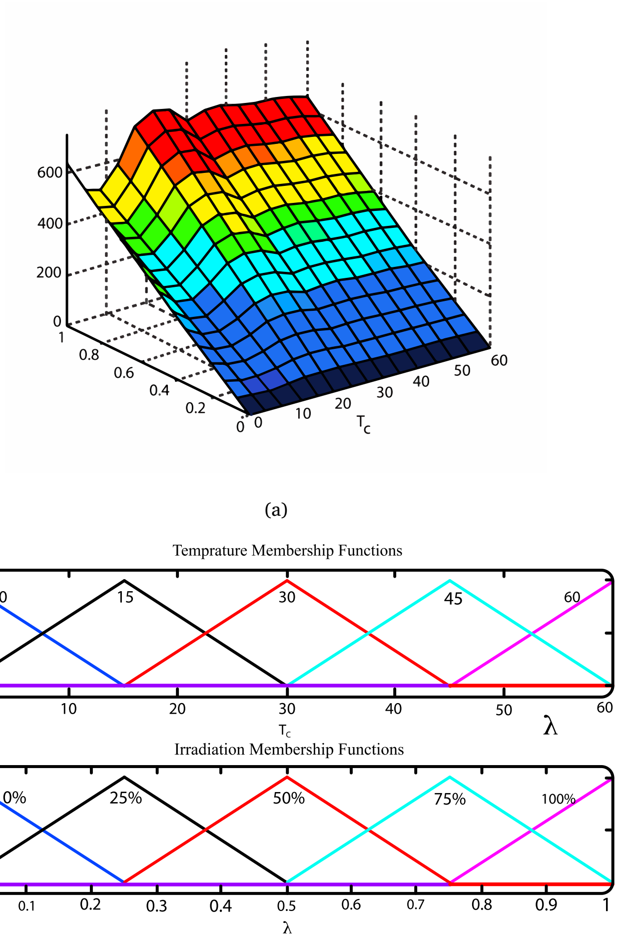
Figure 5. (a) Incremental DC/DC converter implemented, and (b) Two-level inverter used in the structure.



(a)

(b)

Figure 6. (a) Maximum power received from sample systems listed in Table 1 in terms of temperature and radiation, (b) Fuzzy-neural network.



(a)

(b)

Figure 7. (a) Fuzzy surface of the sample fuzzy-neural network, (b) input membership functions of the trained network.

2.6. Design of essential controllers

It is necessary to design two separate controllers for the whole system as follows. The absorbed power controller of the PV system, which should be absorbed from the PV system at any temperature and radiation, can absorb the reference power determined by the fuzzy neural network. This controller performs power adjustment based on the DC/DC converter switching control described in the following sections.

The controller of power transfer to the main grid is required to adjust the transmission power to the network according to the reference value. This is done by controlling the inverter switching described in the following sections. The transmission power will also be determined from the battery charge mode. This is in such a way that if the battery charging mode is desirable, more power than the nominal of the PV system is transferred to the network, which in this case means provision will be part of the power injected by the batteries. Also, if the battery charging mode is low, the power to the network is less than the available power of the PV system, which indicates the transfer of part of the power generated by the PV system to the batteries and causes them to be charged.

2.7. Power controller absorbed from a PV system

This controller must adjust the power transmitted from the PV system according to the reference value generated by the trained fuzzy neural network. For this purpose, at a specified switching frequency, the pulse width of the switching is adjusted according to Figure 8.

2.8. Controller transferred to the network

For this purpose, the output current of the inverter is adjusted after converting to the dq0 frame by switching the controller with mend hysteresis. According to Figure 9, by stabilizing the two 0 and q components, the d component adjusts the current so that the transfer power to the network is equal to its reference value.

Herein, according to the control algorithm discussed previously, the amount of power reference transferred to the main grid should be determined according to the battery charge status, which is applied using a data table as shown in Table 2. K_p is defined as the available power factor of the PV system, and the transfer of power to the network is determined by Equation (8):

$$P_{\text{Ref-Tr}} = K_p, P_{\text{Ref-PV}} \tag{8}$$

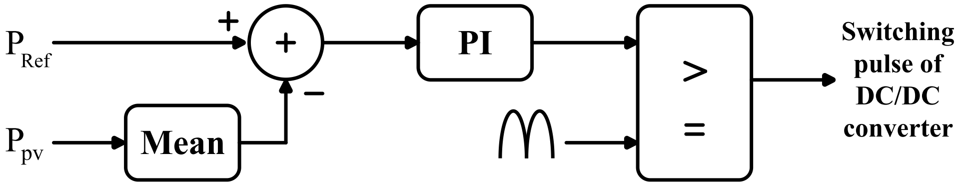


Figure 8. Generation procedure of pulse switching DC/DC converter to control the absorbed power of the PV system.

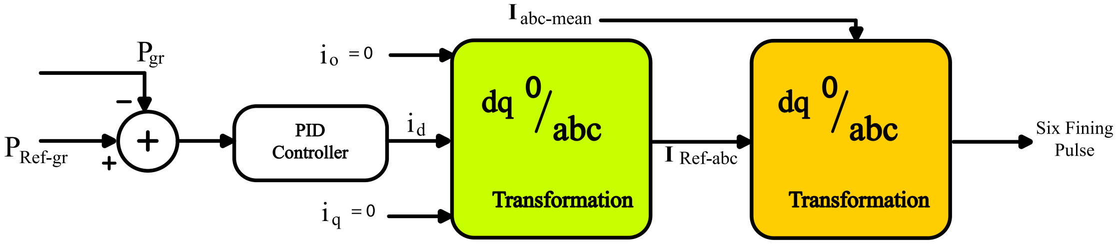


Figure 9. Injectable power controller to the network of the distributed generation system.

Table 2. Input data for battery charge status [29].

S_{oc}	100%	95%	90%	85%	80%	75%	70%
K_p	1.7	1.7	1.5	1.35	1.15	1	0.75

3. Results

3.1. Simulation

The structure shown in Figure 1 is simulated in the Simulink/Matlab environment according to Figure 10, and the parameters related to other parts of the system are under the values listed in Tables 3 to 6. To prove the proposed control performance, different conditions have been analyzed, which are discussed in the next section.

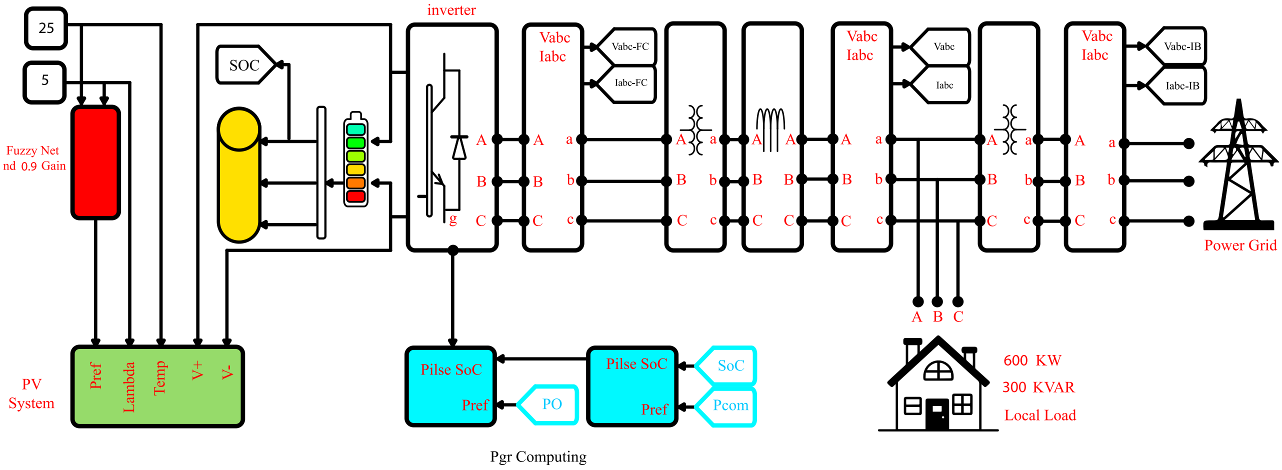


Figure 10. Injectable power controller to the network of the distributed generation system.

Table 3. Features of the implemented batteries.

Parameter	Quantity
N_p	65
$A.h_{Cap}$	110
V_b	10

Table 4. Transformer features connected to inverters.

Parameter	Quantity
N1/N2	0.5/0.5
Srate	1
Lm	470
Rc	470
L1 + L2	0.025
R1 + R2	0.0015

Table 5. Transformer features connected to the grid.

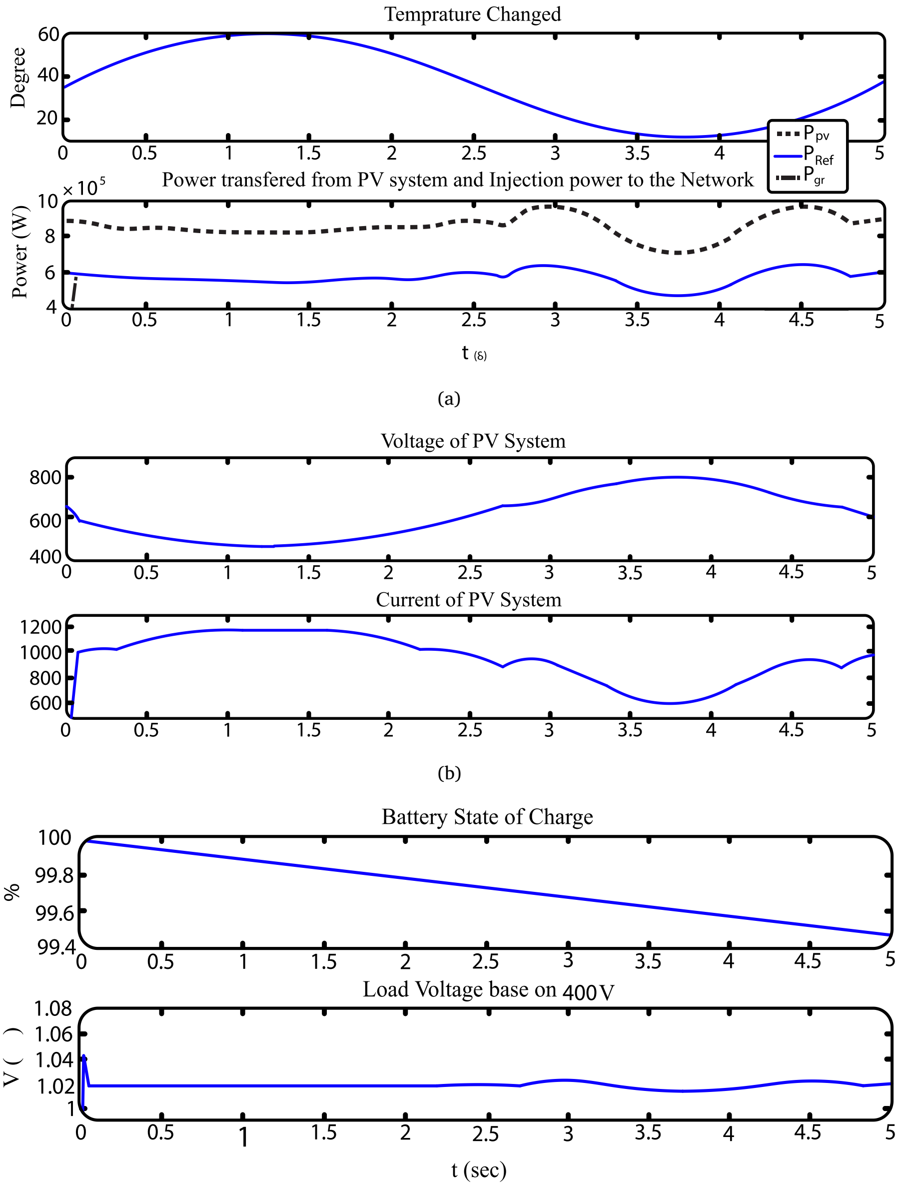
Parameter	Quantity
N_1/N_2	0.5/0.5
Srate	1
L_m	470
R_c	470
$L_1 + L_2$	0.025
$R_1 + R_2$	0.0015

Table 6. Features of the load and overall grid.

Parameter	Quantity
Ssc	520
V	30
F	50
P_L	750
Q_L	350
V_L	360 × 1.08

3.2. Maximum radiation status, maximum charging mode in battery, and variable temperature

In this section, the simulation is performed for a battery with a full charge and maximum radiation ($\lambda = 1$). The ambient temperature is considered a variable temperature according to Figure 11(a). In addition, the temperature variations are assumed to be more extreme and to occur at a faster rate than in reality, due to the shortened simulation time. If the system responds well under these conditions, it can be expected to perform equally well—or better—under real conditions, where temperature changes occur more gradually. In Figure 11(a), in addition to ambient temperature, the power drawn from the PV system (Ppv), injectable power to the global grid (Pπr), as well as the reference power commanded by the controller (P_{COM}) are displayed. In Figure 11(b), the voltage and current of the PV system are displayed, which are changed according to the variable temperature and adjusted by the controller at 90% of its peak value. Since the battery charging status has been favorable, the power transferred to the network exceeds the power drawn from the PV system, which means that part of the power is generated by the batteries, and conspicuously in these conditions, the battery is in discharging conditions. This is specified in the upper part of Figure 11(c). In addition, the load voltage is also stabilized by the inverter to the value of 1 p.u. as specified in the lower part of Figure 11(c).



(a)

(b)

(c)

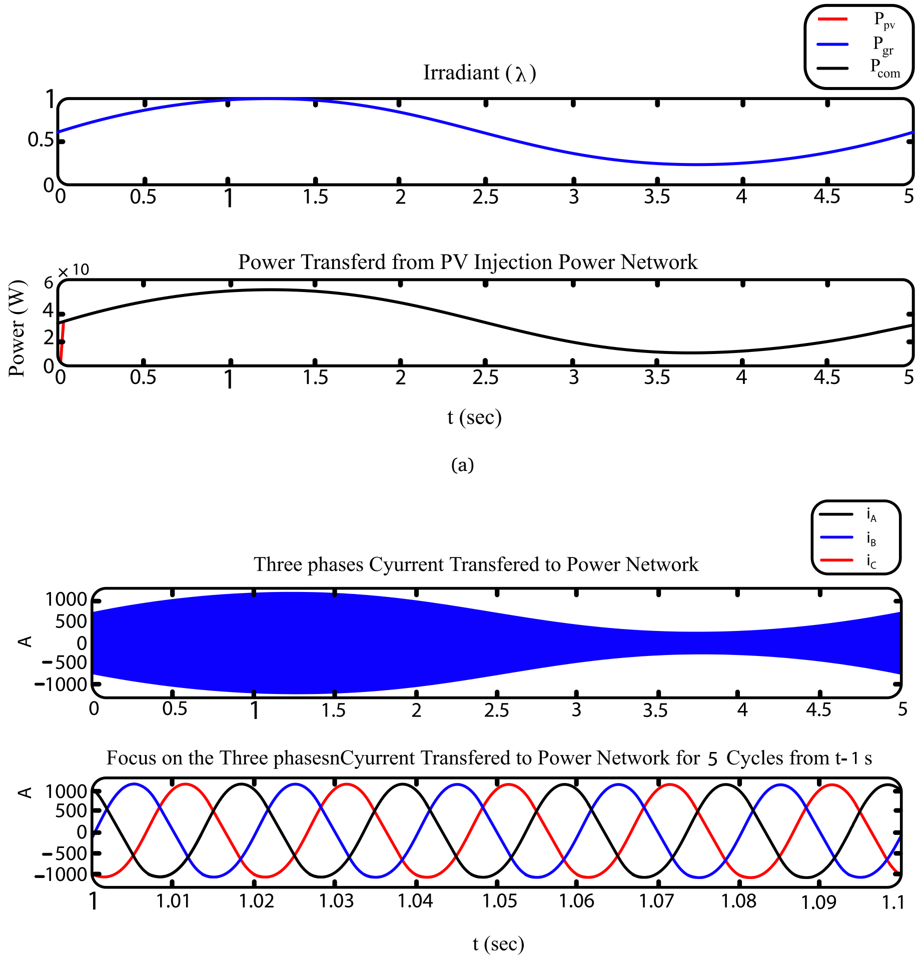
Figure 11. Maximum radiation status, maximum charging mode in battery, and variable temperature.

3.3. Temperature and specified charging mode and different radiation

In this section, a simulation is performed for a certain temperature of 25 °C, charging status of 80% battery, and variable radiation by Figure 12(a), which, due to the reduction of simulation time, radiation changes are considered more than real conditions. According to this figure, the power transferred to the network is exactly equal to the power absorbed from the PV system, and in other words, the battery has no involvement in the transmission of power to the network. The lack of power absorption from the battery is due to the rest state, which has a battery charge mode, and no power is absorbed from the battery. According to these results, it can be concluded that the performance of the controller is accurate, and the transmission power to the network and absorbed from the PV system is set to the desired and predetermined values. In Figure 12(b), to show the harmonic state of the system and the function of the embedded filter, the current waveform is shown along with a small part of it, and as it is known, the harmonic state of the flowing current is appropriate.

3.4. Specified temperatures and radiation, and different modes of battery charge

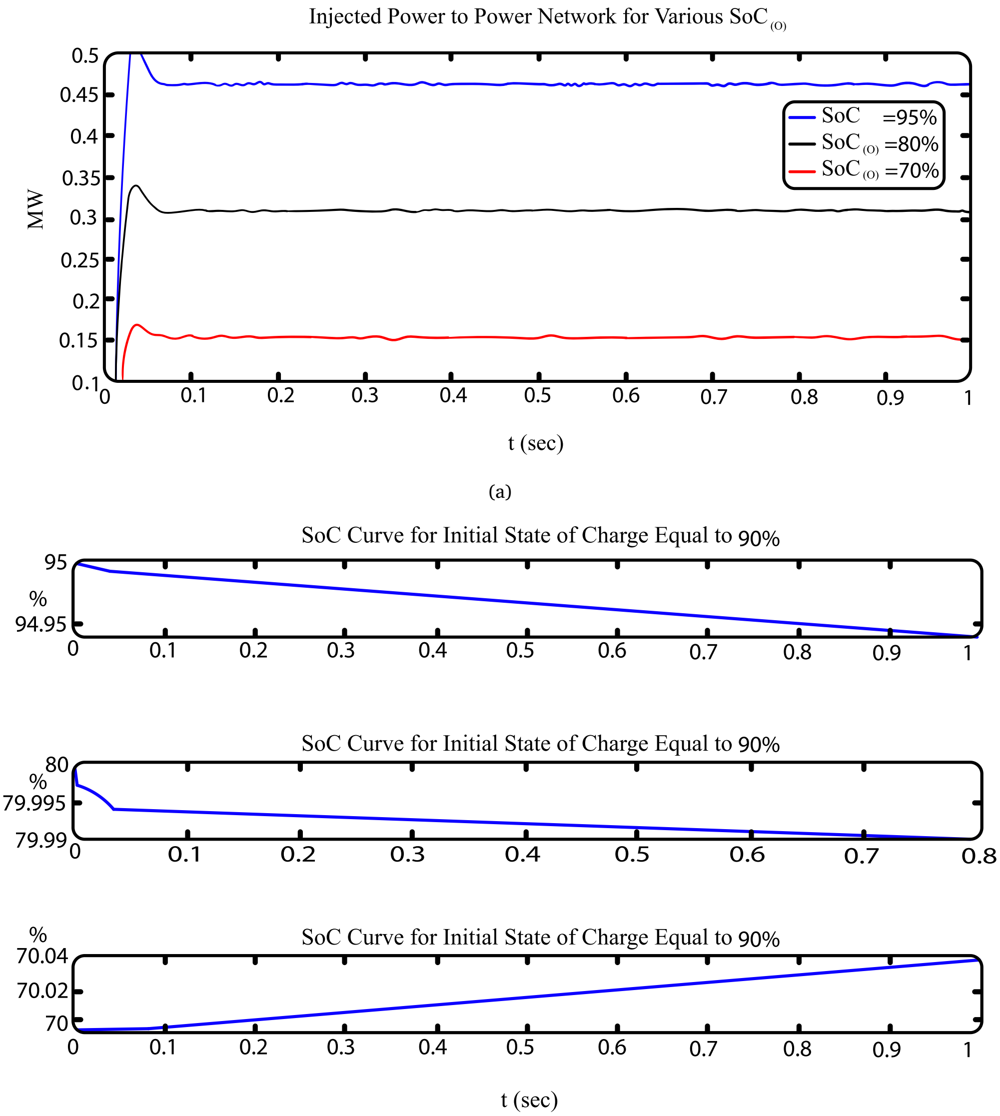
In this section, a simulation is performed for constant temperature and radiation, but with different charging conditions have been performed. The injectable active power is shown in the main grid in Figure 13(a). It is seen that when the charging situation is better, due to the battery's participation in the injection of active power, more power is transferred to the network. In addition, in Figure 13(b), the battery charging status is shown. Due to this, when the battery is charged more, the battery's discharge is done more quickly. Also, as is evident in the lower part of Figure 13(b), in 70% of the charge, the battery is in charge and the charging mode is incremental.



(a)

(b)

Figure 12. (a) Injectable power to the network and drawn from PV systems under variable radiation conditions, (b) Current waveform and part of it under variable radiation conditions.



(a)

(b)

Figure 13. (a) Injectable power to the network in different battery charge situations, (b) Changes in battery charging mode under different battery mode conditions.

4. Conclusions

In this paper, by presenting a suitable structure, a PV system with a battery package as a distributed generation source, with the design of appropriate controllers. The results of this paper showed that at any temperature and radiation, the maximum power received from the PV system can be estimated, and by controlling switching, a converter, the required amount of power can be obtained from the PV system. On the other hand, by designing another control, and controlling the inverter switching, it managed the power transmitted from the battery set and the PV system, and divided between the two sources of battery and PV in a way that the battery charge mode always remained in the above-mentioned state. The results indicate that this structure can serve as an effective distributed generation source. With the appropriate design of the necessary controllers, optimal power management can be achieved. To continue the process of studying, it is recommended to provide different structures for controllers for better performance, as well as different switching structures of converters to reduce switching losses, or to use multilevel inverters.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. The ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, redundancy, have been completely observed by the authors.

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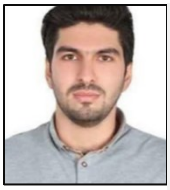

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