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Enhancement of Rooftop Photovoltaic Array Characteristic Interconnected by Grid under Partial Shading Condition Using Cascaded DC/DC Converter

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A B S T R A C T

The photovoltaic (PV) Power generation is the best source of renewable energy due to advantages such as free fuel cost, cleanness, little maintenance, and causing no noise due to absence of moving parts. Egyptian government moves towards encourage consumers to generate electricity from PV array and issues new electricity law that allow consumers to sell the surplus of the generated power of PV to utility. Partial shading is one of the obstacles of the propagation of the electricity generation by PV array. Partial shading may be occurs due to clouds, trees and neighbor building. This paper propose a new method for optimization of power of a rooftop photovoltaic (PV) array connected to grid under partial shading. This work provides a comparative literature review on methods to mitigate these effects and the drawbacks of this method. This paper represent the components of the interconnection between the rooftop PV array and the grid. The Maximum power point (MPP) achieved by perturb and observe technique which control the duty cycle of the buckboost converter. The proposed technique increased the output power of the PV and output efficiency during the partial shading condition.

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INTRODUCTION

Rapid expanding application and demand for alternative energy resources has been increased in recent years. Alternative energy sources such as solar cell or photovoltaic (PV) cell are progressively becoming more popular [1,2] because of availability of sunlight, it is a clean source of energy and new technology led to decreasing the prices of photovoltaic cell. Egypt has a high annual average of irradiance between 2000 to 3200 KWH/m^2/year and the average brightness of the sun in Egypt between 9-11 hours/day [3]. Egyptian government moves toward increase the establishment of the usage of PV array plants to exploit high surface total irradiance as shown in Fig.1. Egyptian government also issued a new electricity law that allows consumers to generate electricity from the PV array and sell surplus of the generated electricity to the electricity company [4]. After gradually removing the governmental subsidies on the price of electricity; It becomes more economical for consumers/investors to produce electricity and sell the surplus to the grid. Also this is very important for government to achieve surplus of the generated power with increasing the population. this surplus of the electricity can support the industrial field .

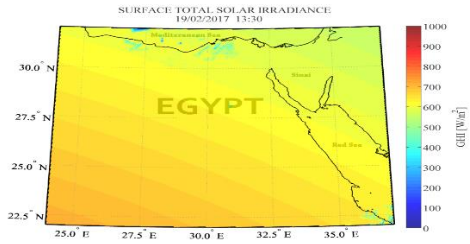

Figure 1. Egypt total surface solar irradiance (SOLAR ATLS)

One of the problems that reduce the effectiveness and economic feasibility of a rooftop PV array is the partial shading of the PV array that may be occurred due to clouds, neighboring homes , trees ,birds, phone pole and power line cable sometimes partially cover the PV modules. The partial shading may also occurred due to mismatching between the characteristic of the PV modules in the same PV array due to manufacturing process. The shaded modules also will consume power from the unshaded modules which may cause occurring of hot spot. Thus, the shaded module may damage so a bypass diode is used to overcome such problem. This bypass power may cause multiple power point as shown in Fig. 2 (b) and loss of power. The partial shading reduces the output power of PV array as shown in Fig. 2 (a, b) and reduces the PV array efficiency less than the primary predicted. Thus lead to increment of initial cost

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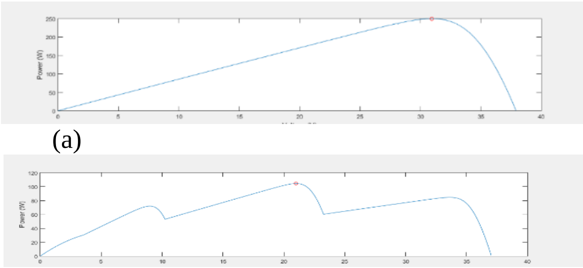
of construction of a rooftop PV array. The interconnection with the grid may be complicated.



(a)

(b)

Figure 2. (a). Power /voltage characteristic under uniform irradiance (b). Power /voltage characteristic under uniform irradiance

An alternative approach was suggested in literature [5-10]. Walker and Serina [5] have conducted a comparison studies between Buck, Boost, Buck-Boost and cuk DC/DC converter for cascaded operation. Buck and Boost converter presented to be the appropriate method. However, this method should be subjected to further comparison for choosing the most appropriate method. Moreover, No control for the cascaded system advised in literature[5].

A basic boost converter with several channel was used by Walid et al. [6] and the output of two channel boost was combined with uncoupled reactor. These two channel boost converters increased the output power of the PV array; also increased the output efficiency of the PV array and reduced the harmonic in the output power. This system is controlled by PWM based PI voltage mode controller; however, this converter has non linearity and non-stability due to its parameter variation. This converter is suitable for low power application only if the power increase the size of reactor increased and also the cost has increased.

Macalpine and Erickson [7] developed power optimizer software for executing a power conversion and distributing maximum power point tracking to capture maximum PV array tied to the electric grid. This software works by taking input parameter data about panel, array, shading obstacles, weather data and using this information to perform plane of array irradiance mapping and using this data to develop annual simulation software for power recovery in array during complete or partial shading. This system required annual update for data and it didn't work accurately if there are unpredictable reason for shading.

Shimizu [8] presented experimental results for a novel technique called generation control circuit which increase the total power of the PV array and keep the maximum power of each module even if these modules didn't received full irradiation by control the output DC of PV array that feed inverter. If there are large numbers of series PV modules it may required high rated DC/DC converter that may increase the cost and increase the power loss.

Paranthagan et al. [9] increased maximum power point from PV array under partial shading condition by performing hill climbing algorithm to identify the global maximum power point using DC/DC converter interface. The output power curve of PV has multiple maximum power points (MPP).

Bidram [10] performed a comparison studies between four categories of solutions used for increasing the output power of the PV array during partial shading conditions. The first group included comparison between modified methods used for tracking the global maximum power point. The second group include comparison between the different array configurations to increase the output power of PV array, namely series-parallel configuration, total cross tie configuration, and bridge link configuration. The third group include comparison between different PV array architecture, namely centralized architecture, series-connected micro-converters, parallel-connected micro-converters, and micro-inverters.

The contribution in this paper are as the follows:

- Providing a simple bidirectional cascaded buckboost DC/DC converter that make completely decoupling between the individual PV modules and provide maximum power point for each PV modules in different irradiation conditions and under partial shading condition.
- Providing maximum power point tracking by using perturb and observe (PO) algorithm.
- Proposing the interconnection between the output of the rooftop PV array and the grid.

This contributions increases the output power of the rooftop PV array, increases output efficiency of PV array under partial shading condition and increases the economic benefits of the owner of PV array that will be able to sell the surplus of the PV array power generation to electric grid.

The components of interconnection system between the rooftop pv array and the grid

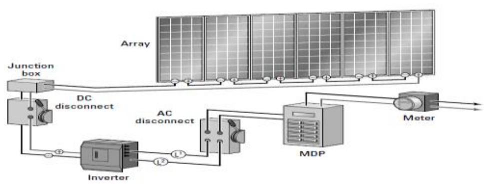


Figure 3. The Components of the direct grid PV system

The PV system may be classified into two categories the stand alone system and the grid connected system. In this paper the grid connected system is recommended.

The required components for the PV system connected with the grid is shown in Fig. 3 which is as the following:

- A PV array with racking

The PV array is the main component of the grid connected system and the sizing of the PV array depends on the loads of consumer and racking of the PV or methods of mounting the PV array depend on the surface tilt angle. This angle is the most significant element for optimization the output power of the PV array as shown in [11] where the tilt angle is the number of degree of the PV modules with the horizontal axis.

- Junction box

A junction box is an enclosure that looks very similar to a combiner box on the outside. Inside, it uses terminals to transition the PV source circuit wires.

- DC Disconnects

A DC disconnects is very important elements for isolation especially for inverter circuit or battery charging circuit.

- An Inverter

It may use an inverter or more than one inverter depend on the sizing of the PV array. It used for converting DC power to AC Power for domestic loads and connection with the grid.

- AC Disconnects

Ac disconnects are used to isolate the inverter from the utility for more safety.

- Main distribution power (MDP)

The utility interconnection across circuit breaker inside MDP.

- The net metering

Net metering, which is when the utility has to credit the system owner with retail rates for

PV-generated energy (within some limits), makes utility-interconnected PV systems a reality. Under net metering, the energy produced by PV recorded.

MATERIAL AND METHODS

Modelling of PV array circuit

Electrical model of PV module (five parameter model)

There are three models for PV cells; ideal, single diode and two diode models .In this paper, a single diode model having five parameters is used as illustrated in Fig. 4. This Electrical circuit of the PV cell represents the behavior of the real cell. This model called single diode five parameter because it depend on five parameters that are the nominal PV current, diode current, series resistance, parallel resistance and output voltage of PV array . These parameters can be estimated as shown in [10].

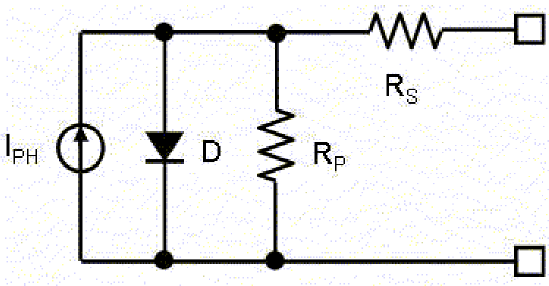


Figure 4. Equivalent circuit of PV cell single diode five parameter model

Mathematical model of PV Module (five parameter model)

From the circuit shown in Fig. 4 it is possible to obtain Eq.1

$$I=I_{PH}-(I_D[e^{\frac{V}{aVt}}-1])-(\frac{V+I\,Rs}{Rp}) \quad (1)$$

where I_{PH} is the photovoltaic current, I_D is the diode current, V is the PV output voltage, Vt is the thermal voltage and Rs is the series resistance, Rp is the parallel resistance and I is the PV output current.

The solution of Eq.1 give the I-V characteristic curve of the PV array.

- Thermal voltage

The thermal voltage of a module with N_c cells is given by the Eq. 2.

$$Vth=\frac{K\,T}{q} \quad (2)$$

where the k is the Boltzmanns's constant ($1.38*10^{-23}$ J/K), q is the electron charge ($1.6*10^{-19}$ C) and T is the temperature.

- Diode reverse saturation current (I_D)

The diode reverse saturation current can be calculated by substituting the open circuit conditions (V=Voc, I=0) as shown in Eq. 3.

$$I_D=\frac{Isc}{\exp(\frac{Voc}{aNcVth})-1} \quad (3)$$

where V_{oc} is the open circuit voltage, I_{sc} is the short circuit current, a is the ideality factor of the diode and N_c is the number of cells.

- Photovoltaic current (I_{PH})

The photovoltaic current I_{pv} depend on the temperature and the solar irradiation as shown in Eq.4.

$$I_{PH}=(I_{ph,reference}+K_t\,(T-T_{ref}))\frac{G}{Gref} \quad (4)$$

where $I_{ph,ref}$ is the photovoltaic current at reference irradiance and temperature (1000 w/m^2 and 25^o C),G is the incident irradiance (w/m^2),T_{ref} is the reference temperature at normal condition (25^o C) and G_{ref} is the reference irradiance or nominal irradiance (1000 w/m^2).

Maximum power point tracking

The Maximum power point tracking is a technique for maximizing the output power of the PV array under different irradiation and temperature condition. It isn't mechanical system by the physical moving of the PV array but it is electronic system which control the operating point of the PV array to maximizing the output power of the PV array and output efficiency. MPPT depends on the maximum power transferring theory that the output power of the circuit is maximum when the source impedance matching the load impedance and this achieved by controlling the duty cycle of the DC/DC converter in [12]. Hence the main obstacles of the MPPT is the matching between source impedance and load impedance.

Comparison between different methods of MPPT

There are different methods of the tracking the maximum power point. Some of the most popular methods [4] are:

- Perturb and observe (hill climbing method)
- Incremental Conductance method.
- Fuzzy logic
- Neural networks

Bidram [10] made a comparison studies between the different methods of the MPPT.

Perturb & observe (PO) algorithm

Based on literature [10] perturb and observe (Power curve Slope) is one of the most accurate methods used for MPPT. The PO algorithm refer to the operating voltage of the PV array is increased by small value ΔV and observe the change in power ΔP. There are two cases if the change of the power ΔP is positive then the increasing of Voltage in the direction of MPP; else the increasing of voltage is going away from the MPP.

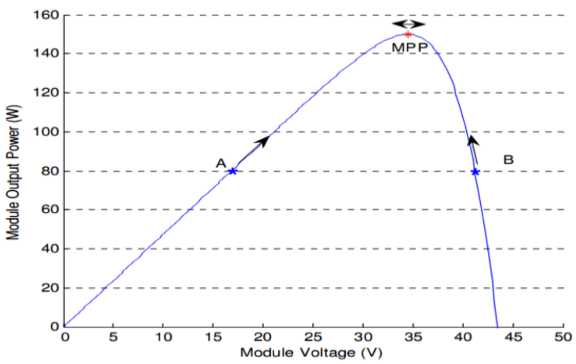


Figure 5. Power/voltage characteristic of PV array at different operating point A,B

Fig.5 shows the power/voltage characteristic of PV array at different operating voltage points at given irradiation level. At point A if the operating voltage increased by small value ΔV then the Power ΔP is positive it means that the increase of voltage in the direction of the MPP. At point B if the operating voltage increased by ΔV then the power ΔP is negative it means the increase of the power in the opposite direction of MPP. The flow chart of PO algorithm is shown in fig. 6.

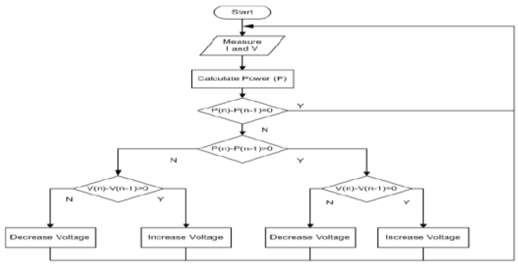


Figure 6. Flow chart of Perturb & Observe method

The buck boost DC/DC cascaded converter

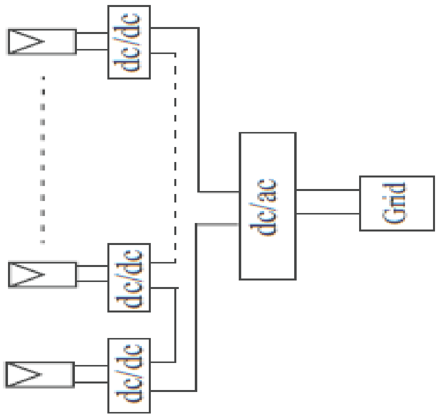


Figure 7. Cascaded DC/DC Converter connected to PV array interconnected with the grid

The operating voltage point of the PV array varied due to different loads and different environmental condition (irradiance and temperature).The maximum power point achieved by increasing the voltage by small value Δv and observe the power. This change of the voltage achieved by the DC/DC converter. Walker and Serina [5] made comparison between the different DC/DC converter and found that the buck boost converter is the most appropriate one. The cascaded DC/DC converter to provide decoupling of the different modules of the array and maximizing the power of each modules under different irradiation conditions. In this Paper, switches of the buckboost converter controlled by Perturb and Observe algorithm to achieve the maximum power and the control system shown in fig. 8.

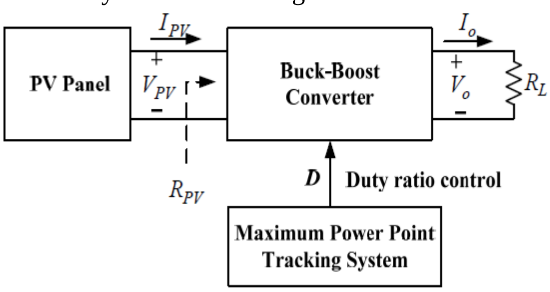


Figure 8. The MPP control system of the buck-boost converter

Mathematical model of the buckboost converter

Assuming the Buckboost is operating in continuous conducting mode; the relation between the output voltage, current and those of the PV array voltage and current is given in Eq. 5.

$$V_o=\left(\frac{D}{1-D}\right)*V_{pv}\,;I_o=\left(\frac{1-D}{D}\right)*I_{PV} \quad (5)$$

where

V_o: the output voltage of the buck-boost converter.

V_{PV}: the output voltage of the PV array.

I_o: the output current of the buck-boost converter.

I_{PV}: the output current of the PV array.

D: duty cycle of buck-boost converter.

The output voltage and current controlled by adjusting the duty cycle D so we can maximizing the output power by adjusting duty cycle at different irradiance level as shown in Fig. 9.

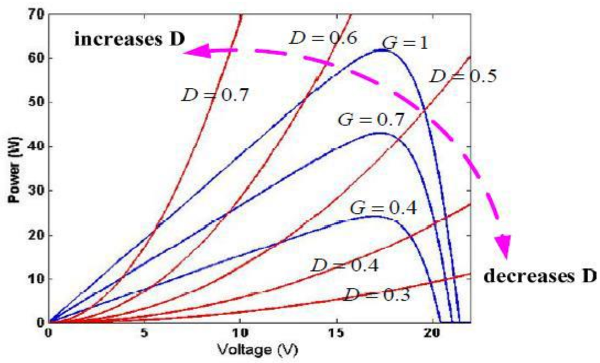


Figure 9. Power/voltage characteristic of the PV array at different duty cycle

RESULTS AND DISCUSSION

Simulation and results

Simulation

The simulated system represent 400 kW PV array connected to a 250 kW grid by cascaded converter controlled by Perturb and observe method as shown in Fig. 10. The PV array consist of four modules delivering each 100 kW at irradiation of 1000W/m^2. A single PV array block consist of 64 parallel strings where each string has 5 Sun Power SPR-315E modules connected in series and the parameter of each PV module shown in Table 1.

Each PV array is connected to a DC/DC converter (average model). The outputs of the buck-boost converters are connected to a common DC bus of 500 V. Each buck-boost is controlled by individual Maximum Power Point Trackers (MPPT) as shown in Fig. 11. The MPPTs use the "Perturb and Observe" technique to vary the voltage across the terminals of the PV array in order get the maximum possible power.

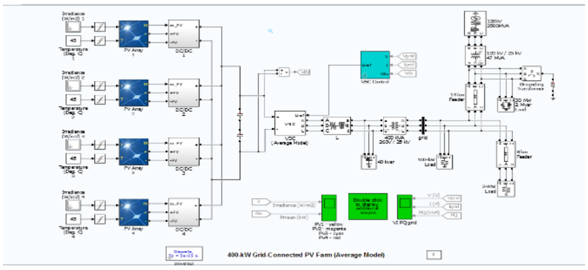


Figure 10. Simulated 400 kW array connected to 250 KW grid.

TABLE I. Parameters of the PV module

Parameter	Value
I_{MPP}	8.07A
V_{MPP}	10.32V
P_{MPP}	83.28W
$I_{s.c.n.}$	8.62A
$V_{o.c.n.}$	13.30V
$I_{0.n}$	1.4176e-10A
a	0.99132
Rs	0.098 Ohm
Rp	82.11Ohm

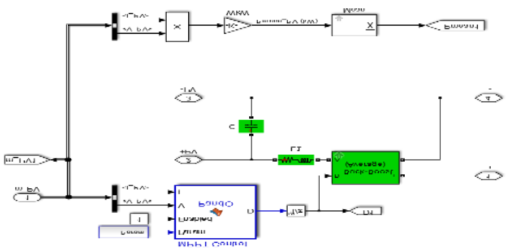


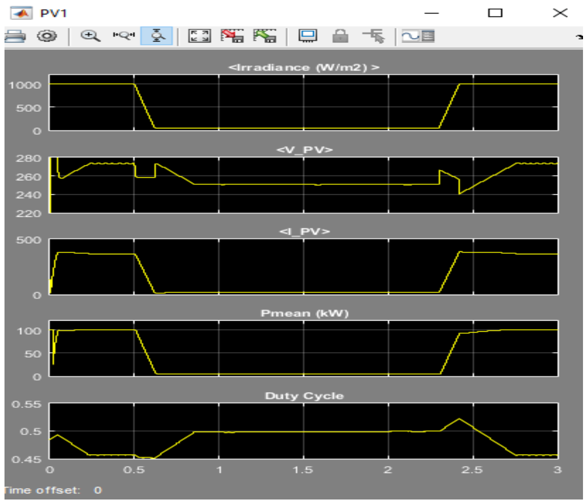
Figure 11. Buck-boost converter controlled by Perturb & Observe algorithm

A three-phase voltage source converter (VSC) converts the 500 V DC to 260 V AC and keeps unity power factor. A 400-kVA 260V/25kV three-phase coupling transformer is used to connect the converter to the grid. The grid model consists of typical 25-kV distribution feeders and 120-kV equivalent transmission system.

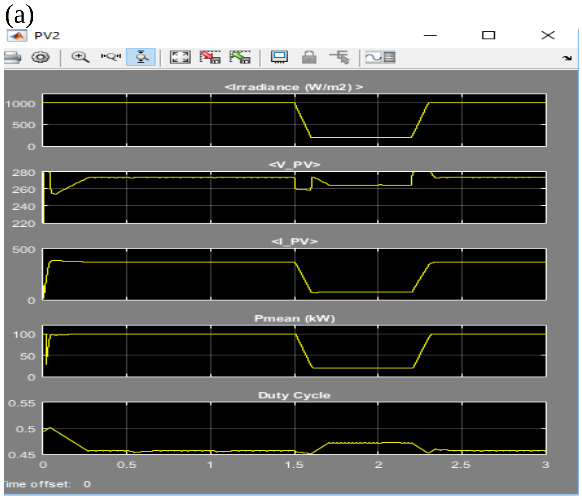
In the average model the buck-boost and VSC converters are represented by equivalent voltage sources generating the AC voltage averaged over one cycle of the switching frequency. Such a model does not represent harmonics, but the dynamics resulting from control system and power system interaction is preserved. This model allows using much larger time steps (50 us), resulting in a much faster simulation.

Results

The partial shading effected on the four PV modules gradually to illustrate the advantages of decoupling system of the 4 cascaded DC/DC converter as shown in Table 2; and the output wave form of each module shown in Fig. 23(a,b).



(a)



(b)

Figure 12. (a). Output wave form of the PV module 1 with MPP. (b). Output wave form of the PV module 2 with MPP.

TABLE II. The irradiance at each module during the cycle time

Time (us)	PV 1 irradiance (w/m^2)	PV2 irradiance (w/m^2)	PV3 irradiance (w/m^2)	PV4 irradiance (w/m^2)
0	1000	1000	1000	1000
0.5	500	1000	1000	1000
1	500	1000	1000	350
1.3	500	1000	600	350
1.5	500	200	600	350
2	500	200	600	1000
2.2	500	1000	600	1000
2.3	1000	1000	1000	1000

Fig.12 (a) illustrates that when the PV module 1 exposed to full irradiance (0 to 0.5 us) the buck converter stepped the voltage down to keep the operating voltage point of the PV 1 and when the PV1 exposed to partial shading (0.5 to 2.2 us) the boost converter step the voltage up to keep the operating voltage point of the PV1. The same phenomenon occurred for the other modules. The buck-boost converters are controlled by perturb and observe operation. This cause the output power of the grid and power of the grid did not effect by the partial shading as shown in Fig. 13.

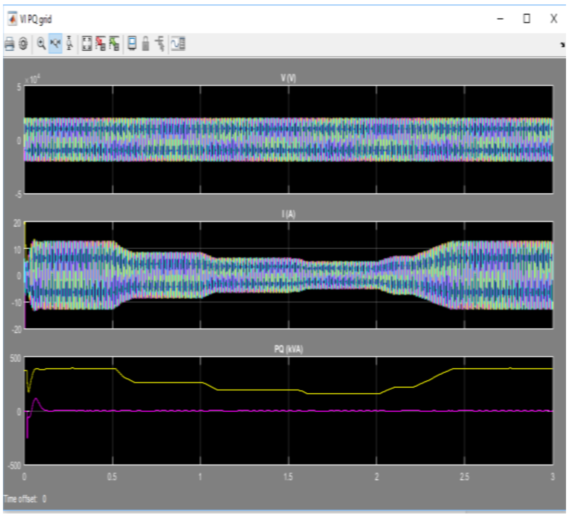


Figure 13. Output wave form of the voltage, current and apparent power of the grid with MPP

CONCLUSION

In this paper, the components of the PV array system interconnected with utility are discussed. Modeling of single diode model is introduced and performing a comparison between different maximum power point techniques. The cascaded buck-boost converter controlled by Perturb and observe presented. Simulation of the 400 kW PV array interconnected to 250 kW with decoupling cascaded DC/DC converter which keep the output power of each module maximum power even if partial shading occurs on the modules. Analysis of results under different irradiance during the cycle with fast switching are introduced. In addition the effect on the grid voltage, current and apparent power were recorded.

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Persian Abstract

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چکیده

تولید انرژی فتوولتائیک (PV) به دلیل مزایای استفاده از قبیل هزینه رایگان سوخت، پاکیزگی، نگهداری کمی و ایجاد سر و صدا ناشی از عدم وجود قطعات متحرک بهترین منبع انرژی تجدیدپذیر است. دولت مصر به دنبال تشویق مصرف کنندگان برای تولید برق از آرایه PV و صدور قوانین جدید برق است که به مصرف کنندگان اجازه می دهد که مازاد تولید نیروی برق PV را به خدمت بفروشند. سایه جزئی یکی از موانع انتشار تولید برق توسط آرایه PV است. سایه ممکن است به دلیل ابرها، درختان و ساختمان همسایه ایجاد شود. در این مقاله یک روش جدید برای بهینه سازی قدرت آرایه فتوولتائیک (PV) پشت بام متصل به شبکه در زیر سایه زنی پیشنهاد شده است. این کار یک بررسی ادبی تطبیقی را در مورد روش های کاهش این اثرات و نقایص این روش ارائه می دهد. این مقاله نشان دهنده اجزای اتصال بین آرایه PV پشت بام و شبکه است. نقطه حداکثر قدرت (MPP) با اختلال حاصل شده و روشی را که کنترل چرخه کار مبدل باکبو را کنترل می کند، مشاهده می کنیم. تکنیک پیشنهادی، قدرت خروجی PV و بازده خروجی را در شرایط سایه زنی جزئی افزایش داد.