Available online at www.sciencedirect.com
ScienceDirect
Energy Conversion and Management 49 (2008) 2307–2316
ENERGY CONVERSION & MANAGEMENT
www.elsevier.com/locate/enconman

Voltage based power compensation system for photovoltaic generation system under partially shaded insolation conditions

Engin Karatepe [a,*], Takashi Hiyama [b], Mutlu Boztepe [a], Metin Çolak [a]

[a] Department of Electrical and Electronics Engineering, Ege University, Izmir 35100, Turkey
[b] Department of Electrical and Computer Engineering, Kumamoto University, Kumamoto 860-8555, Japan

Received 4 June 2007; accepted 14 January 2008
Available online 4 March 2008

Abstract

Partially shaded photovoltaic (PV) modules typically exhibit additional difficulties in tracking the maximum power point since their power–voltage characteristics are complex and may have multiple local maxima. For this reason, conventional techniques fail to track the maximum power point effectively if the PV array is partially shaded or some of its cells are damaged. This paper presents a novel power compensation system for PV arrays for complicated non-uniform insolation conditions. The proposed system is based on recovering the power of non-shaded PV modules into the system again completely by forward biasing a bypass diode of the shaded PV modules. For this purpose, the proposed system uses dc–dc converters equipped with each PV string in the PV array. For identifying which shaded PV modules should be deactivated, the operating voltage of the PV modules are monitored and compared. The proposed system enables the non-shaded PV modules to operate effectively at their normal maximum power point. The effectiveness of the proposed system is investigated and confirmed for complicated partially shaded PV arrays.

Keywords: Photovoltaic array; Maximum power point tracking; Partial shading; Mismatching; Non-uniform insolation

1. Introduction

The world's increasing energy demands and environmental pollution are motivating research and technological investments related to renewable energy sources. Among the various renewable energy systems, PV power generation systems are expected to play an important role as a clean power electricity source since solar energy offer easy installation to end users on roof tops of residences and facades of buildings. It is crucial to improve its efficiency and develop the reliability of PV generation control systems [1]. There are two ways to increase the efficiency of PV power generation. The first is to develop materials offering high conversion efficiency at low cost. On the other hand, the most important issue is to operate PV systems optimally for getting better efficiency. In practical applications, a PV module consists of many solar cells connected in series, and PV modules are wired together into arrays, both in series and in parallel to provide the necessary voltage and/or currents. The output power of a PV array decreases considerably when the current–voltage (*I*–*V*) curves of the solar cells are not identical due to soiling, non-uniform irradiation, cloud, cell damaging, partial shading etc. Shading part of a PV array has a very dramatic effect on its power–voltage (*P*–*V*) curve [2–4]. Shading even a very small fraction of the array may result in a very significant reduction of the total array power. Partial shading can occur by utility poles, chimneys, trees, parts of other buildings etc. In the future, a significant number of PV systems will be installed not only on the roofs but also wherever sunlight is available. Because of the high cost of solar cells, it is necessary to operate the PV array at the optimal operating point. So, tracking the maximum power point (MPP) of a PV array is usually an essential part of a PV system [5]. Therefore, suitable MPP tracking (MPPT)

* Corresponding author. Tel./fax: +90 232 3886024.
E-mail address: engin.karatepe@ege.edu.tr (E. Karatepe).

0196-8904/$ - see front matter © 2008 Elsevier Ltd. All rights reserved.
doi:10.1016/j.enconman.2008.01.012

control systems must be developed for partially shaded conditions, and investigations of mismatching effects must be increased for improving the performance and reliability of PV systems.

Several MPPT algorithms have been proposed so far. Those papers are based on, for example, the so called mountain climbing method, the dV/dI method, fuzzy logic theory, neural network, genetic algorithm and so forth [1,5–7]. Most of these MPPT methods have been developed for uniform insolation conditions. If there are multiple peak points, they are not useful and converge to a local MPP [1,5]. Since a PV array has non-ideal I–V characteristics and conditions such as insolation, ambient temperature and mismatching that affect the output of the PV array are unpredictable [2,8,9], a MPP tracker must successfully manage non-linear and time varying systems. Because of partial shading, multiple local maxima points occur in the P–V curve [2]. In addition, the global MPP of a large scale PV generation system is certainly dependent on the pattern of partial shading [2,10]. It is a very difficult problem to operate the PV system at its optimal point for a conventional MPP tracker when solar cells are partially shaded or if some cells in the PV array are damaged [5,11]. Therefore, in recent years, novel MPPT methods have been widely discussed to overcome partial shading effects [12–18].

Mishima and Ohnishi [12] proposed a system that can control the output power of the array on a PV string basis, which contributes to a more efficient and simpler implementation of the PV power compensation system than that by individual controls of PV modules using dc–dc converters [13]. The basic idea of Ref. [12] is to feed the bias voltage into the shaded PV string so that it generates the maximum power at the same operation voltage as the other blocks. A single partially shaded PV string is chosen by a selector and is fed a bias voltage. If there are partial shadings in more than one PV string, the bias voltage have to be controlled separately due to the fact that the shading level or pattern may not be same in all strings. In other words, each shading string needs a different biasing voltage. For this reason, if a complicated partially shading occurs, this method can not be used. Shimizu et al. [13] proposed a generation control circuit in which a dc–dc converter is provided for each PV module so as to control its operation voltage. However, this approach might result in excessive complexity of the system configuration. This kind of system seems to have limitations in regard to controlling the operation current of the PV module and to generate power losses associated with the many power conversion stages in large scale PV systems. Kobayashi et al. [14] and Irisawa et al. [16] proposed a two stage MPPT control process consisting of a first stage control and a second stage control. The PV system is controlled in such a way that the operating point of the PV system moves to the vicinity of the real peak power point at the first stage and converges to the real power point finally at the second stage. However, this method may not track the real MPP for some non-uniform conditions. For this reason, it requires some additional control process to track the real MPP. Miyatake et al. [15] proposed a MPPT employing a line search algorithm with improved Fibonacci search to find the global MPP when the PV array is partially shaded. However, this approach too can not guarantee to find the global MPP under all conditions [15]. Bekker and Beukes [17] proposed a fractional open circuit voltage method that periodically sweeps the PV array voltage from open circuit to short circuit to update the fraction giving the relationship between MPP voltage and open circuit voltage to find the optimal operating point. This, obviously, causes more power losses. In addition, some doubt exists on how efficiently the system will perform on days with fast moving clouds with this kind of method [17]. Ref. [18] proposed a power compensation strategy based on electric double layer capacitors for a partially shaded PV array. In this method, the current difference between shaded and unshaded PV modules is compensated by a discharge current from an electrical double layer capacitor current.

All of the methods mentioned above did not deal with much more complicated non-uniform insolation when demonstrating the control characteristics of the power compensation system and the feasibility of the system. Consequently, many factors must be considered when designing the power compensation and control system of a PV system, and no single method can be claimed to be the best.

In this paper, in order to overcome the problem of partial shading and obtain generation power more efficiently, a novel power compensation strategy and its system are proposed for complicated partially shaded PV arrays. The proposed system can be realized by using a dc–dc converter for each string instead of each PV module, and the system can be controlled in a very simple manner. Each string has own controller. The design goal for the proposed system is to find a control law such that

(1) the control system shall operate the PV system at its optimal point for much more complicated partially shaded insolation conditions,
(2) the system shall be relatively simply controlled,
(3) the power of non-shaded PV modules shall be recovered into the system again.

In the proposed system, shaded PV modules are deactivated by forward biasing the corresponding bypass diode according to the shading level of the PV module. One important point is to determine how many modules will be deactivated for each string. This is required to determine the bias voltage value to be applied for each shaded PV string. In this paper, the number of deactivated shaded modules is determined by monitoring and comparing the operating voltages of each PV module. The behavior of each string can be investigated separately. As will be shown, the proposed system implies considerable advantages in terms of controller simplicity to overcome the partial shading problem. The system operation is demonstrated, and the compensation effect is verified for much more complicated partially shading scenarios. The results confirm that the proposed technique is robust and insensitive to changes in system parameters and achieves reduced power losses even with non-uniform insolation conditions or the presence of multiple local maxima.

2. Connection of PV array and associated problems

In practical applications, almost all PV modules that consist of 36 series connected solar cells incorporate two bypass diodes to prevent non-recoverable reverse bias breakdown of the solar cells and hot-spots. A bypass diode is installed parallel to each PV module in the series connection of multiple PV modules so that no current limitation may occur at the shaded module. If a bypass diode could be installed inside each solar cell, shading effects would be reduced in some degree [1]. However this is not a convenient approach for commercial purposes due to the technological limitations [1,19]. On the other hand, the bypass diode holds its corresponding group of cells to a small negative voltage of approximately 0.8 V since the bypass diodes are placed across their corresponding groups of solar cells. For this reason, when partial shading occurs, bypass diodes cause drastic changes of the overall *I–V* curve of the PV array. So, several local MPP are formed in the *P–V* curve. This causes serious problem for MPPT control of the system [1,2,13].

There are various shading patterns. In addition, a proposed system must maintain stability for all non-uniform insolation conditions. Both of them are the main difficulties when solving the partial shading problem. Before trying to solve or reduce the partial shading effects, a thorough understanding of their origin and behavior is required. Since field testing is costly, time consuming and depends heavily on the prevailing weather condition, it is necessary to define a circuit based simulation model that properly allows the inclusion of mismatch effects with high accuracy [2,20–22]. In the present paper, we use the PV array model presented in Ref. [2]. Only a single shaded cell in a PV module is enough to change the *I–V* curve characteristic of the PV array [2]. Since Ref. [2], more analysis and data have been presented; modeling of PV arrays is not within the scope of this paper.

In Fig. 1, the MPP voltage is plotted against the uniform insolation levels from 100 W/m^2 to 1000 W/m^2 for a 4 × 3 PV array consisting of four series connected Siemens SM-55 PV modules and three parallel strings. Table 1 shows the specification of the SM-55 PV module. A PV module temperature stays relatively stable over short periods of time due to the thermal time constant of the PV module materials [23]. The biggest influence on the power occurs due to the partial shading. Therefore, cell temperature changes can be omitted [12–18], and the cells temperature is assumed as 45 °C in this paper. As can be seen in Fig. 1, the MPP voltage changes in a very narrow window under the high irradiation level. Extreme power losses due to partial shading are already seen under high level insolation conditions especially. The DC bus voltage of the PV array can be set to the optimum operation voltage according to unshaded PV strings by using an interactive inverter [12] or the output of the PV array can be coupled to a constant voltage load [24]. Therefore, the PV array output can see almost a constant DC voltage [12,18]. So, during the simulations to simplify description of the proposed system, a constant voltage load is used in this paper [24,25]. Ref.

Table 1
Specification of SM-55 PV module

Maximum power (P_{mp})	55 W
Open circuit voltage (V_{oc})	21.7 V
Short circuit current (I_{sc})	3.45 A
Operating voltage at maximum power (V_{mp})	17.4 V
Operating current at maximum power (I_{mp})	3.15 A
(AM 1.5, 1000 W/m^2, 25 °C)	

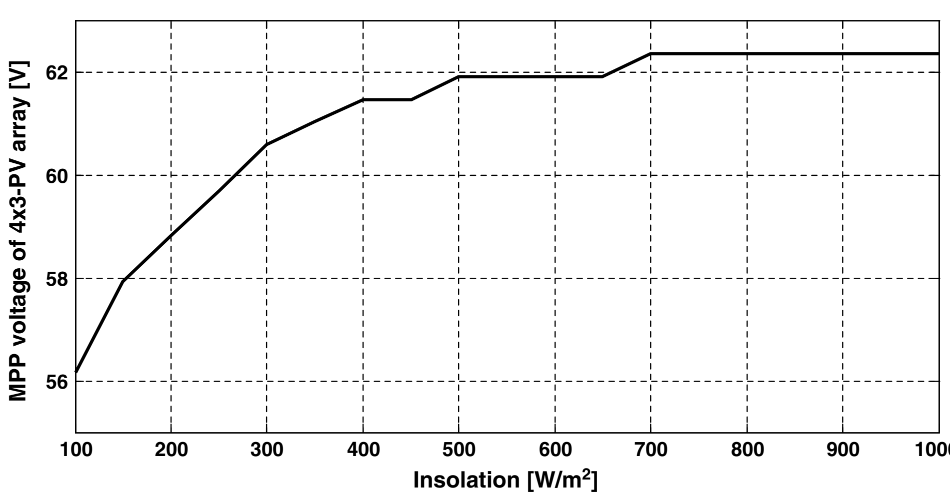

Fig. 1. MPP voltage changing versus uniform insolation condition for 4 × 3 SM-55 PV array for 45 °C.

[13] used a resistance load to simplify the explanation. When PV strings are connected in parallel, they are all constrained to operate at the same DC bus voltage, which could cause voltage mismatch due to shaded modules in the string. It means that unshaded modules begin to operate away from their individual MPPs. Consequently, the operation voltage of the unshaded PV modules, which are connected in series, shifts to a higher than their optimum voltage value to compensate for the voltage drops resulting from the forward biasing bypass diode of a shaded PV module. These phenomena cause the voltage of PV modules to change to unwanted operating points, and the PV array power is drastically reduced. The reason for reducing power is that this kind of operating voltage shifting also causes the operating current of the unshaded PV modules to shift to a smaller current on their *I–V* curve. In this study, we intend to operate unshaded PV modules at their optimum operating voltage again when any partial shading occurs.

3. The proposed system configuration and control principle

The main proposed control system configuration with power compensator is shown in Fig. 2. Although only a 4×3 PV array configuration is investigated in the present paper, the mechanism for other configurations is similar to that for the 4×3-PV array. PV modules are represented as PV-1, PV-2,..., PV-12. Each PV string is fed a different bias voltage, V_{b1}, V_{b2} and V_{b3}. The decision unit supplies the reference voltages V_{ref} for the dc–dc converter by comparing the module voltages in each string separately. When determining the V_{ref} values, we do not need to sense any current. This feature also can facilitate controlling the system. Since each SM-55 PV module has two bypass diodes, one PV module shows two PV module characteristics. Each part consists of 18 series connected solar cells. So, there are 8 PV module characteristics for each string in the 4×3-PV array. The MPP voltage of each part is about 7.7 V for 45 °C temperature within the interval of 400–1000 W/m^2.

The differences between module voltage values in each string can give clues about the shaded level of the PV module. After observing several partial shading conditions, we obtained the following condition: when the difference between a PV module operating voltage value and the highest operating voltage value in that string is greater than 4 V, that shaded PV module should be deactivated. This value means that if the shaded module insolation level is below half of the general insolation level, that module will be deactivated. This voltage criterion may change with module types. It is very difficult to present here all operating voltage values for several non-uniform conditions when getting this voltage criterion. However, this criterion can be obtained easily for any PV module by observing the distribution of operating voltages. Fig. 3 shows the relationship of PV array output power and dc bias voltage and insolation level of shaded PV modules when two shaded parts of the PV modules exist in String-2 in the 4×3 PV array. As can be seen in Fig. 3, when the insolation level of the shaded modules is above half the general insolation level of the PV array, which is about 1000 W/m^2 for this case, the dc bias voltage should not be applied to deactivate the shaded modules. The output power of the PV array increases with increasing dc bias voltage up to the optimum bias voltage level during the period when the shading insolation level is low. If the insolation level of the shaded modules is less than half of the general insolation level, the

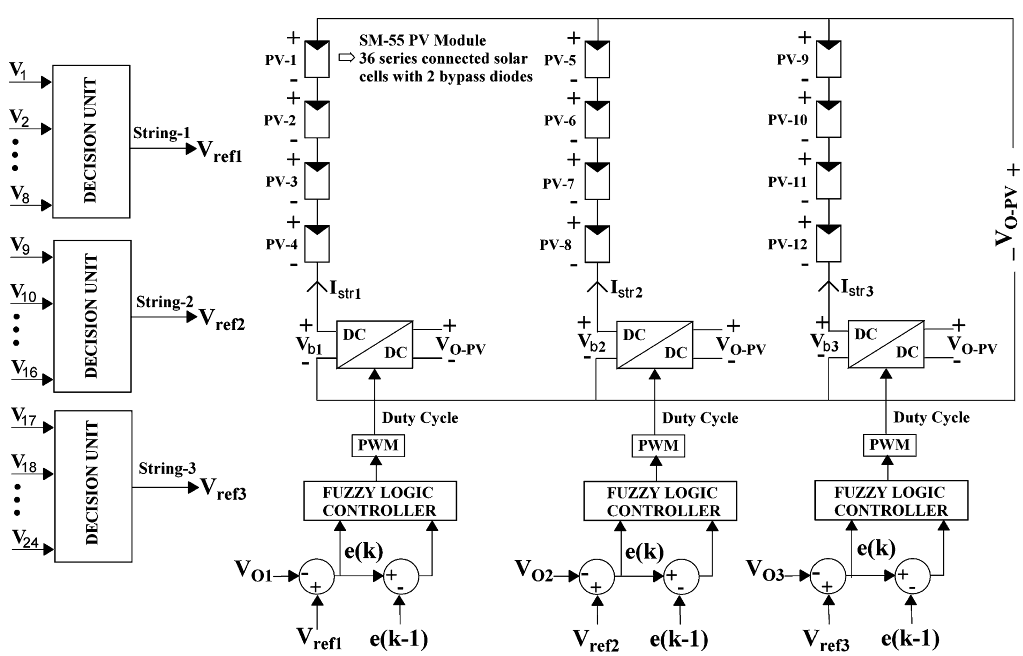

Fig. 2. Configuration of the proposed system for 4×3 PV array (each PV module has two bypass diodes).

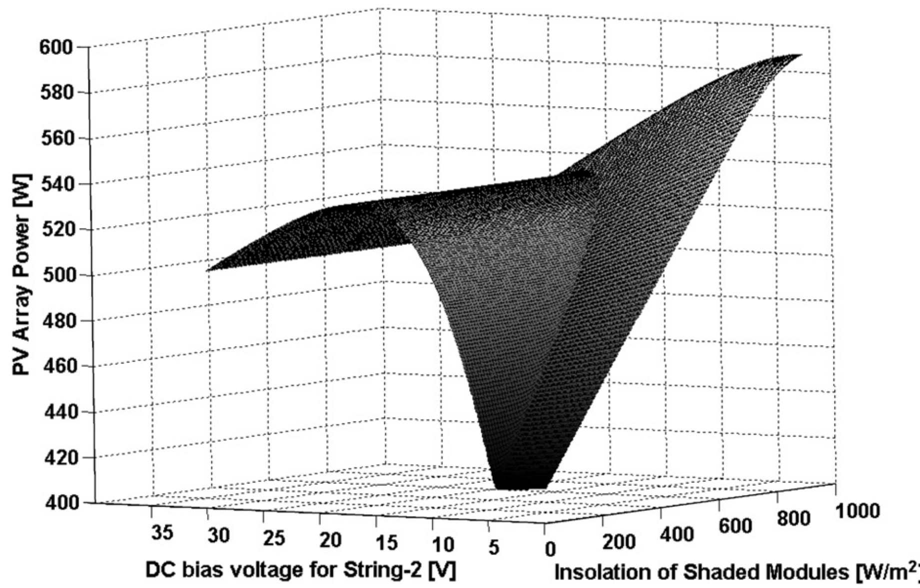

Fig. 3. PV array output power changing versus bias voltages in String-2 and insolation level of two parts of a PV module in String-2 when insolation over unshaded modules is 1000 W/m^2 in 4×3 PV array.

output power decreases with increasing dc bias voltage. Also, for low shading insolation levels, the existence of the optimum dc bias voltage value can be seen easily in Fig. 3. At this optimum dc bias voltage, the bypass diode of the shaded module parts is forward biased completely.

If there are shaded PV modules in a string, it is not important whether their corresponding bypass diodes are forward biased completely or not because their operating voltage becomes smaller than their MPP voltage, and simultaneously, the unshaded PV modules start to operate at higher voltage levels than their normal MPP voltages. The operating conditions heavily depend on the degree of shading on the low current cell. In order to shift the operating voltage of unshaded PV modules to their normal operating voltage value, we need extra voltage that is called the bias voltage. After the bias voltage is applied, shaded modules are deactivated fully, and the unshaded modules can operate at normal MPP. If $(7.7 + 0.8)$ V is supplied by using a dc–dc converter for each shaded PV module, the bypass diode of the shaded PV module can be forward biased completely, and the unshaded modules can be shifted to their optimum operating point. Consequently, the effect of shaded modules can be eliminated from the system. The individual behaviors of strings do not affect each other. It is worth noting that it is impossible to tune a common optimum operating voltage at the same time for all PV modules under partial shading conditions because of the inherent characteristics of the *I–V* curve of PV modules. This is verified for the 4×3 PV array for the following shading scenario. When there are three shaded modules: the one has insolation of 100 W/m^2 in String-1; two have insolation of 200 W/m^2 in String-2; and the insolation over the unshaded modules is 1000 W/m^2, the optimum voltages of the dc–dc converter outputs are investigated for the shaded two strings. As can be seen in Fig. 4, each string has its own optimum bias voltage. In Fig. 4, the incremental voltage step is taken as 0.1 V. The optimum bias voltages of String-1 and String-2 are about 8.5 V $(7.7 + 0.8)$ and 17 V $(2 \times (7.7 + 0.8))$, respectively. Only one global MPP exists after these bias voltages are applied. In addition, the global MPP of the PV array shifts to the normal MPP at which the insolation is uniform. It is about 62 V for this PV array. Therefore, there is no need for a complex control system when the output of the dc–dc converter voltages is adjusted to their optimum value in order to obtain maximum power from the whole PV array. If the bias voltage values go far away from their optimum values for each string, the PV array power starts to decrease again as shown in Fig. 4. As a result, it can be seen easily that it is necessary to deactivate the shaded PV modules to reduce the power losses and recover the power of the unshaded PV modules.

The operating principle of the system is based on observing the operating voltage of the PV modules. We do not need any additional sensors to determine the insolation level on each PV module. If there are more than one shaded PV module in a string, only the most heavily shaded PV module's bypass diode is forward biased first when there is no applied bias voltage. For this reason, enough voltage difference can be observed between this module and the highest operating voltage value in that string to determine the existence of a shaded module. The proposed system firstly applies the biasing voltage for this module. After that, if there are more shaded PV modules in a string, the second heavily shaded PV module's bypass diode is forward biased after the first bias voltage is applied. So, the proposed system can sense that there are two shaded modules and the proposed system starts to apply bias voltage

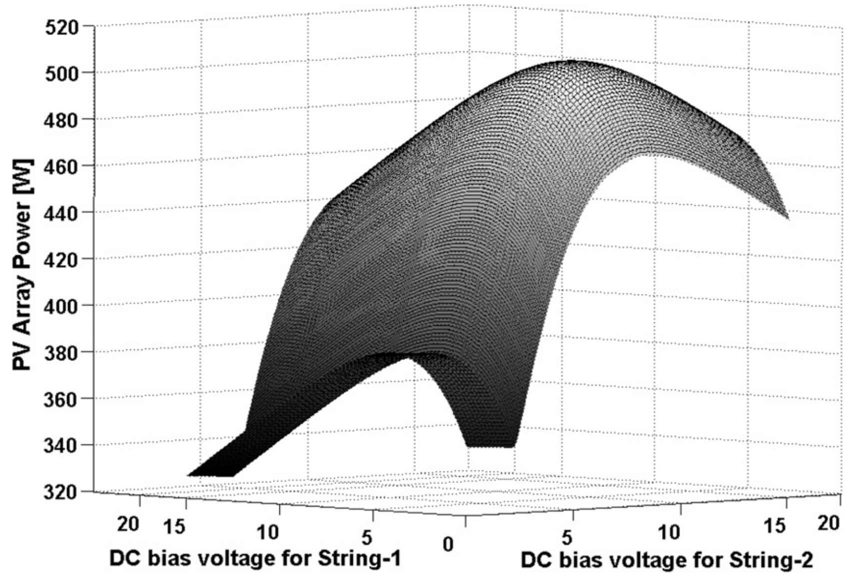

Fig. 4. Optimum bias voltages for String-1 and String-2 when there are three shaded modules: one insolated with 100 W/m^2 in String-1; two insolated with 200 W/m^2 in String-2; and unshaded modules insolated with 1000 W/m^2 in 4 $\times$ 3 PV array.

for the two shaded PV modules. This process continues in a similar manner for all shaded PV modules.

Module voltage values are observed and compared by using a simple decision unit for each string. The decision unit includes a very simple algorithm that is based on the voltage difference to determine the bias voltage values. This bias voltage is used for the reference voltage value in the dc–dc controller. Each converter is supplied from the output terminal of the PV array. In this paper, a general fuzzy controller for dc–dc converters is used [6,26]. Fuzzy controllers are capable of good performances, even for those systems where linear control techniques fail, e.g. when a mathematical description is not available or there are wide parameter variations [6,26]. Fuzzy controller implementation is relatively simple and can guarantee a small signal response as fast and stable as other standard regulators and an improved large signal response. Since the converter output voltage must be less than the input voltage in the proposed system, the buck converter topology is used [27]. The switching frequency of the dc–dc converter is selected as 100 kHz. The efficiency of the dc–dc converter is about 90% during the simulations.

4. Verification of feasibility and operation of proposed system

In order to demonstrate the effectiveness of the proposed system, two different cases are investigated. Cases I and II of partial shading scenarios are generated and given in Tables 2 and 3, respectively. The general insolation level of the 4 $\times$ 3 PV array is about 1000 W/m^2 for Case I. For Case II, it is about 500 W/m^2.

Case I: There are four, three and two shaded module parts in String-1, String-2 and String-3, respectively. The P–V characteristic curve are given in Fig. 5. The module voltages, string currents and dc bias voltage are shown in Fig. 6. Since a deactivating mark does not appear, the bias voltages are about zero for the three strings within 0-5 ms. Artificially created shadows start at 5 ms. Under this insolation level, the power available from a combination of modules is much less than the sum of the powers of the individual modules. The MPP power of each PV module

Table 2
Case-I insolation of modules for 4 $\times$ 3 PV array (W/m^2)

	Insolations for removed the partial shading condition			Insolations for started the partial shading condition		
	1. String	2. String	3. String	1. String	2. String	3. String
1. Row	992	998	996	104	103	106
2. Row	997	993	991	110	128	226
3. Row	995	999	996	117	351	996
4. Row	996	999	997	126	999	997
5. Row	997	992	998	997	992	998
6. Row	993	991	998	993	991	998
7. Row	994	993	995	994	993	995
8. Row	994	994	990	994	994	990

Table 3
Case-II insolation of modules for 4 $\times$ 3 PV array (W/m^2)

	Insolations for removed the partial shading condition			Insolations for started the partial shading condition		
	1. String	2. String	3. String	1. String	2. String	3. String
1. Row	499	498	499	50	130	123
2. Row	492	494	499	78	67	89
3. Row	496	496	494	145	400	494
4. Row	494	497	498	134	497	498
5. Row	498	499	490	498	499	490
6. Row	497	497	493	497	497	493
7. Row	494	491	498	494	491	498
8. Row	490	494	490	490	494	490

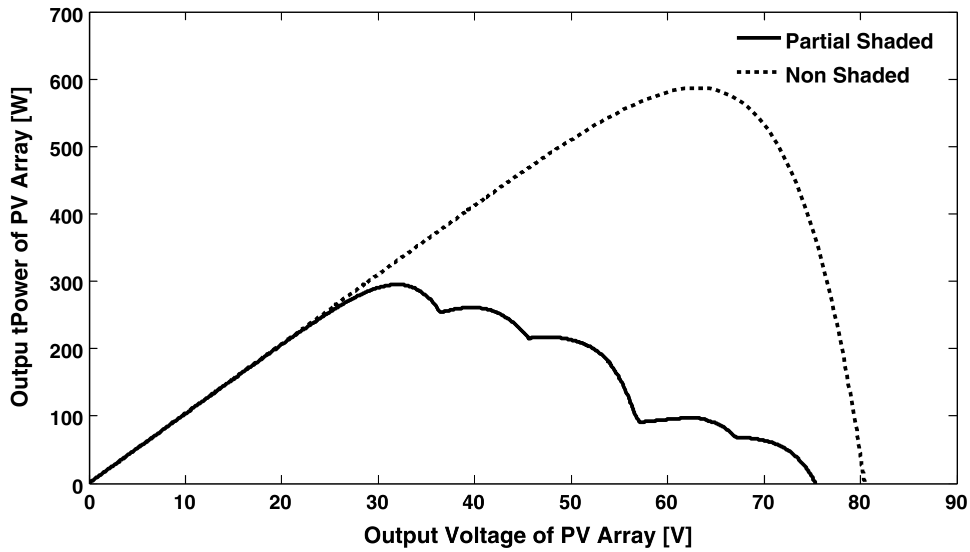

Fig. 5. The output power of 4 × 3 PV array versus output voltage of PV array under the condition given in Table 2.

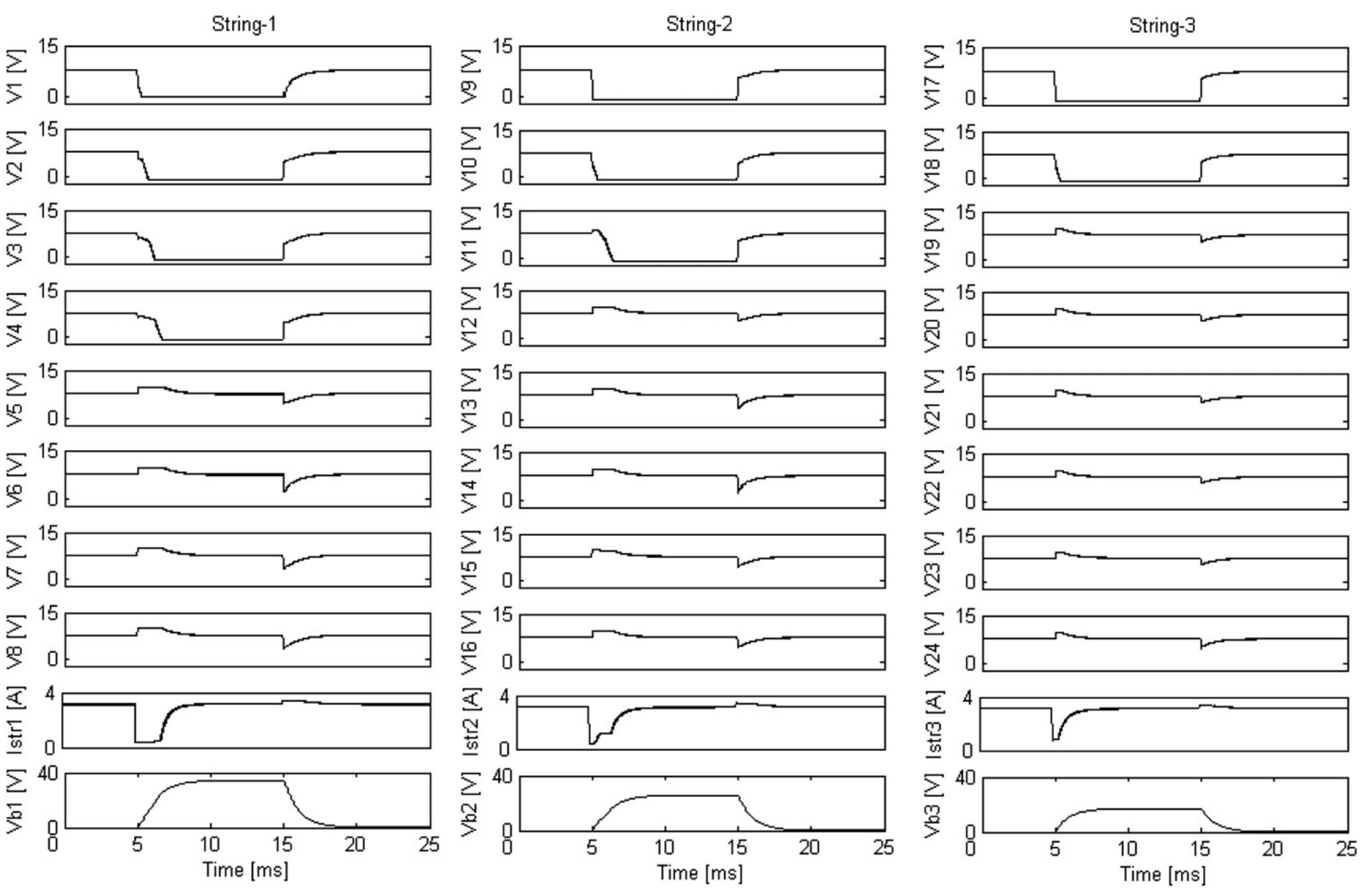

Fig. 6. The PV module parts's voltages, strings currents and bias voltages for Case-I (Table 2) in 4 × 3 PV array.

part is almost 24.4 W at 45 °C and 1000 W/m^2. The total PV array output power rating is 585 W when there is no partial shading. At 5 ms, the proposed compensation system realizes that there is partial shading by comparing the module voltage values in each string. As can be seen in Fig. 6, the proposed system deactivates the shaded PV module parts step by step. At first, a shading mark appears at the PV module that has the lowest insolation level. When the first mark appears, the proposed system begins to apply a dc bias voltage. After the corresponding bypass diode of this PV module part is forward biased completely, the second mark appears at another shaded PV module part. Then, the proposed system starts to apply a dc bias voltage for two PV module parts in String-1. This procedure continues for four, three and two shaded PV modules in String-1, String-2 and String-3, respectively. When the artificially created shadows are removed at 15 ms, the proposed system starts to remove the applied dc bias voltage since the deactivating mark disappears. Then, the generation of power increases again. This result demonstrates that the proposed system performs in stable operation. As can be seen in Fig. 7, when the proposed system is activated, the generated power increased from 100 W to 321 W. This result verifies the ability of the proposed system to prevent large drops in generated power due to shadows on the PV modules.

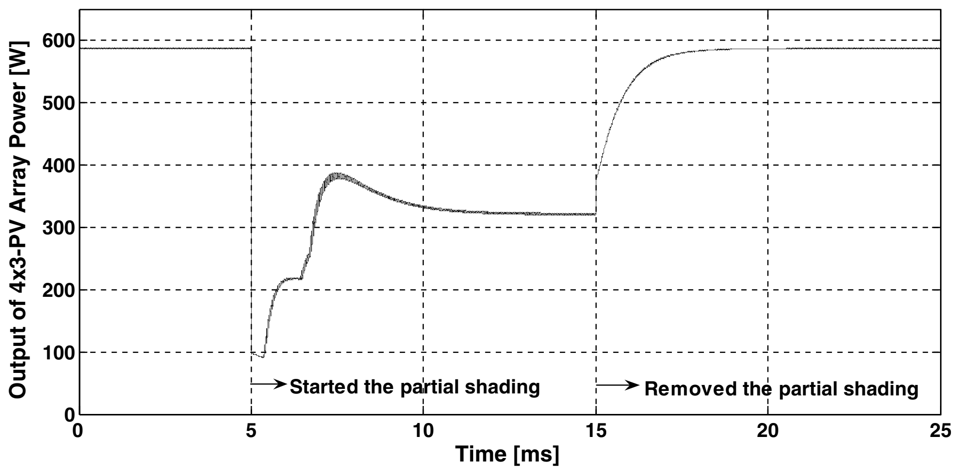

Fig. 7. The output power of 4 × 3 PV array with the proposed system for Case-I (Table 2).

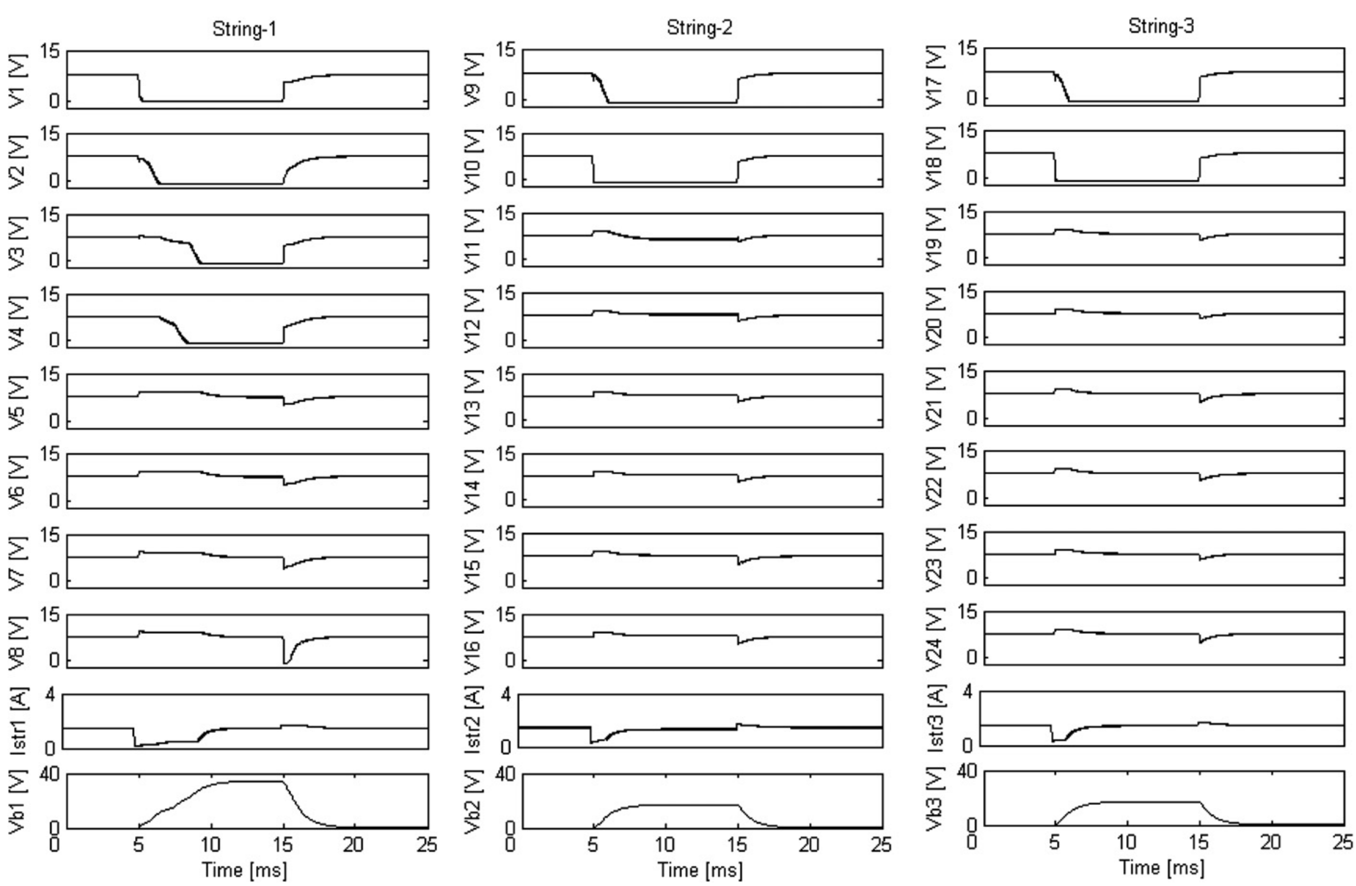

Fig. 8. PV module parts's voltages, strings currents and bias voltages for Case-II (Table 3) in 4 × 3 PV array.

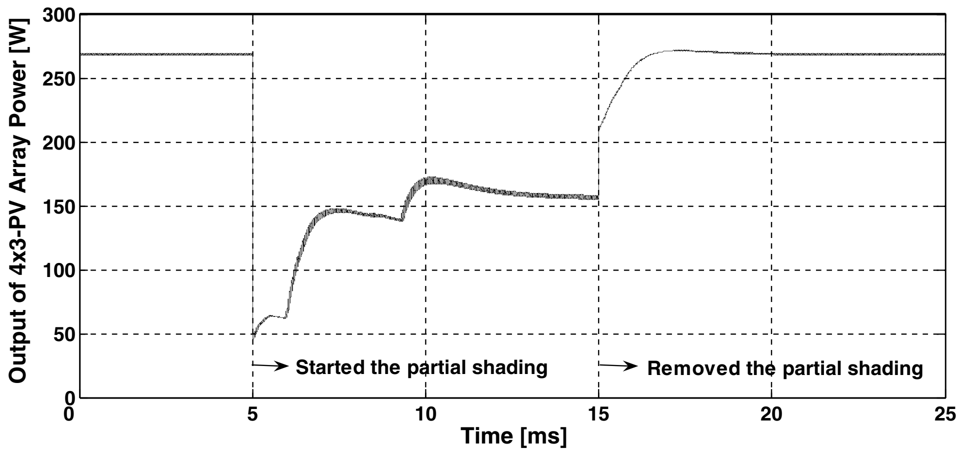

Fig. 9. The output power of 4×3 PV array with the proposed system for Case-II (Table 3).

Case II: In this case, the general insolation level of the PV array is 500 W/m^2. The changing of each string current and voltages are given in Fig. 8. When there is no shading, the output of PV array power is 268.5 W for this case. At 5 ms, the artificially created shadows begin, and the output of PV array power decreases considerably, to 50 W. When the proposed system activates at 5 ms, the generation power increases step by step up to 157 W. Fig. 9 shows the relationship between the test result of the operation time and the generation power. In String-2, the insolation of one module is 400 W/m^2, so, according to the deactivation criteria, this module is not deactivated. So, the bias voltage of String-2 is 17 V ($2 \times (7.7 + 0.8)$) although there are three shaded modules. However, it is operating voltage value becomes smaller than 7.7 V after all the voltages reach their steady state values. In order to demonstrate the reliability of the proposed system, the created shadows are removed at 15 ms. When all the shadows are removed, the marks of deactivation disappear step by step. At the end of 18 ms, all bias voltages have been removed and set to about zero volts. Then, the PV array power increases again to 268.5 W. As can be seen from Figs. 7 and 9, the proposed system successfully performed, and the response time varies from 5 ms to 8 ms, depending upon the partial shading conditions (Tables 2 and 3) and the response of the fuzzy logic controller.

5. Conclusions

A novel power compensation and control system approach to the design of maximum power point tracking systems for partially shaded PV arrays has been presented. It has been shown that the proposed design procedure ensures reducing the power losses due to partial shading in a simple manner. The negative effect of shading on overall array power output performance is minimized by deactivating shaded PV modules by forward biasing the corresponding bypass diodes. The proposed method guarantees obtaining the global maximum power under any partial shading conditions. The system can be applied either to non-uniform insolated PV arrays or in the presence of a fault in the array to prevent a reduction of power due to shaded or faulty modules.

In general, when using an MPPT converter, an estimated increase in power output from the PV array of 20% to 30% can be expected for uniform insolation conditions. This energy output enhancement should, however, be measured against the increased cost and lower reliability of the MPPT converter. The added cost of the MPPT converter should be lower than the estimated savings for the system due to the higher energy output from the same PV array. In this paper, the proposed system can support the increase in power output of a partially shaded PV array of about 300% for the given scenarios. Therefore, the new compensator controller techniques should be developed and start to be used in PV systems for non-uniform insolation conditions.

References

[1] Woyte A, Nijs J, Belmans R. Partial shadowing of photovoltaic arrays with different system configurations: literature review and field test results. Solar Energy 2003;74:217–33.
[2] Karatepe E, Boztepe M, Colak M. Development of a suitable model for characterizing the photovoltaic arrays with shaded solar cells. Solar Energy 2007;81:977–92.
[3] Sharma AK, Dwivedi R, Srivastava SK. Performance analysis of a solar array under shadow condition. IEE Proc Part G: Circ, Dev Syst 1991;138:301–6.
[4] Herrmann W, Wiesner W. Modelling of PV modules – the effects on non-uniform irradiance on performance measurements with solar simulators. In: 16th European Photovoltaic Solar Energy Conf.; 2000.
[5] Esram T, Chapman PL. Comparison of photovoltaic array maximum power point tracking techniques. IEEE Trans Energy Convers 2007;22:439–49.
[6] Veerachary M, Senjyu T, Uezato K. Neural network based maximum power point tracking of coupled inductor interleaved boost converter supplied PV system using fuzzy controller. IEEE Trans Ind Electron 2003;50:749–58.
[7] Hiyama T, Kitabayashi K. Neural network based estimation of maximum power generation from PV module using environmental information. IEEE Trans Energy Convers 1997;12:241–6.

[8] Kawamura H, Naka K, et al. Simulation of *I–V* characteristics of a PV module with shaded PV cells. Solar Energy Mater Solar Cell 2003;75:613–21.
[9] Quaschning V, Hanitsch R. Numerical simulation of current–voltage characteristics of photovoltaic systems with shaded solar cells. Solar Energy 1996;56:513–20.
[10] Kajihara A, Harakawa T. Model of photovoltaic cell circuit under partial shading. In: ICIT 2005 IEEE int conf ind technol; 2005. p. 866–870.
[11] Eugene VS, Shengyi L, Roger AD. Power controller design for maximum power tracking in solar installations. IEEE Trans Power Electron 2004;19:1295–304.
[12] Mishima T, Ohnishi T. A power compensation and control system for partially shaded PV array. Electr Eng Jpn 2004;146:74–82.
[13] Shimizu T, Hirakata M, Kamezawa T, Watanabe H. Generation control circuit for photovoltaic modules. IEEE Trans Power Electron 2001;16:293–300.
[14] Kobayashi K, Takano I, Sawada Y. A study of a two-stage maximum power point tracking control of a photovoltaic system under partially shaded insolation conditions. Electr Eng Jpn 2005;153:774–83.
[15] Miyatake M., Zhao H., et al. Response of Fibonacci search-based maximum power point tracker when a photovoltaic array is partially shaded. in: Power Energy Syst EuroPES Conf.; 2003.
[16] Irisawa K, Saito T, Takano I, Sawada Y. Maximum power point tracking control of photovoltaic generation system under non-uniform insolation by means of monitoring cells. In: Twenty eighth IEEE Photovoltaic Specialists Conf.; 2000. p. 1707–10.
[17] Bekker B, Beukes HJ. Finding an optimal panel maximum power point tracking method. In: 7th African IEEE Conf.; 2004. p. 1125–9.
[18] Mishima T, Ohnishi T. A power compensation strategy based on electric double layer capacitors for partially shaded PV array. In: The Fifth PEDS Int Conf.; 2003. p. 858–63.
[19] Suryanto EH, Wenham SR, Green MA. Shadow tolerance of modules incorporating integral bypass diode solar cells. Solar Cells 1986;19:109–23.
[20] Nagayoshi H, Atesh M. Partial shading effect emulation multi small scale module simulator units. In: IEEE Thirty-first Photovoltaic Specialists Conf.; 2005. p. 1710–3.
[21] Karatepe E, Boztepe M, Colak M. Neural network based solar cell model. Energy Convers Manage 2006;47:1159–78.
[22] Gow JA, Manning CD. Development of photovoltaic array model for use in power-electronics simulation studies. IEE Proc Electr Power Appl 1999;146:193–200.
[23] Sukamongkol Y, Chungpaibulpatana S, Ongsakul W. A simulation model for predicting the performance of a solar photovoltaic system with alternating current loads. Renew Energy 2002;27:237–58.
[24] Shmilovitz D. On the control of photovoltaic maximum power point tracker via output parameters. IEE Proc Electr Power Appl 2005;152(2):239–48.
[25] Balouktsis A, Karapantsios TD, Anastasiou K, Antoniadis A, Balouktsis I. Load matching in a direct-coupled photovoltaic system application to Thevenin's equivalent loads. Int J Photoenergy 2006:1–7.
[26] Mattevelli P, Rossetto L, Paolo Tenti. General-purpose fuzzy controller for DC–DC converters. IEEE Trans Power Electron 1997;12:79–86.
[27] Rashid Muhammed H. Power electronics handbook. Academic Press; 2001.