Power Controller Design for Photovoltaic Generation System under Partially Shaded Insolation Conditions

Engin Karatepe, Takashi Hiyama, *Senior Member, IEEE,* Mutlu Boztepe, and Metin Çolak

***Abstract*-- Partially shaded photovoltaic (PV) modules typically exhibit additional difficulties in tracking maximum power point (MPP), since their power-voltage (P-V) characteristics are complex and may have multiple local maxima. For this reason, conventional techniques fail to track MPP effectively, if the PV array is partially shaded. This paper presents a novel power compensation and control system for PV arrays under complicated non-uniform insolation conditions. The proposed system is based on forward biasing bypass diode of shaded modules by monitoring dynamic resistance and voltage of PV modules. For this purpose, the proposed system is used DC/DC converter equipped with each PV string in PV array. The proposed system can identify which modules are shaded. The effectiveness of the proposed system is investigated and confirmed for complicated partially shaded PV array.**

***Index Terms*-- Photovoltaic array, maximum power point tracking, partially shading, mismatching, fuzzy logic controller.**

I. INTRODUCTION

THE increasing world's energy demands and environmental pollution are motivating research and technological investments related to renewable energy sources. Among 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 to install easily to the end of users in roof-tops of residence and facades of buildings. It is crucial to improve its efficiency and develop reliability of PV generation control systems [1]. In practical applications, a PV module consists of many solar cells which are connected in series and PV modules are wired together into array both in series and in parallel to provide the necessary voltage and/ddor currents. The output power of a PV array decreases considerably, when current-voltage (I–V) curves of solar cells are not identical due to soiling, non-uniform irradiation, cloud, cell damaging, partially shading etc. Shading part of a PV array has a very dramatic effect on its (P-V) curve [2], [3], [4], [17]. Shading even a very small fraction of the array may result in a very reduction of the array power. Partial shading can be occurred by utility poles, chimneys, trees, parts of other buildings. In the future, a significant number of PV system are installed at the roofs but also wherever the sunlight available. Because of the high cost of solar cells, it is necessary to operate the PV array at its MPP. Tracking the MPP of a PV array is usually an essential part of a PV system [5]. Therefore, suitable MPP tracking (MPPT) control systems must be developed for partial shading conditions and investigations of mismatching effects must be increased for improving the performance of PV systems.

Since the PV array has non-linear I–V characteristic [6], [7], MPP tracker must manage nonlinear and time-varying system successfully. Due to partial shading, multiple local maxima points occur on the P–V curve [2]. It is very difficult problem for a conventional MPP tracker [5], [8]. In recent years, novel MPPT methods have been widely discussed to overcome partial shading effects [9]-[16].

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 [5], [11], [15], [18]. Previous MPPT methods have been used under the uniform insolation conditions, if there are multiple peak points they are not useful [1]. It is very difficult to find global MPP in a large scale PV generation system since the power curve characteristic certainly dependent on the pattern of partial shading [2], [19].

There is a significant reduction of total output power from PV power generation system where a couple of PV string are parallel to the DC terminal of interactive inverter because of mismatch of the optimum operating voltages between the PV blocks [9]. The use of different power compensations and control systems for partially shaded PV array were suggested in just a few papers. Reference [9] proposed a system that can control 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 [10]. The basic idea of [9] is to feed the bias voltage into the shaded PV string so that it generates the maximum power at the same operation voltage as other blocks. Only a single partially shaded PV string is chosen by a selector and is fed by a bias voltage. For this reason, if a complicated partially shaded

E. Karatepe is with Kumamoto University, Kumamoto 860-8555, Japan (email:engin.karatepe@ege.edu.tr).
T. Hiyama is with Kumamoto University, Kumamoto 860-8555, Japan (email:hiyama@eecs.kumamoto-u.ac.jp).
M. Boztepe is with Ege University, Izmir 35100, Turkey (email:mutluboztepe@ege.edu.tr).
M. Colak is with Ege University, Izmir 35100, Turkey (email:metincolak@ege.edu.tr)

occurs, this method can not be used. Reference [10] 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 excessively complexity of the system configuration in large scale PV array. Reference [11] and [13] proposed a two stage MPPT control process. 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 converge 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 ones [11]. Reference [12] proposed the MPPT employing line search algorithm with improved the Fibonacci search to find the global MPP. However, this approach can not guarantee to find the global MPP under any conditions. Reference [14] proposed a fractional open circuit voltage method that periodically sweeps the PV array voltage from open circuit to short circuit to update fraction that gives relationship between MPP voltage and open circuit voltage. This obviously causes more power losses. In addition, some doubt exist on how efficiently the system will perform on days with fast moving clouds in this kind of method. Reference [16] 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 module is compensated by a discharged current from electrical double layer capacitor current. So, many factors must be considered when designing power compensation and control system and no single method can be claimed to be the best.

As a measure to avoid this kind of problem and to obtain generation power more efficiently, a novel power compensation strategy and its system are proposed in this paper. The proposed system can be realized by using DC/DC converter for each string instead of each module and the system can be controlled in very simple manner. The design goal for the proposed system is to find a control law such that,

1) the control system shall operate PV system at optimal point for complicated partially shaded insolation conditions
2) the system shall be relatively simple control
3) the system shall aid to find what kind of failure occurs (e.g. which module damaged or shaded level) without using additional expensive sensors

The proposed system operation is demonstrated and the compensation effect is verified for non-uniform insolation.

II. CONNECTION OF PV ARRAY AND ASSOCIATED PROBLEMS

There are various possible patterns shading. In addition the system must keep stability for all conditions. Both of them are the main difficulties when solving the partial shading problem. Before trying to solve or reduce partial shading effects, a thorough understanding of their origin and behavior is required. Since the field testing is costly, time consuming and depends heavily on the prevailing weather condition, it is necessary to define a circuit based simulation model which 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 [2].

The DC bus voltage of grid connected PV array is set to the optimum operation voltage according to unshaded PV strings. In Fig. 1, the MPP voltage is plotted against the insolation levels from 100 W/m^2 to 1000 W/m^2 for 4x3-PV array, consist of 4 series connected Siemens SM-55 PV module and 3 parallel strings. Since cell temperature changes can be omitted [9]-[16], the temperature of cells is assumed as 45^{o}C. The MPP voltage changes in a very narrow window under the high irradiation level. And also extreme power losses due to partial shading are seen under high level insolated conditions especially. Therefore, a DC voltage supply can be used instead of the interactive inverter [9], [16] during the simulations to simplify description of the proposed system. Reference [10] used a resistance load to simplify the explanation.

After getting experience about operating of PV systems [2], [21], we can get operating point of PV modules by using two principles without using additional sensors to figure out which PV modules are shaded and roughly their shading level. And then we can tune required bias voltage value for each shaded PV string. The first principle is observing operating voltage of PV modules. When a PV module is shaded heavily, its operating voltage becomes negative due to bypass diode. This indicator is not enough for some pattern shading scenarios. If there are more than one shaded PV modules in a string, only the most heavily shaded PV module’s bypass diode is forward biased. So we can not figure out the others at the same time. For this reason, the first mark alone does not meet the requirements to obtain the knowledge of which PV modules are shaded. A second mark is needed. We observed that there is relationship between dynamic resistance and operating point. By using the both marks, a large scale PV array can be investigated with module based analysis under non-uniform insolation conditions.

III. DYNAMIC RESISTANCE OF PV MODULE

Dynamic resistance value of a PV module decreases toward to open circuit voltage point (Voc,0) and increases toward to short circuit current point (0,Isc). This characteristic of PV modules helps to understand level of electrical mismatching in a PV array. Dynamic resistance of PV module is very small, when its bypass diode is forward biased. Fig. 2 shows changing dynamic resistance of SM-55 PV module part that consists of 18 series connected mono-crystalline silicon solar cells.

The changing of dynamic resistance can be divided into three regions as shown in Fig. 2. The first region is for when bypass diode is forward biased, the second is for between starting time of forward biasing and MPP, and the third is for the interval between MPP and open circuit voltage point. In a PV array, dynamic resistance of each PV module can give information about whether it is shaded or not and there is fault or not. Nevertheless, as seen in Fig. 2, dynamic resistances of Region-1 and Region-3 have close values.

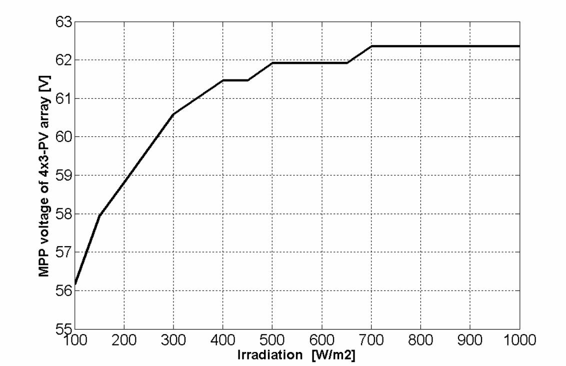

Fig. 1. MPP voltage changing versus irradiation for 4x3 SM-55 PV array under uniform insolation condition

This may lead into error when we decide the location of operating point. In this case, if its bypass diode is forward biased we can follow up voltage of PV module easily to figure out whether PV module is operating in Region-1 or not.

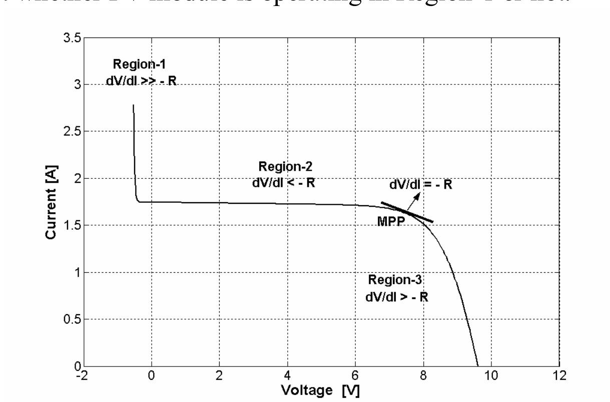

Fig. 2. Dynamic resistance of PV module for an operating condition

IV. THE PROPOSED SYSTEM CONFIGURATION AND CONTROL PRINCIPLE

The main the proposed control system configuration with power compensator is shown in Fig. 3 for 4x3-PV array.

Since each SM-55 PV module has two bypass diodes, there are 8 PV module characteristics for each string in 4x3-PV array. The MPP voltage of the each part in SM-55 PV module (18 solar cells connected in series) is about 7.8 V for 45 ^{o}C and interval of 300 – 1000 W/m^2. If there are shading PV modules in a string, whether their bypass diodes are forward biased or not, their operating voltage becomes smaller than their MPP 2voltage and unshaded PV modules operate at a higher voltage than their MPP voltage. In order to shift the operating voltage of unshaded PV modules to normal operating voltage value, we need extra voltage to compensate the voltage drop. This extra voltage can be applied by using DC/DC converter connected for each string. If (7.8 + 0.8) V is supplied for each shaded PV module part, the bypass diode of shaded PV module can be forward biased completely and unshaded modules can be shifted to optimum operating point.

Consequently, shaded modules effects can be eliminated from the system by using DC/DC converter. Each PV string operation can be dealt with separately. It is impossible to tune a common optimum operating voltage at the same time for all PV modules, shaded and unshaded modules, in a PV string because of the inherent characteristics of the I–V curve. For this reason, it is necessary to deactivate shaded PV modules for reducing the power losses. This is verified for 4x3-PV array for the following shading scenario.

When there are three shaded modules: the one is insolated with 100 W/m^2 in the String-1 and two of them is insolated with 200 W/m^2 in the String-2 and insolation over unshaded modules is 1000 W/m^2, optimum biasing voltages are investigated for two strings. As can be seen in Fig. 4, each string has its own optimum voltage.

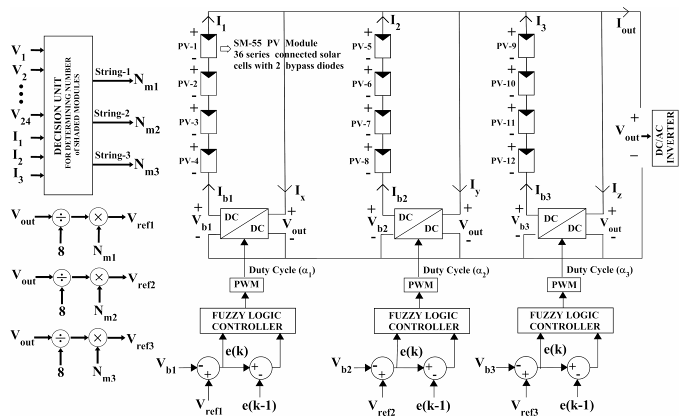

Fig. 3. Configuration of the proposed system for 4x3 PV array (each PV module has 2 bypass diodes)

In Fig. 4, incremental voltage step is taken as 0.1 V. Optimum bias voltages of String-1 and String-2 are about 8.6 V (7.8+0.8) and 17.2 V (2x(7.8+0.8)) respectively. Only one global MPP becomes when these bias voltages are applied. If bias voltage values go far away from their optimum values, PV array power start to reduce again as shown in Fig. 4.

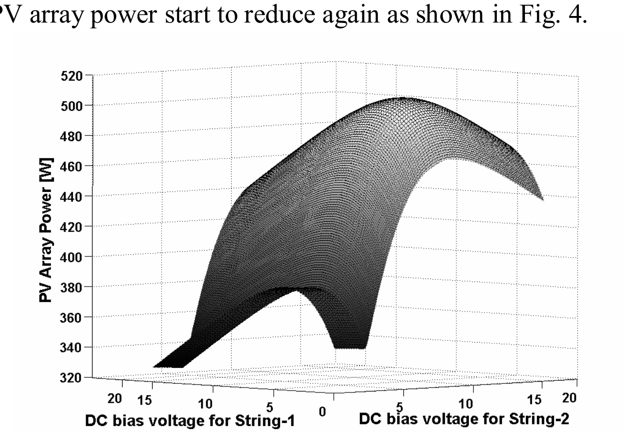

Fig. 4. Optimum bias voltages for String-1 and String-2

For each string, simple decision unit determines how many PV module parts should be deactivated by observing voltage values and dynamic resistances. And then the required bias voltage values are determined. This bias voltage values are used for reference voltage values in DC/DC controller. Fuzzy logic controller is chosen for DC/DC converter [15], [23]. Fuzzy logic controllers have the advantages of working with imprecise inputs, not needing an accurate mathematical model, and handling nonlinearity [15]. During the simulation studies the efficiency of DC/DC converter is about 80 %.

After investigating several partial shading scenarios for

SM-55 PV module type, we obtained condition that when PV module operating voltage is smaller than 1 V and/or absolute value of dynamic resistance is higher than 200 Ω, PV module part should be deactivated. These values mean that if the shaded module insolation level is below half of the general insolation level, that modules will be deactivated. These values may change with module types. The optimum bias voltage values are found for each string via a simple iterative algorithm whose flowchart is plotted in Fig. 5.

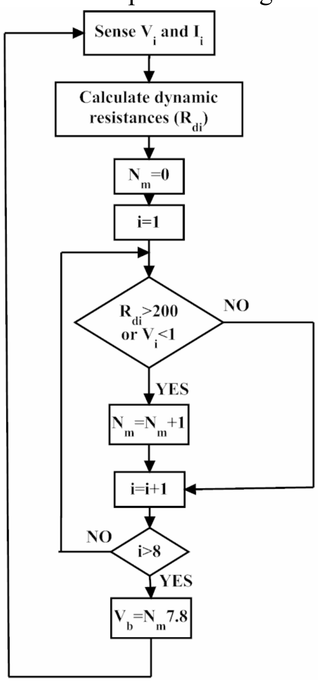

Fig. 5. Flowchart of the decision unit

Assuming that the loss on the compensator circuit is negligible, the following equations can be established

$$V_{b1} = \alpha_1 V_{out} \quad (1)$$

$$V_{b1} I_{b1} = V_{out} I_x \quad (2)$$

$$I_x = \alpha_1 I_{b1} = \alpha_1 I_1^* \quad (3)$$

$$V_{block1}^* = V_{PV1} + V_{PV2} + V_{PV3} + V_{PV4} \quad (4)$$

$$V_{out} = V_{block1}^* + V_{b1} = V_{block2}^* + V_{b2} = V_{block3}^* + V_{b3} \quad (5)$$

$$I_{out} = I_1^* + I_2^* + I_3^* - I_x - I_y - I_z \quad (6)$$

where I_1^*, I_2^*, I_3^*, V_{block1}^*, V_{block2}^*, and V_{block3}^* optimum operating currents and voltages for String-1, String-2 and String-3 respectively.

$$I_{out} = (1-\alpha_1) I_1^* + (1-\alpha_2) I_2^* + (1-\alpha_3) I_3^* \quad (7)$$

$$V_{out} = \frac{V_{block1}^*}{1-\alpha_1} = \frac{V_{block2}^*}{1-\alpha_2} = \frac{V_{block3}^*}{1-\alpha_3} \quad (8)$$

Duty ratio of each string can be adjusted easily as mentioned before. If there are partial shadings in more than one PV string, the bias voltage have to be controlled separately due to the fact that shading level or pattern may not be same in all strings. So each shading string may need different biasing voltage value.

Therefore, the output power, Pout, is expressed as

$$P_{out} = V_{block1}^* I_1^* + V_{block2}^* I_2^* + V_{block3}^* I_3^* \quad (9)$$

Thus, individual control of each of the strings and the proposed generation control are realized.

V. VERIFICATION FEASIBILITY AND OPERATING OF PROPOSED SYSTEM

In order to demonstrate the effectiveness of proposed system, partial shading scenario is generated as shown in Table I. To make easy to understand the dynamic behavior of PV modules and the proposed system, all values are given in table after each control cycle.

At the first cycle, all bias voltage for each string is zero as shown in Table II. Under this insolation level, the power available from a combination of modules is being much less than the sum of power of the individual modules when the proposed system is inactive. The MPP power of each PV module part is almost 24.4 W at 45°C and 1000 W/m2.

TABLE I
PARTIAL SHADING SCENARIO

	Insolation of modules for 4x3-PV Array [W/m^2]		
	String-1 (S-1)	**String-2 (S-2)**	**String-3 (S-3)**
1. row	125.0550	130.0873	131.0224
2. row	101.9238	126.0056	172.2055
3. row	113.7409	127.1911	998.4647
4. row	996.5643	996.1744	999.3203
5. row	994.2409	992.5736	993.0890
6. row	993.5163	996.9743	992.6268
7. row	998.4392	994.1408	996.0522
8. row	992.8984	998.5874	992.4100

The absolute value of dynamic resistances and voltage values at the first step show that there is one module for the 1st string, two modules in the 2nd string, and two modules in the 3rd string. Therefore control system start to apply bias voltages in the second step.

TABLE II
AT THE FIRST STEP OF THE PROPOSED SYSTEM

Bias Voltages [V]			**PV Array Power [W]**
String-1 (S-1)	**String-2 (S-2)**	**String-3 (S-3)**	
0	0	0	87.7676

Dynamic Resistance			**Module Voltages**			**Module Currents**		
S-1	**S-2**	**S-3**	**S-1**	**S-2**	**S-3**	**S-1**	**S-2**	**S-3**
12.3	62	0.21	7.41	6.47	**-0.7**	0.38	0.43	0.59
1.1	**699**	**454**	**-0.6**	2.06	4.54	0.38	0.43	0.59
67.8	**518**	0.39	6.43	4.73	9.75	0.38	0.43	0.59
0.37	0.38	0.39	9.83	9.81	9.75	0.38	0.43	0.59
0.38	0.38	0.39	9.83	9.81	9.75	0.38	0.43	0.59
0.38	0.38	0.39	9.83	9.81	9.75	0.38	0.43	0.59
0.37	0.38	0.39	9.83	9.81	9.75	0.38	0.43	0.59
0.38	0.38	0.39	9.83	9.81	9.75	0.38	0.43	0.59

After the second step, we can observe two modules for the 1st string, three modules for the 2nd string, and two modules for the 3rd string. And then the system updates the bias voltages values at the next step.

At result of the third step, we can see that there is no another shaded module in the 2nd and 3rd strings. For the 1st string, there is another one. So control system will update the bias voltages values at the fourth step.

At the fifth step, although all shadows are removed, control system continues to apply bias voltages. However, the control system can not find any mark for applying bias voltage according to the given criteria before described. Since PV modules can not operate at their optimum voltages, normal PV array power can not be extracted. After the fifth step, all bias voltages are removed and set to zero volts.

TABLE III
AT THE SECOND STEP OF THE PROPOSED SYSTEM

Bias Voltages[V]			PV Array Power [W]
String-1 (S-1)	String-2 (S-2)	String-3 (S-3)	
8.5940	17.1880	17.1880	210.6984

Dynamic Resistance			Module Voltages			Module Currents		
S-1	S-2	S-3	S-1	S-2	S-3	S-1	S-2	S-3
136	0.03	0.01	6.04	**-0.7**	**-0.8**	0.42	1.19	3.13
0.41	0.03	0.01	**-0.7**	**-0.7**	**-0.8**	0.42	1.19	3.13
1.05	0.03	2.46	**-0.6**	**-0.7**	7.82	0.42	1.19	3.13
0.38	0.46	2.44	9.82	9.49	7.82	0.42	1.19	3.13
0.38	0.46	2.62	9.81	9.49	7.77	0.42	1.19	3.13
0.38	0.46	2.63	9.81	9.49	7.77	0.42	1.19	3.13
0.38	0.46	2.53	9.82	9.49	7.80	0.42	1.19	3.13
0.38	0.46	2.64	9.81	9.49	7.77	0.42	1.19	3.13

At the end of the fourth step, control system can not find additional shaded PV module. It has been clear that proposed compensation control system could realize about 400 % improvement of power generation compared with that of inactivated the proposed system.

In order to demonstrate the reliability of the proposed system, created shadows are removed after the fourth step. This condition is given in Table VI.

Finally, the proposed system performs stable operation. The proposed system can understand that there is no partial shading at the fifth step and the system is reactivated. And then PV array power increase again to 586.3451 W as shown in Table VII.

TABLE IV
AT THE THIRD STEP OF THE PROPOSED SYSTEM

Bias Voltages [V]			PV Array Power [W]
String-1 (S-1)	String-2 (S-2)	String-3 (S-3)	
17.1880	25.7820	17.1880	294.7682

Dynamic Resistance			Module Voltages			Module Currents		
S-1	S-2	S-3	S-1	S-2	S-3	S-1	S-2	S-3
0.03	0.01	0.01	**-0.7**	**-0.8**	**-0.8**	1.19	3.13	3.13
0.03	0.01	0.01	**-0.7**	**-0.8**	**-0.8**	1.19	3.13	3.13
0.03	0.01	2.46	**-0.7**	**-0.8**	7.82	1.19	3.13	3.13
0.46	2.53	2.44	9.49	7.80	7.82	1.19	3.13	3.13
0.46	2.64	2.62	9.49	7.77	7.77	1.19	3.13	3.13
0.46	2.51	2.63	9.49	7.80	7.77	1.19	3.13	3.13
0.46	2.59	2.53	9.50	7.78	7.80	1.19	3.13	3.13
0.46	2.47	2.64	9.49	7.82	7.77	1.19	3.13	3.13

In grid connected PV system, the most widely used MPP algorithm is the hill-climbing, which moves the operating point from open circuit voltage point toward the MPP periodically increasing or decreasing the PV array voltage by comparing the power with that of the previous perturbation cycle [5]. Although if there are multiple maxima points on the P-V curve, hill-climbing algorithm can find local maxima nearest to the open circuit voltage. Therefore the DC bus voltage of PV system is set to near the open circuit voltage. For the given insolation conditions in Table I, the maximum power is limited to 92 W by using hill-climbing method.

TABLE V
AT THE FOURTH STEP OF THE PROPOSED SYSTEM

Bias Voltages [V]			PV Array Power [W]
String-1 (S-1)	String-2 (S-2)	String-3 (S-3)	
25.7820	25.7820	17.1880	349.4912

Dynamic Resistance			Module Voltages			Module Currents		
S-1	S-2	S-3	S-1	S-2	S-3	S-1	S-2	S-3
0.01	0.01	0.01	**-0.8**	**-0.8**	**-0.8**	3.13	3.13	3.13
0.01	0.01	0.01	**-0.8**	**-0.8**	**-0.8**	3.13	3.13	3.13
0.01	0.01	2.46	**-0.8**	**-0.8**	7.82	3.13	3.13	3.13
2.51	2.53	2.44	7.81	7.80	7.82	3.13	3.13	3.13
2.57	2.64	2.62	7.79	7.77	7.77	3.13	3.13	3.13
2.60	2.51	2.63	7.78	7.80	7.77	3.13	3.13	3.13
2.46	2.59	2.53	7.82	7.78	7.80	3.13	3.13	3.13
2.61	2.47	2.64	7.78	7.82	7.77	3.13	3.13	3.13

TABLE VI
UNIFORM INSOLATIONS AFTER FOURTH STEP

	Insolation of modules for 4x3-PV Array [W/m^2]		
	1. String	2. String	3. String
1. row	998.8073	996.3122	993.1048
2. row	996.3673	994.8799	995.9759
3. row	999.5842	992.0135	992.5122
4. row	991.7527	999.0654	994.5191
5. row	996.3649	996.5931	994.5351
6. row	997.8828	996.8585	994.5697
7. row	990.6719	998.2962	993.1478
8. row	998.6665	996.7388	990.5934

TABLE VI
AT THE FIFTH STEP OF THE PROPOSED SYSTEM

Bias Voltages [V]			PV Array Power [W]
String-1 (S-1)	String-2 (S-2)	String-3 (S-3)	
25.7820	25.7820	17.1880	382.0791

Dynamic Resistance			Module Voltages			Module Currents		
S-1	S-2	S-3	S-1	S-2	S-3	S-1	S-2	S-3
51	86	41	5.35	4.65	5.59	3.43	3.43	3.41
79	105	28	4.80	4.16	5.94	3.43	3.43	3.41
45	128	45	5.48	2.96	5.50	3.43	3.43	3.41
127	53	33	3.05	5.31	5.78	3.43	3.43	3.41
79	82	33	4.80	4.73	5.78	3.43	3.43	3.41
60	78	33	5.17	4.80	5.78	3.43	3.43	3.41
130	61	41	2.56	5.16	5.60	3.43	3.43	3.41
53	80	62	5.32	4.77	5.15	3.43	3.43	3.41

TABLE VII
AT THE SIXTH STEP OF THE PROPOSED SYSTEM

Bias Voltages [V]			PV Array Power [W]
String-1 (S-1)	String-2 (S-2)	String-3 (S-3)	
0	0	0	586.3451

Dynamic Resistance			Module Voltages			Module Currents		
S-1	S-2	S-3	S-1	S-2	S-3	S-1	S-2	S-3
2.54	2.66	2.51	7.79	7.76	7.80	3.13	3.13	3.13
2.50	2.59	2.69	7.81	7.78	7.75	3.13	3.13	3.13
2.62	2.47	2.67	7.77	7.81	7.76	3.13	3.13	3.13
2.54	2.43	2.52	7.79	7.83	7.80	3.13	3.13	3.13
2.47	2.65	2.49	7.81	7.76	7.81	3.13	3.13	3.13
2.55	2.66	2.58	7.79	7.76	7.78	3.13	3.13	3.13
2.57	2.39	2.45	7.79	7.84	7.82	3.13	3.13	3.13
2.67	2.64	2.56	7.76	7.77	7.79	3.13	3.13	3.13

VI. CONCLUSIONS

A novel power compensation and control system approach to the design of maximum power point (MPP) tracking system for partially shaded PV array have been presented. It has been shown that the proposed design procedure ensures to reduce 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. The system can be applied either to non-uniform insolated PV arrays or presence of a fault in the array to prevent a reduction of power due to shaded or faulty.

VII. RERERENCES

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VIII. BIOGRAPHIES

Engin Karatepe received his MSc from the Dept. of EEE at Ege University, Turkey in 2000, and his Ph.D. from the Institute of Solar Energy from the Ege University in 2006. He is currently part of the academic staff at Dept of EEE of Ege University, Izmir, Turkey and Postdoc fellow at the Dept. of Computer Science and Electrical Engineering at Kumamoto University, Kumamoto, Japan. His current research interests include system modeling, and intelligent systems applications to operation and control of renewable energy systems.

Takashi Hiyama (M'86–SM'93) received the B.E.,M.S., and Ph.D. degrees from Kyoto University, Kyoto, Japan in 1969, 1971, and 1980, respectively, all in electrical engineering. Since 1989, he has been a Professor at the Department of Electrical and Computer Engineering, Kumamoto University, Kumamoto, Japan. His current research interests include intelligent system applications to power system operation, control, and management. He is a member of IEE of Japan, SICE of Japan, and Japan Solar Energy Society.

Mutlu Boztepe received his MSc and Ph.D. from the Institute of Solar Energy from the Ege University in 1995 and 2002 respectively. He is currently part of the academic staff at Dept of EEE of Ege University, Izmir. His research interests are power electronic and renewable energy.

Metin Çolak received his MSc from the Technische Universitaet Darmstadt, Germany, in 1969, and his Ph.D. from the Engineering Faculty from the Ege University in 1977. Since 1995, he has been a Professor at the Department of Electrical and Electronics Engineering, Ege University. His research interests are control systems and renewable energy.