PERFORMANCE ANALYSIS OF SOLAR PHOTOVOLTAIC ARRAY AT SHADOW CONDITION USING BINARY CODING METHOD

Maj Siraj Sikder(1), Lt Imran Hossain Khan(2), Lt K M Ridwanuzzaman(3) and Lt Col Md Golam Mostafa(4)

1-4 siraj_sikder@yahoo.com, ihk.bdnavy@gmail.com, ridwan_zaman@yahoo.com, mostafa3593sigs@yahoo.co.uk
Military Institute of Science and Technology, Bangladesh

Abstract:
An analysis of shadow effect on a 4×4photovoltaic array under varying condition of solar radiation is presented. Binary coding method is used to analyze unsymmetrical shadow patterns. Various performance criteria, e.g. power generation index (PGI) and dependency factor (DF) have been calculated. The results obtained analytically have been experimentally verified as well.

Keywords: *Binary Coding, Dependency Factor, Doorsill Effect, Photovoltaic (PV) Array, Power Generation Index (PGI), Solar Radiation.*

1.0 INTRODUCTION:

Due to abundance, low price, renewability and cleanness solar PV systems are likely to achieve specific level in future energy ranking. It is desirable that the solar PV arrays must produce maximum output power for economic reasons [1].However, partial shading of PV arrays can over proportionately reduce energy yield and degrade system performance. It has been identified as a major reason for reducing the energy yield of grid connected PV systems [2]. It can also lead to early aging and failure of shaded cells [3]. Behavior of PV cells under partial shading condition has been extensively studied by the several researchers [4], [5], [6], [7], [8]. The studies also include modeling and simulation of shading effects in PV modules and arrays [1], [7], [9], [10]. It has been reported that the output power reduction under partial shading is proportional to the shaded area.

Some articles analyzed the effect of different configurations and connections of bypass diodes between modules in a PV array [11]. It is reported that some patterns of bypass diode connections can lead to generation of abnormal over currents in some particular shadow shapes. In solar PV systems, apart from producing usable power output, sun's radiation produces over heating causing unwanted temperature rise. Many studies implied that the temperature rise detrimentally affects the internal resistances of solar cells and causes power losses. Diode characteristics are severely influenced by temperature change and appear as a more effective factor on the behavior of a solar cell [12].

With an attempt to review the recent researches mentioned above, in this paper we reinvestigate the shadow effect and present a performance analysis of a solar PV Array at shadow condition. In our analysis, we use binary coding method which approximates the continuous random shadow phenomenon to be a discontinuous one creating a discontinuous finite set of patterns. Thereby this method of analysis greatly reduces the computational rigorousness.

Remainder of this paper is organized as follows. In Section II, we briefly discuss the shadow effect on PV modules and explain the principles of binary coding method. Section III presents the factors determining the performance criterion of a PV array where power generation index (PGI), average over-current percentage, dependency factor (DF), and doorsill value has been briefly discussed. In Section IV, we present the analysis of a 4×4 PV Array using binary coding method. Section V presents the results and discussion and Section VI concludes the paper.

2.0 SHADOW EFFECT AND BINARY CODING METHOD:

A. Shadow Effect.

The most harmful factor on photovoltaic arrays is shadow. There are two kinds of shadows: symmetric and asymmetric. In symmetric shadow condition, shaded modules are in full dark state (e.g. after sunset) but in asymmetric shadow condition, some modules may have half sun state (shadows caused by passing clouds). On the other hand, shadows may be grouped into two categories: predictable and unpredictable (shadows caused by trees, side buildings, etc). Predictable shadows can be avoided by installing the solar panels meticulously in an open site. Shadows that occur during sunrise and sunset are also predictable. Unpredictable shadows are caused by passing clouds, moving objects, etc.

B. Binary Coding Method.

In real world scenario, the shadow on a PV array can form any shape and each shape has its own effect on the output current, voltage and power. One of the techniques used to study this continuous phenomenon having infinite set of patterns is to convert it into a discrete phenomenon having finite set of patterns.

Binary coding method has been developed to study the shadow effect on PV arrays as a discrete phenomenon with acceptable limit of accuracy. In this method the continuous random shadow effect is assumed as a discontinuous random phenomenon where every PV module of PV array is considered as a binary bit. Binary coding method has four principles [12]:

1. Shadow that occurs randomly on a PV module is considered to be a full dark shadow.

2. PV module when receives full sun radiation is defined as '1' state and when it is shaded is defined as '0' state.

3. All '1s' and '0s' are equally likely and all shadow states have equal chances to occur.

4. The number of shadow pattern that could occur is finite.

3.0 FACTORS DETERMINING THE PERFORMANCE CRITERION OF A PV ARRAY:

A. Power Generation Index (PGI).

PGI is a per unit mathematical expectation value that can be expressed as

$$PGI = \sum_{k=0}^{2^n-1}\left(\frac{1}{n}\right)\left(\frac{1}{2^n}p_k\right) \qquad (1)$$

$$0 \le p_k \le n \text{ and } 0 < PGI \le 0.5$$

where, n is the number of modules in a PV array and pk is the per unit max output power for each code of shadow [13]. An array with higher PGI has higher possibility to produce more power in different states of shadow. PGI depends on bypass diode and blocking diode configuration and interconnections of modules in an array. Thus the best configuration of an array is one that has highest PGI.

B. Average Over-current Percentage.

Average over-current percentage of PV array consisting n modules is expressed as

$$\sum_{k=0}^{2^n-1}\frac{I_k}{2^n}\times 100 \qquad (2)$$

$$I_k = \frac{I_0 - I_{nom}}{I_{nom}} \quad : \text{for } I_0 \ge I_{nom}$$

$$I_k = 0 \quad : \text{for } I_0 < I_{nom}$$

where, I0 is output current of PV array in ampere and Inom is the nominal value of the output current of PV array at full sun state. Ik is the output current at each code of shadow.

C. Dependency Factor (DF).

Dependency between PV modules leads to more power loss at partial shading. An array with higher DF has lower possibility to produce more power in different states of shadow. More PGI value leads to less DF. Maximum PGI value is 0.5. Subsequently, we can define the dependency factor as follows:

$$DF = 0.5 - PGI = 0.5 - \sum_{k=0}^{2^n-1}\left(\frac{1}{n}\right)\left(\frac{1}{2^n}p_k\right) \qquad (3)$$

$$0 < DF \le 0.5$$

For instance, with all series connections, the weakest link in the string determines the quality of the whole system. Therefore, the weakest solar cell with the lowest current defines the total string current. Commonly, the current of some cells could be reduced by mismatches [7], [8]. All connections (whether series or parallel)can cause dependency and power losses during partial shading. If modules work independently, then the shaded modules would not have bad effect on sunny ones. Consequently, the configuration which has better performance on shadow condition would have less dependency factor.

It is clear that the parameters that directly affect PGI will also inversely affect DF, as well. As noted before, PGI depends on bypass and blocking diode configurations andinterconnections of modules in an array so do DF.Hence, the best configuration of an array is one thathas the highest PGI and lowest DF.In addition, the number of rows and columns in the arraymatrix is important.

D. Doorsill Effect.

Doorsill effect means the change in local radiation at shadow condition. Doorsill effect is an observable fact which happens is special conditions. It may doesn't change the local maximum power point (MPP) [12]. It has been observed that any variation in local radiation would change the P-V curve of the total solar energy.

The changes of irradiation intensity would not influence total MPPat shadow condition, as long as this shaded intensity was higher or lower doorsill value. On the other hand, changing of irradiation of local shadow for some cases did not lead to doorsill issue. Now it is possible to define a complete explanation of doorsill effect. Doorsill effect only happens at a time that there exists multi-peak in P-V curve. Multi-peak curve requires bypass diodes determines global MPP and the other part of shadow determines local MPP.

4.0 ANALYSIS BY BINARY CODING METHOD:

A. Analysis of PGI for a 4×4 PV Array.

We find the maximum value of PGI by combining binary coding and mathematical laws. In (1), if diodes and wire losses and reverse current effect ignored, pk will have values {0, 1, 2, ...,n}. When a shaded module has minimum negative effect on the others, PGI value will be the maximum and the configuration will be the best. In eqn (1) n is a constant value which equals to number of modules in an array. Consequently, it is desirable to find the value of.

From the Khayyam-Pascal triangle (See Annex A for details) we can find the maximum value of PGI as

$$PGI_{max} = \frac{525662}{65536 \times 16} = 0.50131034 \text{ (approx.)} \quad (4)$$

B. Analysis of Half Sun Shadow.

In this sub-section, we present the analysis of half sun shadow by binary coding method. Fig. 1 shows a random shadow pattern, where in some of the PV cells, the received radiation is not zero. These cells are shown in gray colour. The dark cells are shown in black colour and the full sun cells are shown in white colour.

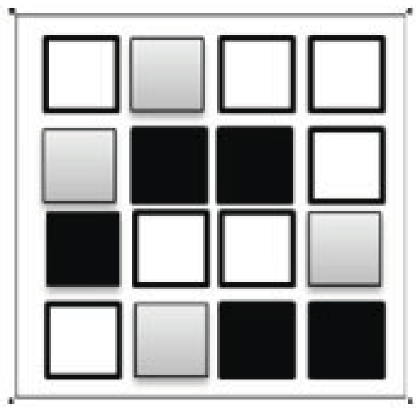

Fig.1. Unsymmetrical shadow pattern which applied on 16- module PV array

We consider the random shadow pattern as shown in Fig. 1 as a PV array configuration. As depicted in Fig. 2, for unsymmetrical shadow condition, two sets of shadow codes are considered. First set considers the half sun shadows as full sun shadow and the second set considers the half sun shadow as full dark shadow. The full sun and full dark modules are kept as usual. Results for these two sets are then computed. The average of these two results is considered as the final result.

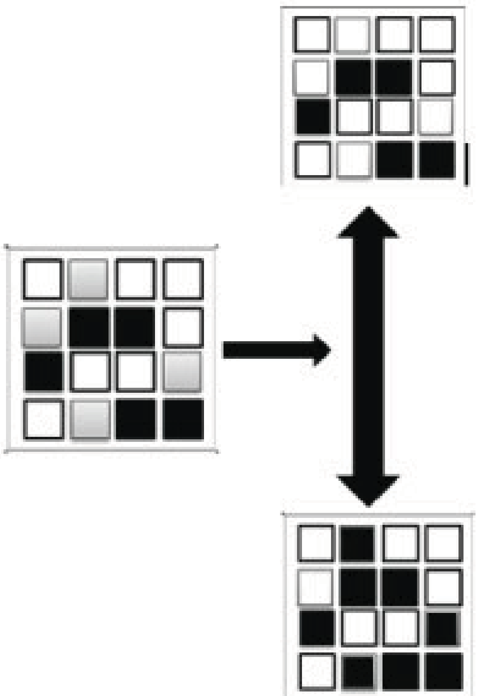

Fig.2. Unsymmetrical shadow pattern with half sun condition which separated into two shadow codes.

From Fig. 2, the two binary codes are 1101 1011 1010 1110 and 1001 0010 1010 1100. Using the experimental setup shown in Fig. 3, we obtain the P-V characteristics of these two codes which are shown in Fig. 4. The red curve shows the P-V characteristics of code 1101 1011 1010 1110 and the blue curve shows the P-V characteristic of code 1001 0010 1010 1100. Averaging the corresponding values of two curves at every point will produce the actual curve, the green one.

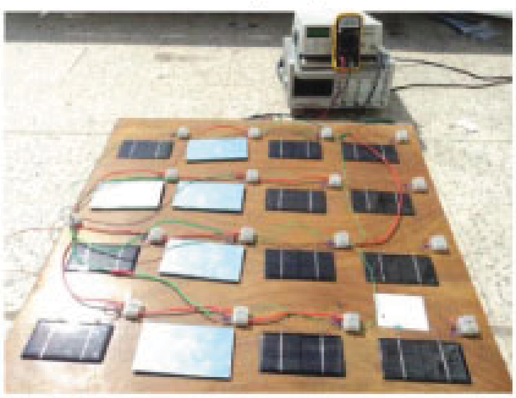

Fig. 3. Experimental Setup for obtaining the PV charecteristics of 4x4 PV array

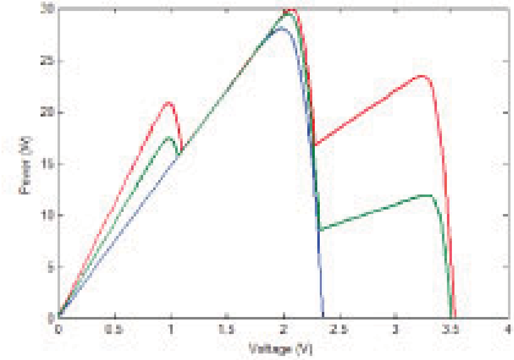

Fig.4. Each half sun shadow pattern could separate into two binary

In practicality, half sun does not alwaysmean a radiation of kW/m^2. It may vary between 0 to1kW/m^2 and sometimes more. Therefore, in somecases taking average of two curves doesnot lead to the correct result. Therefore, we define a linear combination phrase to approach the real curve as

$$P_{(v)} = \sum_{j=1}^{n-1} a_j P_{j\,(v)} \quad (5)$$

where,n is the number of different radiations typereceived on the modules of an array. $P_{j\,(v)}$ is the outputpower of PV array forjth code of shadow. We need to determine the coefficients aj according to the radiation condition. In Fig.5, we consider the 16-module array in which five modules are in full dark condition. Another four modules have 0.1, 0.2, 0.3 and 0.4 kW/m2 radiation. Therefore, there are six different kind of radiation on modules: 0, 0.1, 0.2, 0.3, 0.4 and 1 kW/m2. Consequently, n is equal to 6. Therefore, (5) can be rewritten as

$$P_{(v)} = \sum_{j=1}^{n-1} a_j P_{j(v)} = a_1 P_{1(v)} + a_2 P_{2(v)} + a_3 P_{3(v)} + a_4 P_{4(v)} + a_5 P_{5(v)} \quad (6)$$

The array could be separated into five different codes: 1101 1011 1010 1110, 1001 00101010 1100, 1101 1010 1010 1100, 1001 0011 1010 1110, 1101 0011 1010 1100. For each code, we determine its own P-V curve and multiply the respective $P_{(v)}$ value

by the correct coefficient aj and then the summation of the products gives the desired curve. To determine the coefficients aj, we use the linear radiation equation for each module of an array,

M_i :(Radiation on in real condition)

$=\sum_{j=1}^{j=n-1} a_j$ × (binary code of in coded array) (7)

For this case, we calculate the coefficients by the use of radiation linear equations. Array coefficients for right, middle and left coded array (which are shown in fig.5) are , respectively.

M_0 : $0 = a_1 \times 0 + a_2 \times 0 + a_3 \times 0 + a_4 \times 0 + a_5 \times 0$ (8)

M_1 : $0.1 = a_1 \times 1 + a_2 \times 0 + a_3 \times 0 + a_4 \times 1 + a_5 \times 0$ (9)

M_2 : $1 = a_1 \times 1 + a_2 \times 1 + a_3 \times 1 + a_4 \times 1 + a_5 \times 1$ (10)

M_3 : $1 = a_1 \times 1 + a_2 \times 1 + a_3 \times 1 + a_4 \times 1 + a_5 \times 1$ (11)

M_4 : $0 = a_1 \times 0 + a_2 \times 0 + a_3 \times 0 + a_4 \times 0 + a_5 \times 0$ (12)

M_5 : $1 = a_1 \times 1 + a_2 \times 1 + a_3 \times 1 + a_4 \times 1 + a_5 \times 1$ (13)

M_6 : $0 = a_1 \times 0 + a_2 \times 0 + a_3 \times 0 + a_4 \times 0 + a_5 \times 0$ (14)

M_7 : $1 = a_1 \times 1 + a_2 \times 1 + a_3 \times 1 + a_4 \times 1 + a_5 \times 1$ (15)

M_8 : $0.2 = a_1 \times 1 + a_2 \times 0 + a_3 \times 0 + a_4 \times 1 + a_5 \times 1$ (16)

M_9 : $1 = a_1 \times 1 + a_2 \times 1 + a_3 \times 1 + a_4 \times 1 + a_5 \times 1$ (17)

M_{10} : $0 = a_1 \times 0 + a_2 \times 0 + a_3 \times 0 + a_4 \times 0 + a_5 \times 0$ (18)

M_{11} : $0.3 = a_1 \times 1 + a_2 \times 0 + a_3 \times 1 + a_4 \times 0 + a_5 \times 0$ (19)

M_{12} : $1 = a_1 \times 1 + a_2 \times 1 + a_3 \times 1 + a_4 \times 1 + a_5 \times 1$(20)

M_{13} : $0 = a_1 \times 0 + a_2 \times 0 + a_3 \times 0 + a_4 \times 0 + a_5 \times 0$ (21)

M_{14} : $0.4 = a_1 \times 0 + a_2 \times 0 + a_3 \times 0 + a_4 \times 0 + a_5 \times 0$ (22)

M_{15} : $1 = a_1 \times 1 + a_2 \times 1 + a_3 \times 1 + a_4 \times 1 + a_5 \times 1$ (23)

Equations (8), (12), (14), (18) and (21) are the same. Equations (10), (11), (13), (15), (17), (20), (23) are similar, as well. Thus only 06 equations are lasting:

$1 = a_1 \times 1 + a_2 \times 1 + a_3 \times 1 + a_4 \times 1 + a_5 \times 1$ (24)

$0 = a_1 \times 1 + a_2 \times 1 + a_3 \times 1 + a_4 \times 1 + a_5 \times 1$ (25)

$0.1 = a_1 \times 1 + a_2 \times 0 + a_3 \times 0 + a_4 \times 1 + a_5 \times 0$ (26)

$0.2 = a_1 \times 1 + a_2 \times 0 + a_3 \times 0 + a_4 \times 1 + a_5 \times 1$ (27)

$0.3 = a_1 \times 1 + a_2 \times 0 + a_3 \times 1 + a_4 \times 0 + a_5 \times 0$ (28)

$0.4 = a_1 \times 1 + a_2 \times 0 + a_3 \times 1 + a_4 \times 0 + a_5 \times 1$ (29)

Equation (25) is not considered. Solving equations (24), (26), (27), (28), (29) coefficients are:

$a_1 = 0.1 - a_4, \quad a_2 = 0.6 - a_4, \quad a_3 = 0.2 + a_4, \quad a_4 = a_4, \quad a_5 = 0.1$

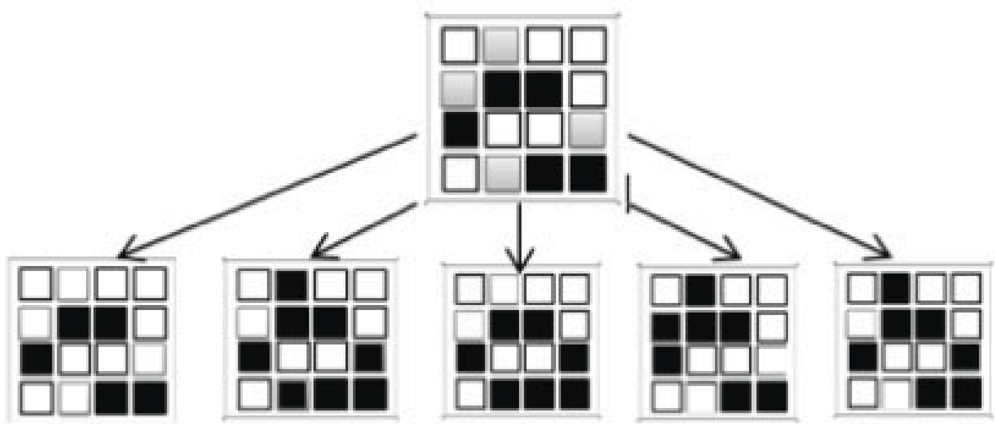

Fig.5. Anarray with five different radiations on its module is divided into three shadow coded array

Hence:

$$P_{(v)} = \sum_{j=1}^{j=m-1} a_j P_j(V) = (0.1 - a_4) \times P_{1(V)} + (0.6 - a_4) \times P_{2(V)} + (0.2 - a_4) \times P_{3(V)} + a_4 \times P_{4(V)} + 0.1 \times P_{5(V)}$$

The above equation stands good for any value of Considering , we compare the coefficient factors of 3×3 PV array with those of 4×4PV array, as appended below

3x3	4x4
$a_1 = 0.2$	$a_1 = 0$
$a_2 = 0.6$	$a_2 = 0.5$
$a_3 = 0.2$	$a_3 = 0.3$
	$a_4 = 0.1$
	$a_5 = 0.1$

5.0 RESULTS AND DISCUSSION:

In this paper, combining binary coding and mathematical laws, the detail analysis of PGIof 4×4 PV arrayhas been done. The PGI value is found close to 0.5. The array coefficient factors were found as follows:

$a_1 = 0$, $a_2 = 0.5$, $a_3 = 0.3$, $a_4 = 0.1$, $a_5 = 0.1$.

Finally, the total power equation is

$P_{(V)} =$

$$\sum_{j=1}^{m+1} a_j P_j(V) = 0 \times P_{1(V)} + (0.5) \times P_{2(V)} + (0.3) \times P_{3(V)} + (0.1) \times P_{4(V)} + (0.1) \times P_{5(V)}$$

6.0 CONCLUSION:

In this paper, we analyzethe effect of different kind of shadow pattern on PV systemsusing binary coding method. Depending upon the voltage, current and power which is needed to feed a load or parameters that should be matched with network in grid connected solar plants,the PV array configuration should be chosen differently.

When modules in a PV array connected in parallel, it acts as an n-bit binary number having the bit values independent from each other. So when an array has one row, modules act better than the other configurations. But this configuration is not common. Most of PV arrays which are connected to a network have the same number of rows and columns (e.g. 4×4).But it is better to use fewer rows because as the numbers of rows are increased the dependency factor between modules will increase. Therefore, it is better to use modules which have higher voltages to produce needed output voltage with less number of rows. Moreover, fewer number of rows will cause fewer number of bypass diodes to be utilized. When modules in an array produce high power under full sun will become higher consumer themselves under shadow state. Therefore it is necessary to use blocking diodes.

Binary coding method can also be used for other purposes such as thermal analysis of solar PV arrays. In future, we plan to work on the harmful overcurrent and thermal effect on P-V arrays on different diode configurations by using binary coding method.

References:

[1] R. Ramaprabha, and B. L. Mathur, "Modeling and Simulation of Solar PV Array under Partial Shaded Conditions", Proc. ICSET 2008, pp. 7-11.

[2] Woyte, J. Nijs, R. Belmans, "Partial Shadowing of Photovoltaic Arrays with Different System Configurations: Literature Review and Field Test Results", Solar Energy 74, 2003, pp. 217-233.

[3] D. Sera, R. Teodorescu, P. Rodriguez, "Partial Shadowing Detection Based on Equivalent Thermal Voltage Monitoring for PV Module Diagnostics", Proc. 35th IEEE Annual Conf. on Industrial Electronics, pp. 708-713, 2009.

[4] T. Shimizu, M. Hirakata, T. Kamezawa, and H. Watanabe, "Generation Control Circuit for Photovoltaic Modules," IEEE Trans. on Power Electron., vol. 16, pp. 293-300, 2001.

[5] H. Kawamura, K. Naka, N. Yonekura, S. Yamanaka, H. Ohno, and K. Naito, "Simulation of I-V Characteristics of a PV Module with Shaded PV Cells", Solar Energy Materials and Solar Cells, vol. 75, pp. 613- 621, Feb 2003.

[6] T. Mishima and T. Ohnishi, "Power Compensation and Control System for Partially Shaded PV Array," IEEJ Trans. Industry Application, vol. 122, pp. 799-806, 2002.

[7] E. Karatepe, M. Boztepe, and M. Colak, "Development of a Suitable Model for Characterizing Photovoltaic Arrays with Shaded Solar Cells," Solar Energy, vol. 81, pp. 977-992, 2007.

[8]N. D. Kaushika and A. K. Rai, "An Investigation of Mismatch Losses in Solar Photovoltaic Cell Networks", Energy, vol. 32, pp. 755-759, May 2007.

[9] D. King, J. Dudley and W. Boyson, "PVSIM: A Simulation Program for Photovoltaic Cells, Modules, and Arrays", Proc. 25th IEEE Photovoltaic Specialists Conf., pp. 1295–1297, 1996.

[10] M. C. Alonso-Garcia, J. M. Ruiz, W. Herrmann, "Computer Simulation of Shading Effects in Photovoltaic Arrays," Proc. Renewable Energy 31, pp. 1986 – 1993, 2006.

[11] S. Silvestre, A. Boronat, and A. Chouder, "Study of Bypass Diodes Configuration on PV Modules," Applied Energy, vol. 86, no. 9, pp. 1632– 1640, 2009.

[12] H. Ziar, S. Mansourpour, A. Arjhangmehr, A. Salimi and E. Afjei, "Analysis of Thermal Effect on Solar Cells with Considering Bypass Diodes at Shadow Condition through Binary Coding Method", 2ndInternational Conf. on Electric Power and Energy Conversion Systems (EPECS), 2011.

[13] H. Ziar, S. Mansourpour, E. Afjei, "Detecting Harmful Overcurrents in PV Arrays at Shadow Condition through Binary Coding Method", 3rd International Conf. on Power Electron. and Drive Systems Technology (PEDSTC), 2012