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Research paper

Shadow dispersion of PV Array under variable irradiance for superior power Generation by Magic Square Configuration

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Abstract

The PV array generates smaller amount of the power compared with other electrical power generation components. There are many components that are adversely effected the output of PV array in such components, one is partial shading. Due to this, each module in PV array receives different solar irradiations causes different P-V characteristics of its peak values. This paper presents a pioneering method called as Magic Square configuration has been proposed to enhance the generated power of photovoltaic modules by configuring those are under affect of shade. Thus there is no change of electrical arrangement of PV modules in an array but only the objective location in the total cross tied (TCT) array is rearranged according to the magic square arrangement. Proposed paper gives comparison data with the conventional configuration method and hence the performance is calculated. The proposed technique provides a better solution that how shadow effect on the PV modules has been reduced and how this shadow is distributed, and not only that also gives an idea about how the inequality losses due to the partial shading is effectively reduced. The power loss of various configurations of 3X3 and 4X4 array has been compared. The proposed technique is validated through MATLAB/Simulink environment.

***Keywords**: Photovoltaic Cells; Mismatch Loss; Shading Patterns; Partial Shading; Magic Square; Power Enhancement; Global Peaks; Total Cross Tied (TCT).*

1. Introduction

In presently developed technology even today's the sun rays conversion of the electrical efficiency of PV is about 20% with increased advances in solar cell technology this number is likely to increase not only their small range conversion efficiency but also the solar photovoltaic panels has high initial investment cost and the variations in output power because of the continuous changes in irradiance is due to several effects like shades of various objects such as neighbour buildings ,clouds, bird's shit, height of the poles, snow, advertising boards ,trees and etc , these will reduce the generated power [1],thereby the overall efficiency of the system has been decreasing[2] and also that the output power of the PV array is condensed due to partial shading and improvement of the power is obviously depends on the physical location and position of the module which is under shade[3].The improvement of the output power is done only when the modules/ arrays are reconfigured. Hence, in this anticipated arrangement, the substantial position of the PV modules has been changed whereas the electrically all the tie are not altered. Due to the partial shadings each panel or module of the PV array receives irradiations at different strengths. this result in multiple local maxima in P-V curves. Therefore due to the partial shading, multiple peaks can be observed in P-V characteristics leads to a local peak less than the global peak. [4-7]. Different configurations are presented in [8] for analysis of this partial shading techniques, they are (i) series-parallel (SP) (ii) bridge link (BL), and (iii) total cross tied (TCT). From all the above three configurations of PV array the third type of configuration (i.e) TCT configuration is more generated power than the remaining methods, under the shade with the total cross tied connection to increase the power output, a novel technique was employed in [9] whereas in the [10] about the new method namely Sudoku pattern gives how the output power from the PV is increased by 6% by changing from TCT to Sudoku and it cleared that the drawback of sudoku is that it can perform only on 9X9 array. [11, 15-16] presents the different powers such as actual power and the mismatch power (obtained from PV) for a proposed three configurations SP, BL and TCT. The present proposed system by using a new technique called magic square overcomes the drawback of the Sudoku method just by configuring the physical location of the TCT modules whereas in the electrical connections are unaltered by doing this modification the effect of shadow has been dispersed throughout the array and thereby lowering the influence of shadow effect of that module in that row [12, 13]. Alterations in the arrangement in the solar arrays were discussed in [14] but it is concluded with only one irradiation values, it is required to conclude the same with multiple irradiations. The method used in [17] uses a sub-arrays concept to reduce some typical issues like reducing wiring length etc., but the complexity in array configuration is retained. Similar to this method another method name as a magic square arrangement is proposed for 3X3 and 4X4 array systems for the reduction of the wiring length as well as reduction of the complexity of the array system.

A comparison between magic square and the TCT configurations with two different patterns as 3X3 square and 4X4 square has been made in the present paper, and the approach did in this paper gives an idea about installation and commissioning of few KW range plants on building rooftops to get the maximum power where the shadow of other buildings or any obstacles to PV modules, present paper study includes improvement of performance at various types of shading pattern and the mismatch losses of power in traditional methods of array configuration has been compared with the proposed method. Theoretically and also in simulation wise, the proposed magic square configuration yields improved results by comparing with the TCT arrangement.

2. Modeling of Photovoltaic(Pv) Module

a. Mathematical Equation of a Solar Cell

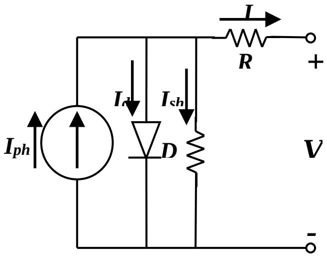

Fig. 1. The equivalent circuit of a single solar cell.

In [18], it is explained that an assortment of equivalent circuits of a solar cell, most far and wide worn is the one diode and dual diode models. whereas in the equivalent circuits with the one-diode model is effortless model compare to dual diodes for design and have high accuracy and best opt for numerous circuit configurations, the above Fig.1 represents one diode with the combination of series and parallel resistance equivalent circuit of a solar cell. Also, the author[18] distinguished the cryptogram of the above Fig.1

$$I = I_{ph} - I_o\left\{e^{\frac{q(V+R_sI)}{AKT}} - 1\right\} - \frac{V + R_sI}{R_{sh}} \quad (1)$$

b. Model of Photovoltaic module:

It is chosen commonly, the shunt resistance (*R_{sh}*) value as an infinite, at this condition the above equation (1) can be again written as

$$I = I_{sc} - I_0\left(e^{\frac{q(V+RsI)}{AKT}} - 1\right) \quad (2)$$

The above equation (2) is valid for the photovoltaic model of simple solar cell, which is having a numeral of series and parallel cell connections, therefore above equation for a PV model is again written as

$$I = I_{sc} - I_0\left(e^{\frac{q(V+R_sI)}{N_sAKT}} - 1\right) \quad (3)$$

the above equation (3) can be rewritten as below, if the module is open circuit condition then there will be zero current (i.e) I=0,

$$\frac{q}{N_sAKT} = \frac{\ln\left(\frac{I_{sc}}{I_0} + 1\right)}{V_{oc}} \quad (4)$$

Substituting (4) into (3), we get

$$I = I_{sc}\left[1 - \frac{I_o}{I_{sc}}\left(e^{\ln\left(\frac{I_{sc}}{I_o}+1\right)\frac{(V+R_sI)}{V_{oc}}} - 1\right)\right] \quad (5)$$

$$I = I_{sc}\left[1 - \frac{1}{k}(k+1)^{\frac{V+R_sI}{V_{oc}}} + \frac{1}{k}\right] \quad (6)$$

where $k = I_{SC}/I_0$, in general, Boltzmann constant (*k*) is high since I_0 value is a smaller amount when compared with I_{SC}. Further, the above same equation (6) is simplified as below,

$$I = I_{sc}\left(1 - k^{\frac{V+R_sI}{V_{oc}} - 1}\right) \quad (7)$$

as the temperature increases the consequently there will be a decrease of total voltage across PV module. And hence it is concluded that the temperature and the irradiance conditions are the affecting factors for the voltages and currents of a PV module, in equation (7) I_{ref} represents the output current under Standard Test Conditions (STC). Hence, while modeling of the PV system the insulation and temperature are considerable factors. But in the present work, it is considered only the different variation of irradiance conditions.
The mathematical jargon to rectify the voltage and currents are shown below

$$I_{sc} = I_{sc(ref)}\left[1 + \alpha(T - T_{ref})\right]\frac{G}{G_{ref}} \quad (8)$$

$$V_{sc} = V_{sc,ref}\left[1 + a\ln\frac{G}{G_{ref}} + \beta(T - T_{ref})\right] \quad (9)$$

as per the standard test condition[19], the temperature of the Solar Photovoltaic module is expressed as *T*, reference Solar Photovoltaic (SPV) module *α* is the temperature coefficient of I_{sc}, in-plane solar irradiance written as G, temperature with T_{ref}, under standard test condition (STC) G_{ref}, is the reference irradiance, the irradiance correction factor of V_{oc} and the coefficient of temperature is *β at* V_{oc}.

3. Validation of the PV model in MATLAB Simulink

By using MATLAB with a 36 number of solar PV cells are under simulation process, PV system model is simulated to employ and to validate for the proposed model, a mathematical model to validate the PV system model is simulated. The model specifications under STC are shown in Table I.

Table-I: at 1000W/m^2 and 25°C disclaimer of PV module Simulated results of a Single PV Module under standard test conditions (STC)

Parameter	*Variable*	Value
Maximum Power (W)	P_{max}	83.27
Open circuit Voltage (V)	V_{oc}	12.64
Short Circuit Current (A)	I_{sc}	8.62
Voltage at mpp (V)	V_{mpp}	10.31
Current at mpp (A)	I_{mpp}	8.07

To estimate the exploit qualities of the PV model, for measurement of V–I and P- V characteristic curves of individual PV module under different input conditions are analyzed. Testing conditions are irradiance at 400 W/m^2, irradiance at 600 W/m^2, irradiance at 800 W/m^2 and irradiance at 1000 W/m^2. Fig.2 shows the different lines represents the simulated results at different irradiance.

4. Shading effect on PV array configurations

The three basic topology configurations with the combination of both 3X3 and 4X4 PV arrays are discussed [14] and are shown in Fig.4

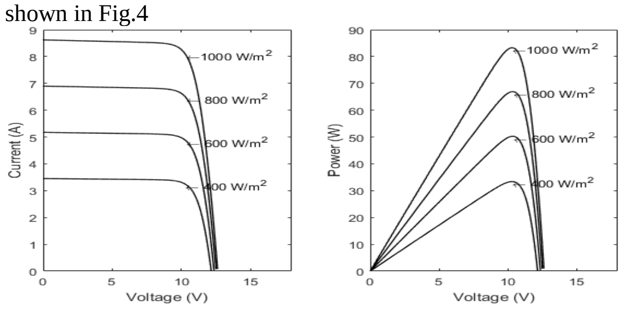

Fig.2 Characteristics of I-V and P-V at constant 25^0 temperature with different irradiations

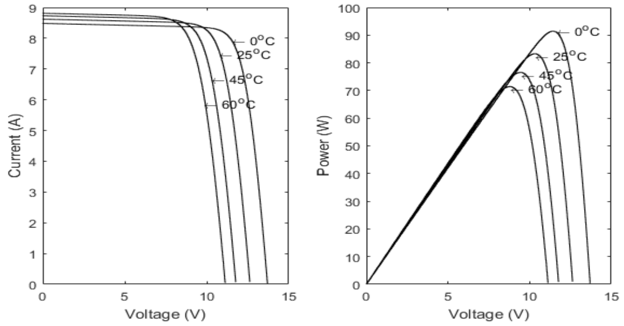

Fig. 3: Characteristics of I-V and P-V at different temperature with constant irradiation of 1000 W/m^2

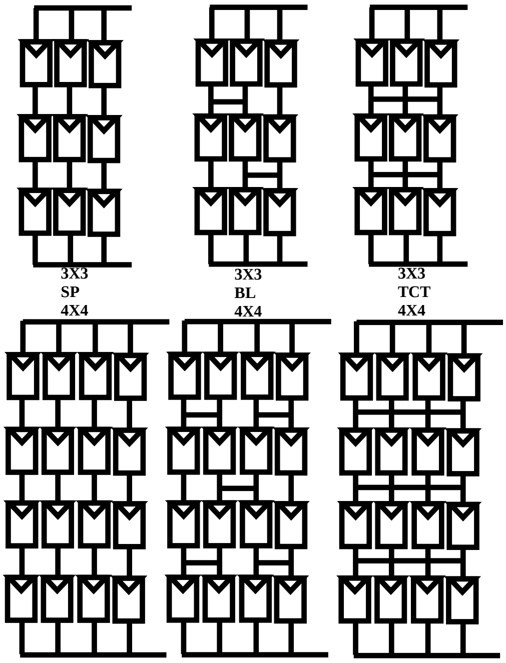

Fig. 4 Connection diagram of three topologies of 3X3 and 4X4 arrays.

5. Magic Square arrangement of Photovoltaic Solar array

The numbers which are arranged from 1 to n^2 as an nXn matrix form so as a magic square arrangement each number is placed one time exactly such that the sum of any row, any column, any diagonal are the same and applied this technique for the both square matrix 3X3 and 4X4. Fig. 5(a) and Fig. 5(e) are the square matrix, first accommodating the diagonal elements by vacating other elements. Except for the diagonal element of TCT configuration keeps the other elements vacantly, diagonal elements are filled with initial priority (Fig. 5(c), 5(g)). As this paper proposes a 3X3 and 4X4 configurations, there exist 9 and 16 elements respectively. All the unused elements are used in declining order starting from the last element (i.e.) 9th in 3X3 and 16th in 4X4 configuration thus all elements are arranged in a column-wise to fill all the remaining ones left out as shown in Fig. 5(c), and 5(g). which results from the change in physical location of each module without any distressing of their electrical connections of 3X3 and 4X4 PV arrays. The physical and electrical connections both 3X3 and 4X4 are shown in Fig.6, here the current and voltage equations are same since their electrical connections are not altered as in the TCT connection. It can be observed that the panels in the row in the TCT configuration are now in different rows in the magic square technique of the 3X3 and 4X4 arrays.

1	4	7
2	5	8
3	6	9

(a)

1	4	7	1000 W/m^2
2	5	8	800 W/m^2
3	6	9	600 W/m^2

(b)

4	9	2
3	5	7
8	1	6

(c)

4	9	2
3	5	7
8	1	6

(d)

1	5	9	13
2	6	10	14
3	7	11	15
4	8	12	16

(e)

1	5	9	13	1000 W/m^2
2	6	10	14	800 W/m^2
3	7	11	15	600 W/m^2
4	8	12	16	400 W/m^2

(f)

1	15	14	4
12	6	7	9
8	10	11	5
13	3	2	16

(g)

1	15	14	4
12	6	7	9
8	10	11	5
13	3	2	16

(h)

Fig. 5 Shading pattern for 3X3 and 4X4 arrangements (a) TCT arrangement; (b) irradiation levels; (c)magic square arrangement; (d) shade dispersion with magic square technique; for 3x3 PV array; (e) TCT arrangement; (f) irradiation levels; (g) magic square arrangement; (h) shade dispersion with magic square technique; for 4x4 PV array.

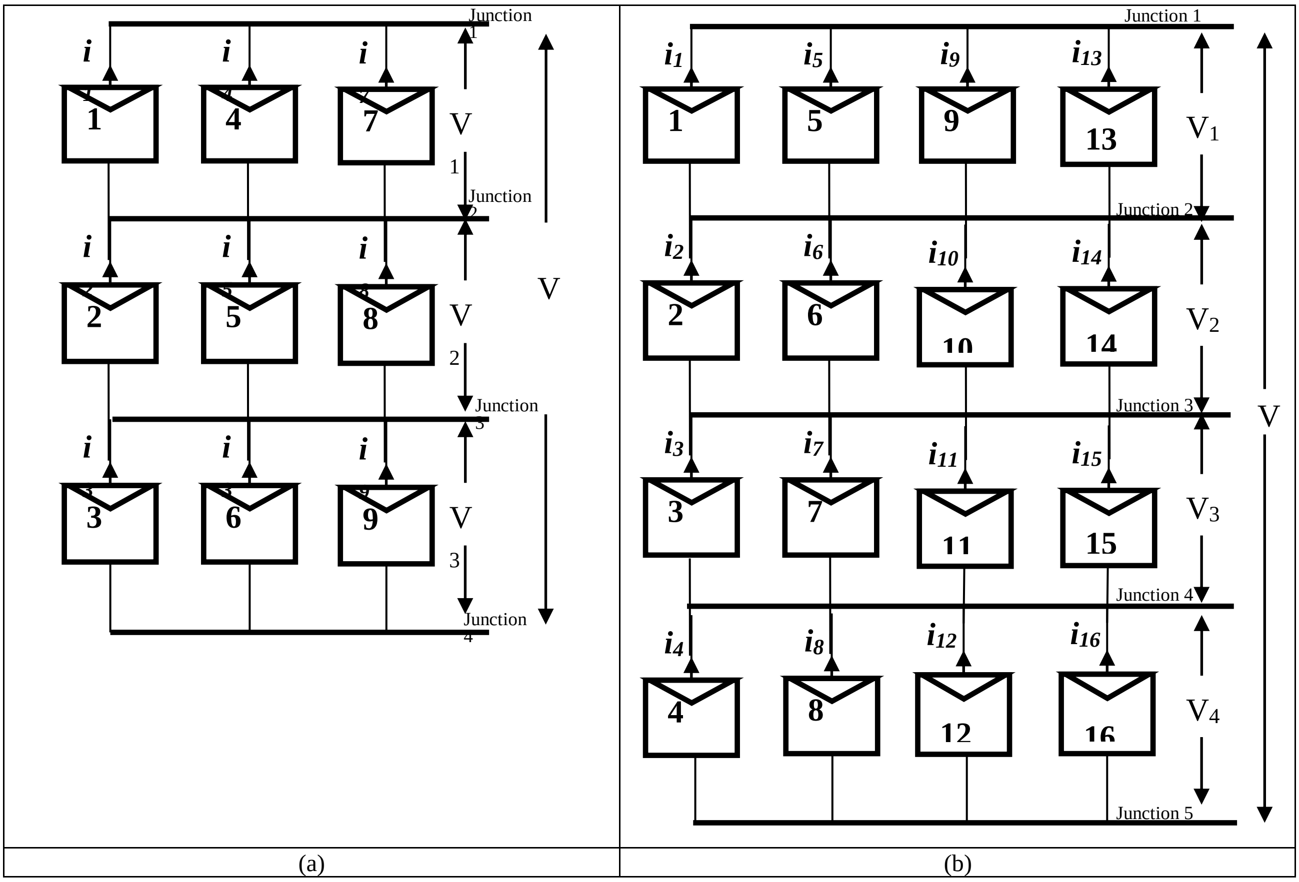

Fig. 6. PV array connected in TCT configuration- physical and electrical connections both 3X3 and 4X4 PV array

By adding the bypass diode to the proposed solar PV panel of a magic square technique the currents diverges thought it when the panel is subjected to shadow. Also that the bypass diodes are used to avoid the hotspot in the PV array systems. the representation of the proposed magic square technique of Fig. 5(a), 5(e) is shown in Fig. 5(d) and 5(h) and it helps how to distribute the shadow effect to entire array and thus reduces its effect on a single row by reduc ing the number of bypass panels the current flowing towards the junction increases thereby the enhancing the power generation with the same panels for similar shading pattern.

6. Simulations and results

In order to evaluate the performance of the proposed system, a 3X3, and a 4X4 solar PV array, as shown in Fig. 6(a) and (b), is subjected to three and four types of different shading patterns respectively. From the bottom of the both arrays, each row of arrays is considered as one group. In this proposed system, in the 3X3 array (Fig.6(a)) module 3, module 6, module 9 are considered as one group and they are fed with the irradiation of 600W/m^2. Module 2 module 5 module 8 are considered as another group and they are fed with the irradiation of 800W/m^2 and module 1, module 4, module 7 are considered as one group and they are fed with the irradiation of 1000W/m^2. Similarly, in the 4X4 array (Fig.6(b)), modules 4, 8, 12 and 16 are considered as one group and fed with 400W/m^2. Modules 3, 7, 11 and 11 are considered as one group and fed with 600W/m^2. Modules 2, 6, 10 and 13 are considered as one group and fed with 800W/m^2 and remaining are considered as one group and fed with 1000W/m^2.

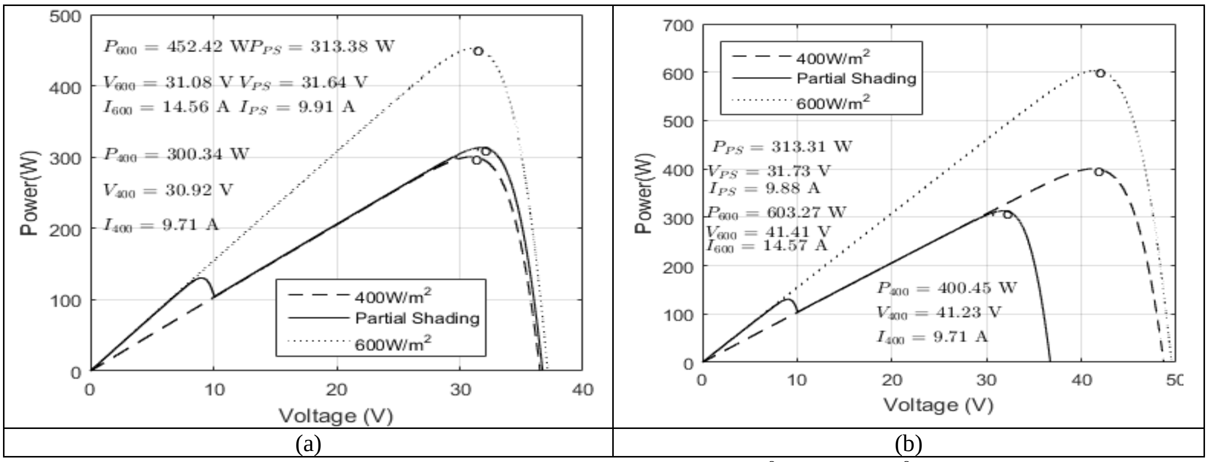

Fig.7. Multiple peaks of proposed arrays. (a) 3X3 array with irradiations 600 W/m^2 and 400 W/m^2 and (b) 4X4 array with irradiations 600 W/m^2 and 400 W/m^2

1	4	7	= 749.51W
2	5	8	
3	6	9	

(a)

1	4	7	= 494.34W
2	5	8	
3	6	9	

(b)

1	5	9	13	= 1332.46W
2	6	10	14	
3	7	11	15	
4	8	12	16	

(c)

1	5	9	13	=645.20W
2	6	10	14	
3	7	11	15	
4	8	12	16	

(d)

Fig. 8. Effect of the reduced power due to variation in irradiation level.

2,5,8 cells received 80% of irradiation therefore total output power is

$$P_m=V_m(I_m*0.8+ I_m *0.8+ I_m *0.8) \text{ W}.$$

Similarly 3,6,9 cells received 60% of irradiation therefore total output power is

$$P_m=V_m(I_m*0.6+ I_m *0.6+ I_m *0.6) \text{ W}.$$

Resulted in the reduction of the total power 494.34 W. Due to the generation of the different powers with different rows caused different power peaks, resulted in multiple power peaks. Now, the mismatch power in each row is having a cumulative effect on the total output power. In this case, there is a mismatched power of 252.17 W. This is true in a case of the 4X4 array also, In this 4X4 array case a mismatched power of 647.26 W. To avoid the mismatch power loss the magic square technique is employed. The magic squares for 3X3 and 4X4 are already shown in Fig. 5(d). and 5(h) respectively. The theoretical calculation with the magic square is shown in Fig.9(a) and (b) respectively.

4	9	2	=601.41W
3	5	7	
8	1	6	

(a)

1	15	14	4	=935.35W
12	6	7	9	
8	10	11	5	
13	3	2	16	

(b)

Fig. 9. Effect of the magic square pattern for reduction of shading effect.

It can be observed that due to the employment of the magic square technique the obtained power in 3X3 array is 601.41W and in 4X4 array is 935.35 W. The mismatch power loss
due the magic square in 3X3 array is 148.1 W and in 4X4 array is 397.11 W. The PV curves shows the enhancement in the power from PV array as in Fig.10. From Fig.10, the top line (dotted line) is having the global peak, which is obtained with the maximum irradiance level. The bottom line is having multiple peaks due to the shading effect and the middle line is due to the magic square technique. Due to the employment of the magic square technique, the curves are smoother like the global peak curves and also the multiple peaks are also eliminated.

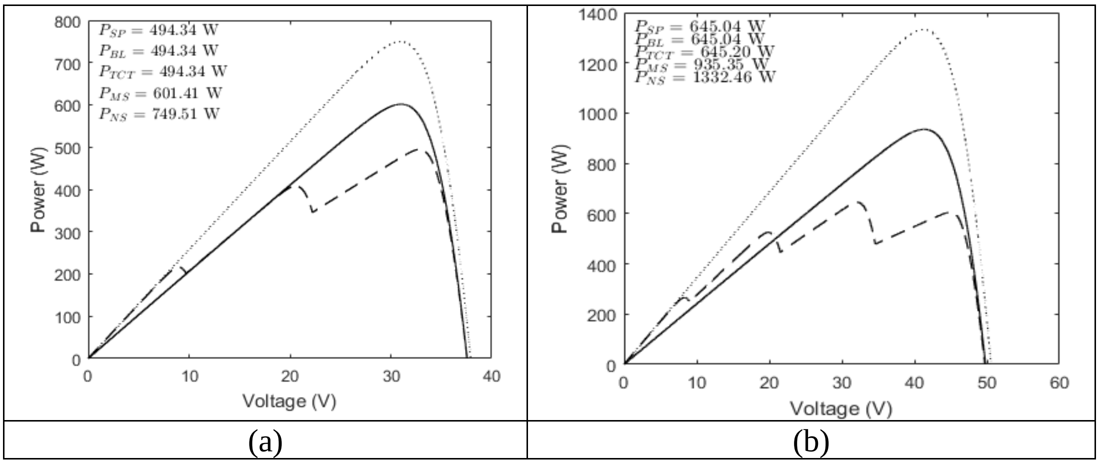

Fig.10. With partial shadings and without partial shadings of different configurations. (a) 3X3 array and (b) 4X4 array

Table.2: shows the comparison of the powers in different configurations of the PV arrays with partial shading effects.

Array Type	Case	Maximum Power (W)		Power loss (W)
		Without Partial shading	With partial shading	
3X3	Series - Parallel	749.51	494.34	252.17
	Bridge Link	749.51	494.34	252.17
	TCT	749.51	494.34	252.17
	Magic Square	749.51	601.41	148.1
4X4	Series - Parallel	1332.46	645.04	647.26
	Bridge Link	1332.46	645.04	647.26
	TCT	1332.46	645.04	647.26
	Magic Square	1332.46	935.35	397.11

7. Conclusions

In this paper, an approach is proposed to allocate the effect of partial shading on the PV array in 3X3 and 4X4 arrays without altering the electrical connections of PV modules just only by the change of physical location their performance improvement has been discussed (The power loss of magic square method in both 3X3 and 4X4 is 148.1watts and 397.11 watts respectively and are less compared to the other cases). The individual locations of global peaks in SP, BL, TCT and the magic square configurations of a PV array for 3X3 and 4x4 are calculated theoretically and they are also verified by simulation in MATLAB/SIMULINK environment. Also obtained power voltage characteristics of a 3X3 and 4X4 array for various shading conditions of three configurations like SP, BL and TCT addition to the magic square configuration. It is observed that a wrinkle-free PV characteristics are obtained from the proposed configuration when compared with the conventional PV array. Proposed method identified that the global peak tracking is simplest compared to the SP, BL and TCT systems. Hence it is found out that finally considerable power enrichment of a PV array in the magic square configuration with respect to the SP, BL and TCT configuration.

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