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A Novel Array Configuration Technique for Improving the Power Output of the Partial Shaded Photovoltaic System

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ABSTRACT Power conversion efficiency is the most important factor to be considered in PV systems because it is affected by various environmental conditions. The effect of partial shading is the most influenced factor in the reduction of power output. Various research schemes like Maximum Power Point Tracking (MPPT), array configuration scheme, reconfiguration, etc., work on the PV system to reduce the impact of partial shading. This paper presents a new kind of array configuration scheme that forms the PV array based on the moves of the Knight coin in the chess game. This arrangement creates the squared PV array of rows with distinct PV modules which is capable of evenly dispersing the shading in the partially shaded PV array. Also, this scheme is applicable for the non-squared PV arrays to create PV rows with the PV modules from a distinct location or from the same row with optimized distance to disperse the maximum level of shading. The proposed method has been discussed with the proper mathematical formulation with all necessary constraints and also it been validated with the hardware arrangements and MATLAB/Simulink® model.

INDEX TERMS Array configuration, maximum power point, partial shading (PS), photovoltaic system (PV), screw pattern, series-parallel (Se-P), Sudoku pattern, total cross tied (TCT).

I. INTRODUCTION

In recent years, the energy demand and the depletion of fossil fuels lead to the utilization of renewable energy sources. Solar Photovoltaic System is the finest energy source among other renewable sources based on its benefits [1]–[4]. PV system converts the photons in the sunlight to electrical energy by the photovoltaic effect. The revolution in semiconducting technology increases the hope of Solar PV systems [5]. Researchers in the Photovoltaic field were working to reduce the cost, increase the user-friendly nature, resist the effect of hard-charging environmental conditions, and enhance the power conversion efficiency [6]. Various environmental factors are influencing the reduction of PV's power conversion efficiency. Among these factors, partial shading is the major one in reducing the PV efficiency. PV cells and PV modules are connected in series and parallel to generate efficient power to meet the energy demand. The partial shading on a cell or module limits the current of the unshaded cell/module connected series with it. Due to this limiting current in the string directly reduces the power generation of the PV array [7]. In earlier, the bypass diode technique has been used to avoid the effect of shaded PV cells over the unshaded ones. The bypass diode offers a high resisting path under the normal operating condition and in the shading condition, it offers a low resistance path than the PV cell, which avoids the isolate the shaded PV cell. This technique reduces the effect of partial shading. but the major drawback

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is the current generation from the shaded PV cell is completely unavailable in the output power [8], [9]. Later the Maximum Power Point Tracking (MPPT) technique has been developed by the researchers. MPPT algorithms make the PV cell resistance (source resistance) and the Load resistance to be equal by changing the duty cycle of the power converter connected with it. The conventional algorithms have been integrated with soft computing methods like Artificial Intelligence (AI), Ant Colony Optimization (ACO), Neural Network (NN), Fuzzy Logic Control, etc., with it. However, under the uneven partial shading condition, the PV system operates with multiple Local MPP and the MPPT algorithm fails to obtain the Global MPP among multiple LMPP [10]–[12]. The reduction in output power depends on the array configuration and the shading pattern that occurred on it. The series array configuration scheme has poor performance during the shading because the shaded module in series limits the string current. Different array configuration methods had been developed such as Series parallel, (Se-P), Total Cross Ties (TCT), Bridge-Linked (B-L), Honeycomb (HC), Sudoku puzzle pattern (SPP), Futoshiki Puzzle Pattern (FPP) by the researchers to limit the influence of shaded PV module in the PV array [13]–[16]. The electrical reconfiguration method has been developed for PV array in [17]–[22]. EAR rearranges the PV module's interconnection by the power electronic switches to generate maximum power with the corresponding shading pattern. The controller operates the switches based on the shading patterns and the inner faults in the PV modules. The reconfiguration has been done by various parameters such as short circuit current, power output from each PV row, shading pattern. Also, the reconfiguration technique has been developed by image processing as presented in [22]. Also, the power electronic optimizers are used with the PV array to compensates for the limiting current of the shaded module. The DC optimizer is connected with each PV module/ PV string that injects the reduced current caused by the shading and enhances the output power [23]. But in the large PV plant, the concept of EAR and DC optimizers are complicated to implement, because this arrangement requires more sensors, switches, and controllers.

This paper proposes a novel array configuration scheme like TCT, with the enhanced capability of shade dispersion. The movement of the chess coin is the basic ideology behind this array configuration scheme. The array configuration has been defined with the proper mathematical formulation with all necessary constraints. There are various factors are defined as the mathematical expresseion, that satisfies the all assumption has taken on the knight pattern array configuration. For any kind of PV arrays such as squared and non-squared, this configuration frames each row by distinct PV modules or the PV modules from the same row with an optimized location without affecting the shade dispersion rate using the mathematical function. This proposed knight pattern array configuration scheme has been implemented in 4 × 4 (squared) and 4 × 5 (non-squared) PV arrays in both hardware and MATLAB/Simulink®. The enhanced performance of the proposed knight pattern array configuration has been analyzed with all possible shading patterns and it's been compared with the conventional array configuration scheme.

This paper is organized as follows: Section II discusses the mathematical model of the PV cell and the conventional array configuration schemes. The mathematical formulation and the methodology of the proposed knight pattern array configuration are presented in Section III. The result and discussion of the proposed method with convention schemes on the 4 × 4 and 4 × 5 PV array have been discussed in Section IV. The inference and the advantages of the proposed scheme have been discussed in the conclusion and presented in Section V.

II. SYSTEM DESCRIPTION

A. MATHEMATICAL MODEL OF PV MODULE

The mathematical model of a PV system can be written as the equation (1). Where a shunt resistance R_{sh} is connected parallel with the current source of I_{ph}, as shown in the equivalent circuit of the solar cell. A single PV cell alone cannot supply the energy demands. For balancing the energy demand, n number of PV cells are connected in series, parallel, and series-parallel combinations. These combinations allowed the PV cells to group as a large power source. The single diode model of the Solar PV cell is constructed with the single current source with a shunt-connected resistance [24].

$$I_m = I_{ph} - I_{sat}\left[exp\left(\frac{V_m + I_m R_s}{(nKT/q)}\right) - 1\right] - \frac{V_m + I_m R_s}{R_{sh}} \tag{1}$$

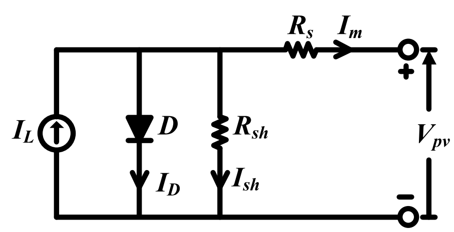

FIGURE 1. Equivalent circuit of solar cell.

where,
I_m - Maximum output current
V_m- Maximum output voltage
I_{ph} - Photoelectric Current
I_{sat} - Saturation current
R_s - Series Resistance
R_{sh} - Shunt Resistance
T - Ambient Temperature
n - Number of PV cells connected in series
K - Boltzmann's constant.

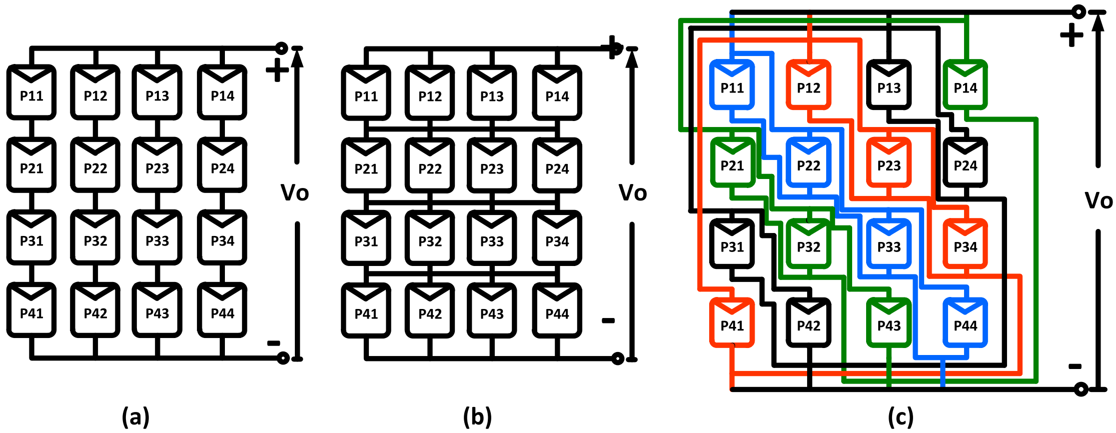

FIGURE 2. 4 × 4 PV array with (a) Series-Parallel (b) TCT (c) Sudoku puzzle pattern.

B. CONVENTIONAL ARRAY CONFIGURATIONS

The PV modules are grouped as PV arrays to meet the energy requirement. The PV array has been formed based on the various array configuration schemes. In the earlier days, PV cells are connected in series and series parallel, and these schemes are experienced more electrical stress due to the partial shading, hotspots, and other factors. The current and voltage equation for the array configuration has given in equation (2)-(5) for the n × m PV array, For series connection,

$$V_{\max} = \sum_{i=1}^{m} V_i \tag{2}$$

$$I_{\max} = I_1 = I_2 = I_3 = \ldots.. = I_n \tag{3}$$

For Parallel array configuration

$$V_{\max} = V_1 = V_2 = V_3 = \ldots.. = V_m \tag{4}$$

$$I_{\max} = \sum_{i=1}^{n} I_i \tag{5}$$

The main drawback associated with this array configuration is, if one panel in series connection is affected by any kind of defects, then the power output from the entire PV string will be reduced and also causes the high electrical stress on the string. Later the Total Cross Tied (TCT) array configuration has been developed. For the n × m PV array, 'm' numbers of PV modules have been connected in parallel as 1 × m PV array. Totally 'n' numbers of 1 × m PV rows have been further connected in parallel to form an n × m PV array. This TCT array configuration reduces the electrical stress and the mismatch loss associated with the series-parallel configuration and it can be further reduced by the configuration of the SUDOKU puzzle pattern. In the sudoku pattern, each row of PV array has been constructed with the PV panels belongs to distinct PV rows and columns of TCT. The pictorial representation 4 × 4 PV array with series-parallel, TCT, and Sudoku puzzle patterns has shown in Fig.2. These strategies reduce the mismatch loss in the PV system with the series or series-parallel array configuration. Equation (6) represents the mismatch loss calculation,

$$MismatchLoss, (ML) = P_{R\max} - P_{R\min} \tag{6}$$

The main objective of the MPPT tracking and array configuration schemes on the PV system was to minimize the mismatch losses present on it. The mismatch loss is never dependent only on the shading level but also on the shading patterns. The shading pattern differs from the types of objects that cause the shading. The shading cannot be avoided or minimized, but the shading pattern can be altered to disperse the shading uniformly over the PV array by the static and fixed array configuration. The TCT, Sudoku array configurations were some techniques in the fixed array configuration and the reconfiguration methods (to change the electrical connection between panels based on the shading) is the technique in the static configuration.

III. PROPOSED ARRAY CONFIGURATION

The research work discussed in this paper proposes a novel array configuration like TCT, Sudoku to evenly disperse the shading in the partially shaded PV array, where the array size is not a constraint on its effectiveness. This work created PV rows using a pattern that is related to a strategical game. The knight coin in the Chess game follows a pattern like 'L' for its moments towards and backward as shown in Fig.3(b). This pattern has been used in the PV array to create every PV row with the PV modules from a different place with uniform propagation.

The number of propagations is based on the number of columns in the PV array. The ultimate aim of this method is to create a PV row (i.e. 1 × m) with distinct PV modules with uniform optimized distance so that the array can evenly disperse the shading in the PV array. For the n × m PV array, (m-1) numbers of 'L' propagations will be made by the knight pattern optimization algorithm. Figure 5. represents a 5 × 5 PV array, where the number of columns is 5. The algorithm makes four numbers of 'L' propagations from the starting node in this case.

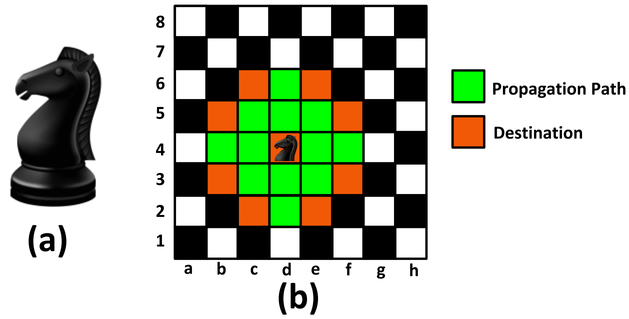

FIGURE 3. **(a) Knight coin of chess game (b) Knight pattern.**

There are two possibilities in the PV array size such as a squared-PV array, Non-Squared-PV array. Based on the array size with an odd number of columns and even number of columns the mathematical formulation has slightly differed but the optimization problem remains the same.

A. METHODOLOGY

For any kind of PV array, the PV modules are reallocated with respect to its functional equation. The functional equation is differing from the array size. The number of columns is the factor to be considered for choosing the functional equation. For the n × m PV array, Pij will be the position of each PV module, where i represents the row and j represents the columns (for example, P35 is the module in the 3rd row of the 5th column). The functional equation modifies the i and j of each module to make each row with PV modules from distinct rows and columns or the same row with the maximum possible distance. So that each PV row is capable to evenly disperse the shading in the array, and thus improve the output power.

Three different factors had been used such as Propagation Control Factor (PgF), Row Factor (RF), and Column factor (CF), for the row creation in the Knight Pattern Propagation algorithm. The propagation factor has been defined by the number of columns in the PV array. For the PV array with odd numbers of the column, the PgF will be (m-1)/2 and for the PV array with even numbers of the column, the PgF will be (m-2)/2, where m is the number of columns of the PV array. This factor defines the limit of 'L' propagation. Secondly, the row factor (RF) has been used for altering the PV module's row position by propagation. Finally, the column factor (CF) is used for defining the position for PV modules at their column position. For the PV array with an odd number of columns, the CF will be varied from j to j+PgF and j-PgF to (j-1) and for the even numbers of the column, the CF will be varied from j to j+PgF and j-PgF to j.

The Propagation factor for PV array with odd no of columns and even no of columns can be defined as,

$$PropagationFactor(PgF)_{odd} = \frac{Numberofcolumns - 1}{2} = \frac{m-1}{2} \tag{7}$$

$$PropagationFactor(PgF)_{even} = \frac{Numberofcolumns - 2}{2} = \frac{m-2}{2} \tag{8}$$

The Row factor is the same for the PV array with both odd and even numbers of columns and it is defined as,

$$RowFactor, (RF) = i + j - 1 \tag{9}$$

The column factor that can be defined for odd and even propagations is given in equation 10 and equation 11, as shown at the bottom of the next page.

The functional equation of the knight pattern algorithm can be defined by combining these factors. The row factor and column factor were deciding the position of the PV array and the propagation factor limits its propagation. The functional equation of the PV array with an odd no of columns and even number of columns be expressed as equation 12 and equation 13, as shown at the bottom of the next page.

B. PV ARRAY WITH ODD NO OF COLUMNS

The main objective function for the n × m PV array is,

(i) To evenly disperse the shading in the partially shaded PV array
(ii) Create a PV row by PV modules from the distinct location or the PV modules from the same row with maximum possible distance, as by the following function

The constraints for the above functional equation are given as follows, If the row factor is exceeding the number of rows in the PV array, then Row Factornew, (RF)new should be used in the array for further propagation. The mathematical representation has given below as,

If $RowFactor(RF) > n$, then

$$RowFactor, (RF)_{new} = RF - n = (i + j - 1) - n$$

where n - the no of rows in the PV array.

Let consider a 9 × 9 PV array,

Step-1: Obtain the no of propagation = (m-1) = 8
Step-2: Find the Propagation factor (PgFodd)

$$PgF_{odd} = \frac{m-1}{2} = \frac{9-1}{2} = 4$$

Step-3: Frame the PV rows propagates from j to (j+PgFodd) and (j-PgFodd) to j
Step-4: If, Row Factor, RF > n, then find RFnew as, RFnew = RF – n
For example: i = 6 and j = 6,
(i+j-1) = 6+6-1 = 11
(i+j-1) new = 11 - n
= 11 – 9 = 2

A pictorial representation of the proposed method for 9 × 9 PV array has shown in fig.4.

TABLE 1. Propagation table for 9 × 9 PV array.

i & j varies from 0 to 5		j=1	j=2	j=3	j=4	j=5	j=6	j=7	j=8	j=9
Rows		P(i+j-1) (j)	P(i+j-1) (j+1)	P(i+j-1) (j+2)	P(i+j-1) (j-2)	P(i+j-1) (j-1)	P(i+j-1) (j-1)	P(i+j-1) (j-1)	P(i+j-1) (j-1)	P(i+j-1) (j-1)
PR1	i=1	P11	P23	P35	P47	P59	P62	P74	P86	P98
PR2	i=2	P21	P33	P45	P57	P69	P72	P84	P96	P18
PR3	i=3	P31	P43	P55	P67	P79	P82	P94	P16	P28
PR4	i=4	P41	P53	P65	P77	P89	P92	P14	P26	P38
PR5	i=5	P51	P63	P75	P87	P99	P12	P24	P36	P48
PR6	i=6	P61	P73	P85	P97	P19	P22	P34	P46	P58
PR7	i=7	P71	P83	P95	P17	P29	P32	P44	P56	P68
PR8	i=8	P81	P93	P15	P27	P39	P42	P54	P66	P78
PR9	i=9	P91	P13	P25	P37	P49	P52	P64	P76	P88

C. PV ARRAY WITH EVEN NO OF COLUMNS

The main objective function for the n × m PV array is,

(i) To evenly disperse the shading in the partially shaded PV array Create a PV row with PV modules from the distinct location or the PV modules from the same row with maximum possible distance, as by the following function

The constraint for the above functional equation is given as follows, If, the row factor is exceeding the number of rows in the PV array, then Row Factornew, (RF)new should be used in the array for the further propagation. The mathematical representation has given below as,

If $RowFactor(RF) > n$, then

$$RowFactor, (RF)_{new} = RF - n = (i + j - 1) - n$$

where n is the number of rows in the PV array.

Let consider for a 6 × 6 PV array,

Step-1: obtain the no of propagation = (m-1) = 7

Step-2: Find the propagation factor, PgFeven

$$PgF_{even} = \frac{m-1}{2} = \frac{8-2}{2} = 3$$

Step-3: Frame the PV rows propagates from j to (j+PgFeven) and (j-PgFeven) to j

Step-4: If, Row Factor, RF > n, then find RFnew as, RFnew = RF – n

For example: i = 6 and j = 6,

(i+j-1) = 6+6-1 = 11

(i+j-1) new = 11 - n

= 11 – 8 = 3

IV. HARDWARE SETUP

The knight pattern algorithm has been implemented for the 4 × 4 PV array and 4 × 5 PV as shown in Fig.5(a) for experimenting with the effectiveness of the proposed array configuration with all other existing configurations. The panel rating has been given in table.3. There are twenty numbers of Monocrystalline type of PV modules of 250Wp/each has been used for the experimental setup.

A solar power meter has been used along with this setup for measuring the irradiation level in W/m2. For validating the proposed method, a reference atmospheric condition has been framed by considering the temperature and solar irradiation. The output has been observed from the inverter when the atmospheric condition and irradiation are nearly the same with the ±10% of reference. Generally, at 11 am-2 pm the atmospheric condition laid near the reference atmospheric condition. At this time, the irradiance and output current and power have been stored and the power output relies on or

TABLE 2. Propagation table for 8 × 8 PV array.

i & j varies from 0 to 5		j=1	j=2	j=3	j=4	j=5	j=6	j=7	j=8
Rows		P(i+j-1) (j)	P(i+j-1) (j+1)	P(i+j-1) (j+2)	P(i+j-1) (j+3)	P(i+j-1) (j-3)	P(i+j-1) (j-2)	P(i+j-1) (j-1)	P(i+j-1) (j)
PR1	i=1	P11	P23	P35	P47	P52	P64	P76	P88
PR2	i=2	P21	P33	P45	P57	P62	P74	P86	P18
PR3	i=3	P31	P43	P55	P67	P72	P84	P16	P28
PR4	i=4	P41	P53	P65	P77	P82	P14	P26	P38
PR5	i=5	P51	P63	P75	P87	P12	P24	P36	P48
PR6	i=6	P61	P73	P85	P17	P22	P34	P46	P58
PR7	i=7	P71	P83	P15	P27	P32	P44	P56	P68
PR8	i=8	P81	P13	P25	P37	P42	P54	P66	P78

TABLE 3. Rating of PV module.

S.No	Parameters	Specification	Units
	Short Circuit Current (Isc)	8.95	Ampere
	Open Circuit Voltage (Voc)	37.23	Volts
	Maximum Current (Im)	8.42	Ampere
	Maximum Voltage (Vm)	29.7	Volts
	Maximum Power (Pm)	250	Watts

$$ColumnFactor, (CF)_{odd} = j, (j+1), (j+2), \ldots, (j + PgF_{odd}), (j - PgF_{odd}), \ldots, (j-2), (j-1) \quad (10)$$

$$ColumnFactor, (CF)_{even} = j, (j+1), (j+2), \ldots, (j + PgF_{even}), (j - PgF_{even}), \ldots, (j-2), (j-1), j \quad (11)$$

$$P_{Ri_{ODD}} = [P_{(i+j-1)(j)}\ P_{(i+j-1)(j+1)}\ P_{(i+j-1)(j+2)}\ P_{(i+j-1)(j+3)} \ldots P_{(i+j-1)(j+PgF_{odd}-2)} \times P_{(i+j-1)(j+(PgF_{odd}-1))}\ P_{(i+j-1)(j+(PgF_{odd}))}\ P_{(i+j-1)(j-(PgF_{odd}))}\ P_{(i+j-1)(j-(PgF_{odd}-1))} \times \ldots P_{(i+j-1)(j-3)}\ P_{(i+j-1)(j-2)}\ P_{(i+j-1)(j-1)}] \quad (12)$$

$$P_{Ri_{EVEN}} = [P_{(i+j-1)(j)}\ P_{(i+j-1)(j+1)}\ P_{(i+j-1)(j+2)}\ P_{(i+j-1)(j+3)} \ldots P_{(i+j-1)(j+(PgF_{even}-2))} \times P_{(i+j-1)(j+(PgF_{even}-1))}\ P_{(i+j-1)(j+(PgF_{even}))}\ P_{(i+j-1)(j-(PgF_{even}))}\ P_{(i+j-1)(j-(PgF_{even}-1))} \times \ldots P_{(i+j-1)(j-3)}\ P_{(i+j-1)(j-2)}\ P_{(i+j-1)(j-1)}\ P_{(i+j-1)(j)}] \quad (13)$$

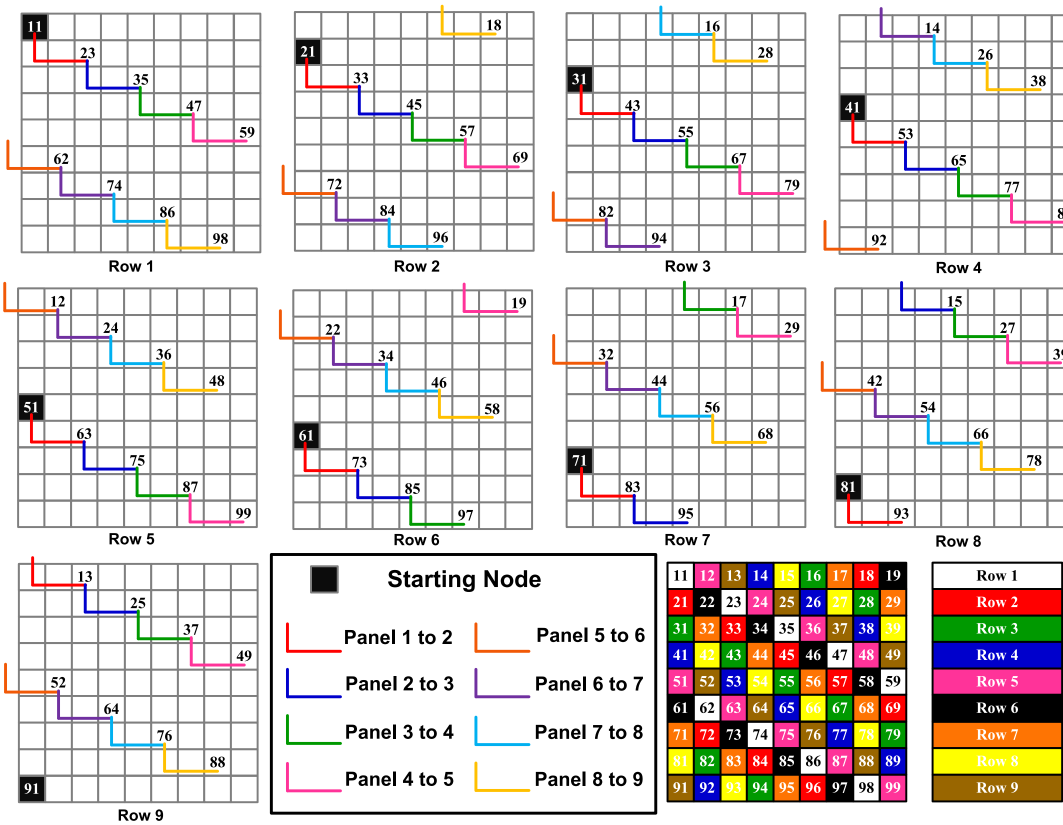

FIGURE 4. Propagation of 'L' for 9 × 9 PV array.

FIGURE 5. 5kWp PV system for the experimental verification.

nearly on the reference atmospheric conditions. For the 4 × 4 PV array, four kind of array configurations such as Series-Parallel, TCT, Sudoku, and the proposed Knight pattern has been validated and compared and for the 4 × 5 PV array, three kind of array configurations has been validated except Sudoku due to its limitations. Six kinds of shading patterns have been manually created on the PV array for validating the performance of the proposed knight patter array configuration over others.

V. RESULTS AND DISCUSSION

The performance of the proposed Knight Pattern method has been compared with the conventional methods under the six possible shading patterns as short and narrow (S&N), short and wide (S&W), diagonal, random, long and narrow (L&N), and long & wide (L&W) as shown in Fig.6. These shading patterns have been applied to the PV array by covering it using the cardboard sheet. The experimental output has been compared with the simulation result. The output analysis has been carried out by calculating the mismatch losses caused by the shading pattern.

The random shading pattern has happened in the PV array due to the taller objects, trees, or nearby objects. The shading and its pattern are unpredictable and uncontrollable phenomenon by nature. The objective of the proposed method is to evenly disperse the shading in the partially shaded PV array. Proposed method directly influenced the mismatch loss generation by the partial shading. The even dispersion of shading reduces the mismatch loss and improved output power. The 4 × 4 PV array for with the knight pattern method has been framed by the function equation of knight pattern algorithm as (i) number of propagation will be 3 (ii) the propagation factor is 1 ((m-2)/2) (iii) Frame each row of PV array as follows, $P_{Row(4\times5)}$ shown at the bottom of the next page.

For the 4 × 5 PV array (i) number of propagation will be 4 (ii) The propagation factor is 2 ((m-1)/2) (iii) Frame each row

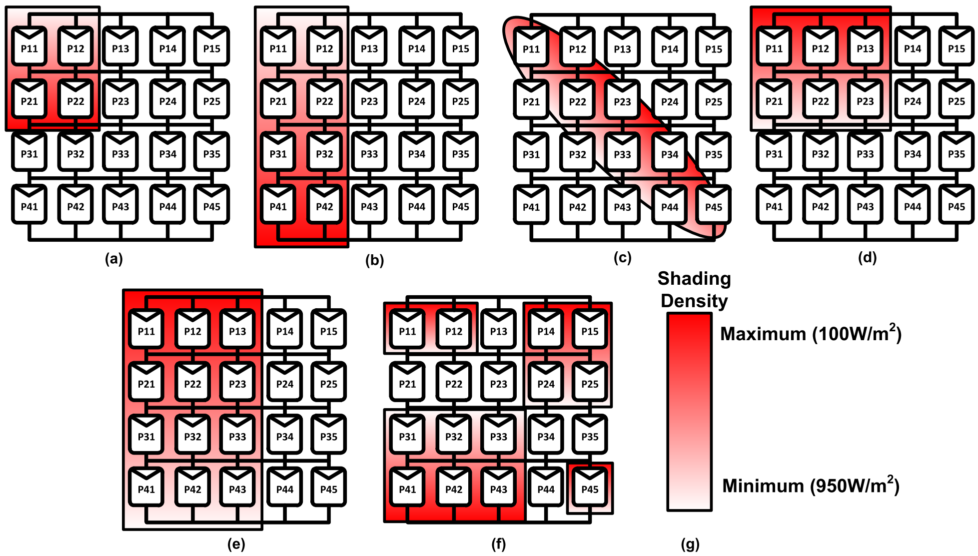

FIGURE 6. Shading patterns of (a) Short and narrow (b) Short and wide (c) Diagonal (d) Long and narrow (e) Long and wide (f) Random (g) Shading density.

of PV array as, $P_{Row(4\times5)}$ shown at the bottom of the next page.

Let us consider the random shading pattern as shown in figure.7 that has been occurred in the PV array. The shade dispersion rate can be measured by calculating the current generation of every individual PV row. The current generation of a single panel can be measured by the equation. The row current can be measured by the equation,

$$I_{m_{actual}} = S \times I_m \tag{14}$$

where S is the irradiance factor that can be defined as the ratio between the actual irradiance available in the environment to the irradiance value at the STC and it can be expressed as,

$$S = \frac{S_{actual}}{S_{STC}} = \frac{S_{actual}}{1000} \tag{15}$$

The row current can be measured by the following equation

$$I_{mRi} = \sum_{j=1}^{n} \left(\left(\frac{S_a}{S_{STC}} \right) \times I_{mj} \right) \tag{16}$$

The row current in the TCT array configuration has been calculated as,

$$I_{m_{R1}} = \left[\left(\frac{950}{1000} \times I_m \right) + \left(\frac{200}{1000} \times I_m \right) + \left(\frac{950}{1000} \times I_m \right) + \left(\frac{200}{1000} \times I_m \right) \right] = 2.3 I_m$$

$$I_{m_{R2}} = \left[\left(\frac{950}{1000} \times I_m \right) + \left(\frac{600}{1000} \times I_m \right) + \left(\frac{950}{1000} \times I_m \right) + \left(\frac{800}{1000} \times I_m \right) \right] = 3.3 I_m$$

$$I_{m_{R3}} = \left[\left(\frac{950}{1000} \times I_m \right) + \left(\frac{400}{1000} \times I_m \right) + \left(\frac{800}{1000} \times I_m \right) + \left(\frac{950}{1000} \times I_m \right) \right] = 3.1 I_m$$

$$I_{m_{R4}} = \left[\left(\frac{200}{1000} \times I_m \right) + \left(\frac{950}{1000} \times I_m \right) + \left(\frac{400}{1000} \times I_m \right) + \left(\frac{600}{1000} \times I_m \right) \right] = 2.15 I_m$$

The row current in the Sudoku array configuration has been calculated as,

$$I_{m_{R1}} = \left[\left(\frac{950}{1000} \times I_m \right) + \left(\frac{600}{1000} \times I_m \right) + \left(\frac{800}{1000} \times I_m \right) + \left(\frac{600}{1000} \times I_m \right) \right] = 2.95 I_m$$

$$I_{m_{R2}} = \left[\left(\frac{950}{1000} \times I_m \right) + \left(\frac{400}{1000} \times I_m \right) + \left(\frac{400}{1000} \times I_m \right) + \left(\frac{200}{1000} \times I_m \right) \right] = 1.95 I_m$$

$$P_{Row(4\times5)} = [\,(i+j-1)(j) \quad (i+j-1)(j+1) \quad (i+j-1)(j-1) \quad (i+j-1)(j)\,]$$

$$P_{Row(4\times5)} = [\,(j+i-1)(j) \quad (j+i-1)(j+1) \quad (j+i-1)(j+2) \quad (j+i-1)(j-2) \quad (j+i-1)(j-1)\,]$$

TABLE 4. Mismatch loss calculation under random shading pattern.

Configuration	Row Currents				Expected output	% of mismatch
	IR1	IR2	IR3	IR4	current	loss
TCT	2.3Im	3.3 Im	3.1 Im	2.15 Im	2.15 Im	34%
Sudoku	2.95 Im	1.95 Im	3.65 Im	2.3 Im	1.95 Im	47%
Proposed	2.7 Im	2.9 Im	2.35 Im	2.7 Im	2.35 Im	20%

TABLE 5. Performance of 4 × 4 PV array in various shading conditions.

Shading Pattern	Array configuration	Simulation Result				Experimental Output		
		Im	Vm	Pm	M.L	Im	Vm	Pm
Random	Se-P	8.42	78.8	663.7	-	7.8	76.1	596.1
	TCT	18.11	100.2	1814.3	34.8	16.8	96.3	1616.6
	Sudoku	16.42	98.3	1614.2	46.6	15.4	94.7	1454.9
	Proposed	19.79	101.8	2014.4	20.3	18.6	98.6	1833.1
S&N	Se-P	25.27	105.5	2664.8	-	23.2	101.2	2347.0
	TCT	25.27	105.5	2664.8	25	23.3	101.9	2371.9
	Sudoku	25.27	105.5	2664.8	25	23.3	101.5	2369.7
	Proposed	29.48	107.4	3165	0	27.2	103.1	2802.4
S&W	Se-P	21.9	103.4	2264.6	-	20.1	100.2	2015.9
	TCT	21.9	103.4	2264.6	35	20.2	100.2	2026.4
	Sudoku	22.74	104	2364.6	25	21.1	100.7	2119.2
	Proposed	25.27	105.5	2664.8	9.1	23.3	101.2	2357.0
Diagonal	Se-P	16.84	98.8	1664.3	-	15.7	95.7	1505.0
	TCT	26.95	106.3	2864.9	15.8	25.0	102.4	2564.2
	Sudoku	16.84	98.8	1664.3	50	15.7	95.4	1497.5
	Proposed	26.95	106.3	2864.9	20	25.2	103.0	2597.5
L&N	Se-P	20.21	102.1	2064.5	-	18.5	97.6	1806.0
	TCT	20.21	102.1	2064.5	33.3	18.5	97.4	1805.5
	Sudoku	21.9	103.4	2264.6	23.5	20.2	99.0	1995.6
	Proposed	23.58	104.5	2464.7	12.5	21.8	100.2	2181.1
L&W	Se-P	13.48	93.8	1264	-	12.3	89.4	1103.4
	TCT	13.48	93.8	1264	52.9	12.4	89.7	1108.5
	Sudoku	18.53	100.6	1864.4	26.7	17.0	96.4	1636.9
	Proposed	20.21	102.1	2064.5	7.7	18.6	97.4	1807.5

$$I_{mR3} = \left[\left(\frac{950}{1000}\times I_m\right)+\left(\frac{950}{1000}\times I_m\right)+\left(\frac{950}{1000}\times I_m\right) + \left(\frac{800}{1000}\times I_m\right)\right] = 3.65I_m$$

$$I_{mR4} = \left[\left(\frac{200}{1000}\times I_m\right)+\left(\frac{200}{1000}\times I_m\right)+\left(\frac{950}{1000}\times I_m\right) + \left(\frac{950}{1000}\times I_m\right)\right] = 2.3I_m$$

The row current in the Knight pattern array configuration has been calculated as,

$$I_{mR1} = \left[\left(\frac{950}{1000}\times I_m\right)+\left(\frac{950}{1000}\times I_m\right)+\left(\frac{400}{1000}\times I_m\right) + \left(\frac{600}{1000}\times I_m\right)\right] = 2.7I_m$$

$$I_{mR2} = \left[\left(\frac{950}{1000}\times I_m\right)+\left(\frac{800}{1000}\times I_m\right)+\left(\frac{950}{1000}\times I_m\right) + \left(\frac{200}{1000}\times I_m\right)\right] = 2.9I_m$$

$$I_{mR3} = \left[\left(\frac{950}{1000}\times I_m\right)+\left(\frac{400}{1000}\times I_m\right)+\left(\frac{200}{1000}\times I_m\right) + \left(\frac{800}{1000}\times I_m\right)\right] = 2.35I_m$$

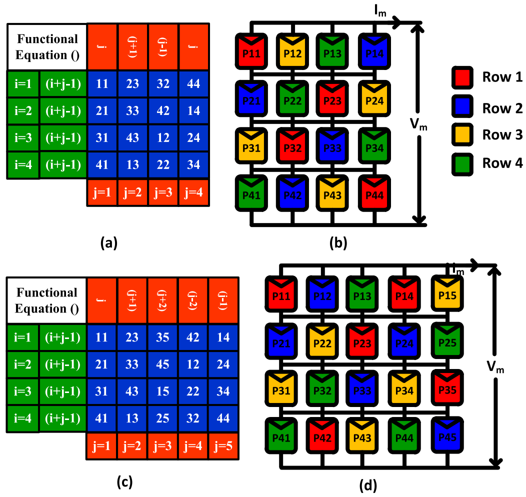

FIGURE 7. (a) Array formation diagram of 4 × 4 PV array (b) Representation of proposed configuration on 4 × 4 (c) Array formation diagram of 4 × 5 (d) Representation of proposed array configuration on 4 × 5.

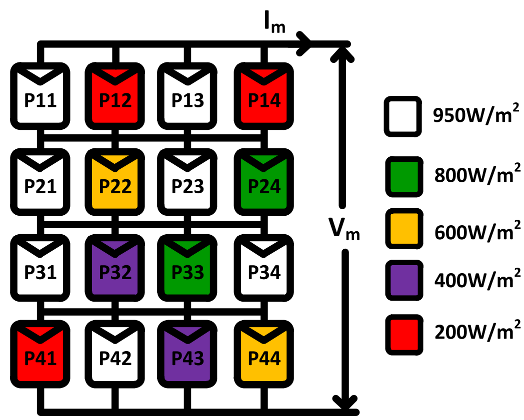

FIGURE 8. Random shading pattern on 4 × 4 PV array.

$$I_{mR4} = \left[\left(\frac{200}{1000}\times I_m\right)+\left(\frac{950}{1000}\times I_m\right)+\left(\frac{600}{1000}\times I_m\right) + \left(\frac{950}{1000}\times I_m\right)\right] = 2.7I_m$$

In the Series parallel array configuration, PV modules are connected in series and the mismatch loss has been calculated by the PV module which generating maximum power and minimum power in the same string. And in the parallel connection, the PV string current has been summed on the output terminal. So that the mismatch loss has been varied for every string. The mismatch loss of string is completely depending on the type of shading pattern. The theoretical values of mismatch loss calculation based on the shading pattern and the current generation of rows for TCT, Sudoku, and the proposed array has given in Table.4.

The I-V (Current-Voltage) and P-V(Power-Voltage) characteristics of the various array configurations and the proposed method have been obtained by the MATLAB/

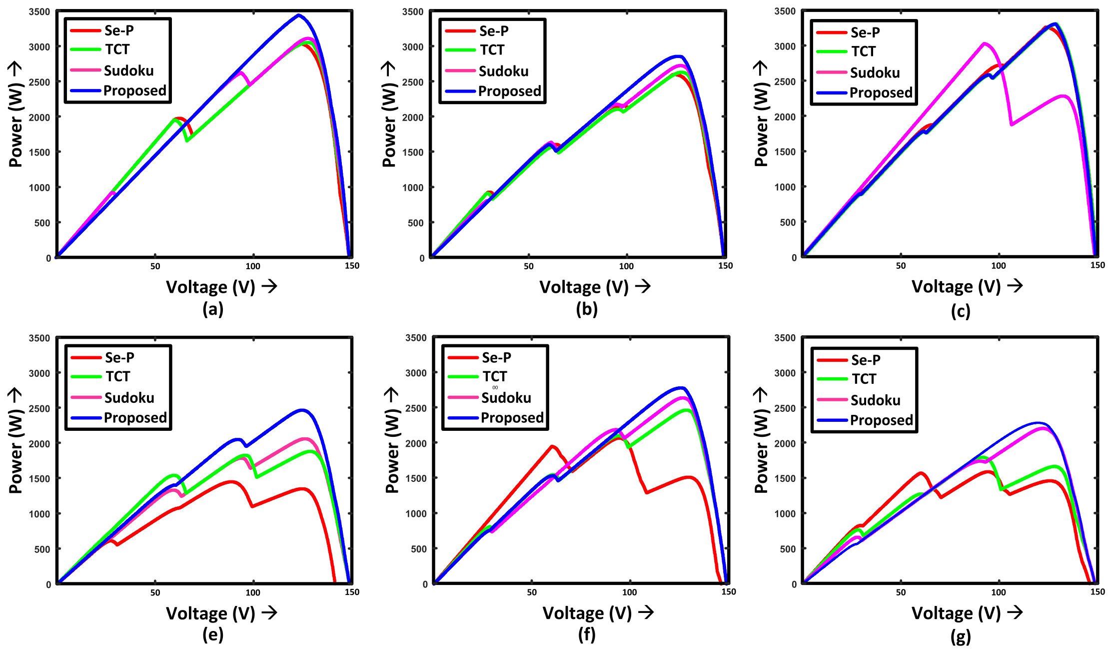

FIGURE 9. P-V Characteristics of 4 × 4 PV array under (a) Short and narrow (b) Short and wide (c) Diagonal (e) Random (f) Long and narrow (g) Long and wide.

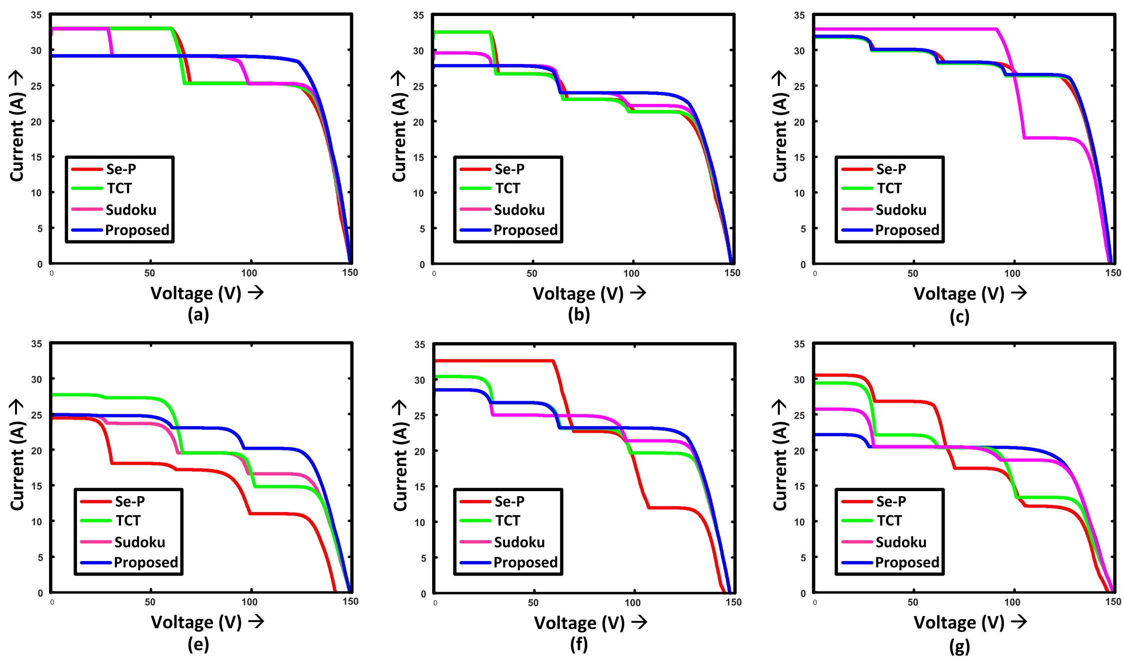

FIGURE 10. I-V Characteristics of 4 × 4 PV array under (a) Short and narrow (b) Short and wide (c) Diagonal (e) Random (f) Long and narrow (g) Long and wide.

Simulink® as shown in Fig.9 and Fig.10. Six kinds of shading patterns have been created and plotted as the P-V, I-V Characteristic curves. The smoothness of the curve shows the various LMPP present in the output which directly indicates the shading present in the PV array. Series parallel array configuration has a poor performance than the other three methods in all shading conditions. The TCT configuration scheme equally generates power and had a smooth curve near the proposed configuration scheme in short and narrow, long, and narrow and in the diagonal shading patterns. The sudoku configuration gives a better performance equal with the proposed method on short and narrow, short, and wide, long, and wide shading patterns. In all the cases, the proposed knight pattern array configuration method obtains the best performance than other configurations and, in some cases, it gives them equal performances to the TCT and

Sudoku. Also, in all cases, the proposed array configuration scheme has smooth P-V and I-V curves which shows its shade dispersing ability it. In reference [15], the author states that the sudoku puzzle pattern gives the best performance than the TCT, BL. HC, SP array configuration schemes with detailed experimental investigations. From the P-V and I-V curves under the shading conditions, it is observed that the proposed knight pattern array configuration scheme gives the best performance than the Sudoku puzzle pattern.

The output analysis has been carried out in a 4 × 4 PV array (Squared PV array) and 4 × 5 PV array (Non-Squared PV array). A solar power meter is been used for measuring irradiation in real-time. A lux meter is used with some additional circuit in this meter, that measures the solar irradiation in terms of lux and gives the value in terms of W/m2. Also, the results were carried out in not a single day. It's been taken almost 10days for us to achieve the hardware results. We have taken the results of each shading pattern on every single day. Every day we have created the shading pattern using the cardboard sheets as in Figure.6, and we have waiting for the reference value of atmosphere irradiation and atmospheric temperature. When the reference value is between ±10%, the results were been noted and they are presented in Table 5 and Table 6. The simulation and hardware output under the six kinds of shading conditions are given in Table.5. Fig.10 represents the output power comparison chart of the proposed configuration with others under six shading conditions. Among the conventional PV array configuration methods, the sudoku puzzle pattern generates more power than the TCT and SP in the long and narrow, short, and wide long and wide shading conditions. And the TCT generates more power than the Sudoku and SP array configuration schemes in the random and Diagonal shading patterns. Under the short and narrow shading conditions, all the three conventional configuration schemes give the same output power but the proposed knight pattern scheme generates more power by evenly dispersed the shading in all the PV rows. In the short and narrow and long and narrow the proposed method gives the best performance because the propagation of L always skips the column between two nodes. So, at the narrow shading patterns, it works more efficiently than the other configuration schemes. At the diagonal shading pattern, the sudoku failed in dispersing the shading, due to the row creating a pattern of it. The output power is not much affected in the TCT and SP configuration schemes, because the shading pattern itself disperse it uniformly over it. The proposed configuration scheme does not generate more power than TCT and SP in the diagonal shading pattern, also it never failed like the sudoku configuration. In all cases, the proposed method effectively disperses the shading over the PV array and generates maximum power as it can be.

The proposed knight propagation algorithm is also implemented in the 4 × 5 PV array and its output has given in Table.6. Fig.11 represents the output power comparison chart of the proposed configuration with others under six shading patterns. The Sudoku configuration scheme is not considered for this array size due to its limitation. The 4 × 5 PV array has been framed with the given mathematical formulation and it has been analyzed by creating the six shading patterns. In the diagonal shading condition, the TCT array configuration method generates more power than the proposed method because the proposed method has the repeated PV modules

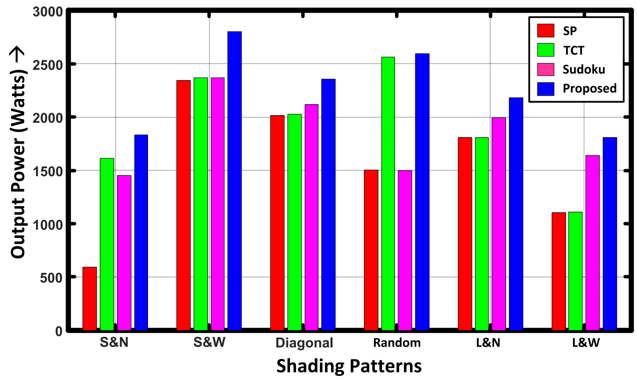

FIGURE 11. Output power of 4 × 4 PV array various shading patterns.

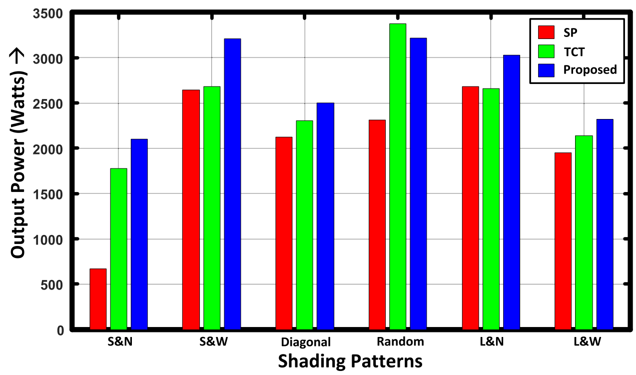

FIGURE 12. Output power of 4 × 5 PV array various shading patterns.

TABLE 6. Performance of 4 × 5 PV array in various shading conditions.

Shading Pattern	Array configuration	Simulation Result				Experimental Output		
		Im	Vm	Pm	M.L	Im	Vm	Pm
Random	Se-P	10.11	77.1	779.6	-	9.4	74.4	697.6
	TCT	20.21	98	1980.3	35.1	18.8	94.7	1775.9
	Proposed	23.16	100.6	2330.5	17.9	21.5	97.5	2100.3
S&N	Se-P	28.63	104.1	2980.8		26.4	100.0	2642.5
	TCT	28.63	104.1	2980.8	32	26.6	100.8	2678.4
	Proposed	33.69	106.3	3581.1	16.7	31.2	102.9	3208.8
S&W	Se-P	23.58	100.9	2380.5	-	21.9	96.9	2121.4
	TCT	25.27	102.1	2580.6	40	23.4	98.3	2301.5
	Proposed	26.95	103.2	2780.7	23.8	25.1	99.7	2498.1
Diagonal	Se-P	25.27	102.1	2580.6	-	23.4	98.9	2313.4
	TCT	35.37	106.9	3781.2	12.5	33.0	102.4	3377.7
	Proposed	33.69	106.3	3581.1	20	31.4	102.3	3214.3
L&N	Se-P	28.63	104.1	2980.8	-	26.8	100.0	2682.3
	TCT	28.63	104.1	2980.8	26.1	26.7	99.6	2657.1
	Proposed	32	105.6	3381	9.5	29.9	101.3	3026.4
L&W	Se-P	21.9	99.6	2180.4	-	20.4	95.7	1949.3
	TCT	23.58	100.9	2380.5	33.3	22.1	96.7	2140.7
	Proposed	25.27	102.1	2580.6	21.1	23.6	98.2	2322.4

from the same row. This could happen in the non-squared PV array, but it has an enhanced shade dispersing ability. The power conversion efficiency of the proposed method for non-squared PV array may be lesser than the effectiveness of the squared PV array, but it can generate more power than the series-parallel configuration. In some kind of shading pattern, this may occur but, in most cases, the proposed method generates more power than the SP and the TCT array configuration schemes. It is inferred that in the non-squared PV array the mathematical function of the proposed method creates a PV row with the repeated PV modules with optimized distance, which will reduce the effectiveness but not lesser than the convention array configuration schemes. In some cases, the TCT configuration scheme generates more power or nearly to the proposed configuration scheme.

VI. CONCLUSION

The knight pattern array configuration scheme has been proposed in this work for enhancing the power conversion efficiency of partial shaded photovoltaic system. The proper mathematical formulation with necessary constraints for the row and array creation has been discussed in this paper. Based on the number of columns in the PV array, two kinds of mathematical function have been defined with examples. The performance of the proposed configuration scheme has been validated for various shading patterns. For the random, diagonal, SN, SW, LN and LW shading condition the proposed method has the generated more power than the series parallel array configurations as, 1402.1W, 566.3W, 376.7W, 900.9W, 344.1W, 383.1W respectively. The percentage of power enhancement over the existing method is also greater. From the simulation and hardware validation, the power generation of the proposed scheme in all kind of shading condition is greater than the other existing array configuration schemes. Also, the mismatch power between the PV rows of knight pattern array configuration is very lesser than the mismatch losses of existing methods. The proposed scheme does not require any special arrangements like sensors, switches, controllers, or any other special devices. It is very simple and economic to install the proposed scheme with high resistivity to power distortion during the partial shading conditions.

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