Performance Enhancement of Partial Shaded Photovoltaic System With the Novel Screw Pattern Array Configuration Scheme

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ABSTRACT The performance of the solar photovoltaic system is affected by the unpredictable phenomenon of partial shading. This causes the mismatch losses that suppress the power generation of healthy PV modules in it. The objective of the proposed work in this paper is to bring out the maximum power from each PV module in the PV array by reducing the mismatch losses. A new array configuration method is proposed in this paper, which follows the screw pattern in the row formation. Each PV row is created with distinct PV modules from the rows of the conventional array configuration. This proposed work allows the PV system to operate with minimum mismatch losses by even shade dispersion over the PV array. The proper mathematical expression with all necessary constraints was derived for the array formation of the proposed work. The output analysis is been validated in the simulation of the 9 × 9 PV array in MATLAB/Simulink®. The mismatch loss generation and output power enhancement are measured and compared with the various conventional array configuration methods under six kinds of partial shading patterns. The proposed array configuration is 40% more efficient than the conventional series-parallel array configuration and also performs better than the total cross-tied and sudoku puzzle pattern methods. The shade dispersion rate of the proposed array configuration has highly reduced the mismatch losses in the PV system and hence, it improves the power output.

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 Global development introduces various technologies which reduce human effort. Worldwide these technologies raise the energy demands for accessing them. On the other hand, population growth and depletion of conventional energy sources have caused the scarcity of energy. These affairs paved a clear path for the growth of renewable energy sources. The utilization of solar photovoltaic (PV) systems is incredibly increased across the world, because of the feasibility, simple installation and, simple maintenance [1], [2], [3]. The PV systems have evolved in various stages from a single PV cell with 4% of efficiency to a PV array with 24% of efficiency. The sun emitted an enormous quantity of photons in the form of light and heat due to the nuclear fusion reaction on it. The PV system works based on the photovoltaic effect which directly converts the photons in the sunlight into the electron [4], [5]. The performance of the PV system is directly depending on the light received by the PV surface. The power output is been reduced by various factors such as partial shading,
The MPPT algorithm is been discussed. The algorithm follows reliability than the conventional methods in terms of scanning is been used for the maximum power generation. It has better and improved MPPT algorithm based on the cuckoo search performance in obtaining the MPP. So that hybrid MPPT algorithms. However, every method had some limitations in its techniques developed from the conventional MPPT algorithm (ACO) based MPPT, Genetic Algorithm (GA) based MPPT, Fuzzy Logic based MPPT are the various MPPT algorithms has been discussed. Particle Swarm Optimization (PSO) based MPPT, Neural Network (NN), Artificial Neural Network (ANN) based MPPT, Ant Colony Optimization (ACO) based MPPT, Genetic Algorithm (GA) based MPPT, Fuzzy Logic based MPPT are the various MPPT techniques developed from the conventional MPPT algorithms. However, every method had some limitations in its performance in obtaining the MPP. So that hybrid MPPT algorithms are discussed in the review article of [10], In [11], and improved MPPT algorithm based on the cuckoo search is been used for the maximum power generation. It has better reliability than the conventional methods in terms of scanning time and accuracy. In [12], the musical chair game-based MPPT algorithm is been discussed. The algorithm follows many stages before obtaining the maximum Power Point. Many factors are been used to obtain the MPPT, wherein the first step a game like a musical chair is executed as the algorithm to eliminate the unavailable factors and the factors are in rated value. In the last stage of execution, the factors highly affected due to the shading and faults are filtered and based on the variation these factors, the accurate MPP can be tracked. The performance evaluations of various MPPT algorithms of both conventional and soft computing-based are methods are carried out in [13]. Each method is having superior performance on some operating conditions and shading patterns. Based on the accuracy of MPP tracking, scanning time, duration of voltage fluctuations, and efficiency, the evaluation is performed.

The PV array configuration is also playing a vital role in shade dispersion. Earlier, the series and parallel configurations are majorly used in the PV system. Series-parallel array configuration has been used later in the PV system. The total cross-tied array configuration method is been introduced as in [14], [15], for enhancing the shade dispersion capability of the PV array. The total cross-tied configuration has the better performance, as compared with the Series, Parallel, and Series-Parallel array configurations. Because of the advantages of TCT, various researches have been carried out for improving its performance further. The row creation of the TCT configuration is been modified with many innovative ideas such as honeycomb structure, bridge linked connection, Sudoku puzzle pattern, etc., In [16], the honeycomb array configuration is discussed with the power enhancement analysis. This performance is been further enhanced by the bridge-linked array configuration as in [16]. Later the Sudoku puzzle pattern array configuration-based array configuration is proposed which has a better performance than the other array configurations. The advantage of the sudoku puzzle pattern-based array configuration is the creation of PV rows. The PV rows are created with the distinct PV modules from each row of conventional TCT configuration which allows the PV array with the maximum shade dispersion rate. This enhances the power generation of the PV system. But the sudoku puzzle pattern array configuration is only applicable for the squared array configuration.

There are some other methods such as reconfiguration schemes, current compensation methods are developed. In reconfiguration methods [17], the PV array is capable to change its PV module position concerning the level of partial shading. Switches, current measuring units, voltage measuring units, power measuring units, irradiation measuring units, temperature measuring units, and control units are used in the reconfiguration enabled PV array. The measuring units find the values of electrical parameters such as current and power and also measure the environmental factors such as temperature and irradiation. Based on these measurements control units find the level of partial shading affected on the PV system and rearrange the PV modules interconnections by operating the switches. This method highly reduces the effect of partial shading and enhances the power output. In [18], the couple matching best generation algorithm-based reconfiguration method is discussed. The PV array is been
In General, the output current at the load terminal of the modules is only interchanged in the proposed method. The electrical interconnection of the PV modules is the same as the location in the conventional TCT array configuration. The physical location of the PV modules is constructed with distinct PV modules from the PV rows. Each PV row follows a unique pattern for the row creation. Each PV row has been proposed. This proposed array configuration follows the screw pattern in the row creation of PV modules.

The rest of the paper is organized as follows. Section II presents the proposed array configuration method and its classification. Section III presents the mathematical formulation of the proposed array configuration. Section IV presents the obtaining of results with the P-V and I-V characteristic curves and section V summarizes and concludes the paper.

II. PROPOSED ARRAY CONFIGURATION

The proposed array configuration is implemented based on the screw structure. This propagation allows selecting the PV modules to be presented in the PV array with the optimized distance of each. For example, each row is been constructed with distinct PV modules from the different rows of the conventional PV array. For the 9 × 9 PV array, each row should contain nine numbers of PV modules. In the conventional method, the first row will be P11, P12, P13, P14, P15, P16, P17, P18, and P19. In the proposed array configuration, the first row will contain PV modules from each row of the conventional method.

In this paper, a new kind of static array configuration method has been proposed. This proposed array configuration method follows the screw pattern in the row creation of PV the PV array. Like the sudoku puzzle pattern, this method follows a unique pattern for the row creation. Each PV row is constructed with distinct PV modules from the PV rows of conventional TCT array configuration. The physical location of the PV modules is the same as the location in the conventional TCT, whereas, the electrical interconnection of the modules is only interchanged in the proposed method.

In General, the output current at the load terminal of the parallel configuration (with various current sources) will be the value of the minimum current source. As in the PV array, the minimum current generating row’s current will be available in the load terminal. The partial shading and any faults in the PV array tremendously reduce the row current which causes the high mismatch loss in the PV array. The mismatch loss can be defined as the percentage of the difference between the maximum and minimum power generating rows. This work operates the PV array with the minimum amount of mismatch losses, by creating the PV rows with the even current generation. This directly increases the power generation of the PV array.

The actual screw pattern and the node creation from it have shown in the figure. The screw pattern can be propagated in two kinds such as horizontal propagated screw pattern and vertical propagated screw pattern. The size of the PV array splits into two equal parts such as male and female parts, and based on the row current generation the controller executes the reconfiguration algorithm by coupling male and female parts. In [19], a similar kind of reconfiguration algorithm is developed with the high-power enhancement with the minimized number of switches and measuring units. The current compensation method is developed in [20], which injects the compensation current across each PV row. This setup requires a high number of switches and n number of dc-dc converters and other arrangements. However, this method enhances the performance of the PV system, the installation cost is quite high as compared to all other methods. In addition, the Ken-Ken puzzle [21], firefly-based [22], L-Shape propagated array [23], Spiral Pattern reconfigurations [24] for extraction of maximum power from solar PV are developed. It is also necessary to keep the PV system in safe operating mode with proper design, fault identification, and fault diagnostic system. In [25], discusses the proper design of the PV system. In this case, two equal power-generating PV system of 100MWp of each is analyzed in similar environmental conditions. Where the properties of two PV arrays are slightly different from others in terms of tilt angle, spacing between the PV rows, degradation level, negative temperature coefficient values. Various studies were carried out on this analysis, which gives the result as the PV plant with the proper design has the best performance over another one with the financial savings of 0.85 million USD per annum. In [26], the necessity of safety measurements in a PV system has been discussed. The risk mitigation solutions are discussed in two different aspects such as positioning of PV modules and fault diagenetic methods. By adjusting the space between the PV modules can slightly reduce the hotspot effect whereas the fault diagnostic system can avoid fire accidents before the faults caused the fire. A comprehensive review of widely used PV reconfiguration based on their advantages and limitations is detailed in [27]. This article helps as a perfect guide to new researchers who wish to carry out their work in the field of PV reconfiguration. A total of around 64 various reconfiguration techniques whichever implemented so far including conventional, bio-inspired, and dynamic based reconfigurations are presented in [28]. Further, the author also presented perfect suggestions, possibilities, and paths to implement future research in this field of work. Another puzzle-based technique based on the prime number for the shade dispersion is proposed by authors in [29].
is to be considered on choosing the kind of array propagation. Each kind of array configuration has two different propagations such as odd propagation and even propagation. The horizontal screw pattern array propagation and the node creation has shown in figure 2. (a) and figure 2. (b). The vertical array propagation and the node creation has shown in Figure 2. (c) and Figure 2. (d).

**III. MATHEMATICAL FORMULATION**

The mathematical formulation of the proposed array configuration is given in equation 1 to equation 4, as shown at the bottom of the next page. Different expressions are derived for the horizontal and vertical screw propagation pattern. In each kind, it has further two classifications based on the number of columns in the PV array. The PV array with the even number of columns and an odd number of columns had different derivations. Row creation for the horizontal screw propagation with an odd number of columns starts with (1)(i) and ends with (n)(i+(n+1)/2) as in the equation (1), as shown at the bottom of the next page. For the horizontal screw propagation with an even number of columns, the row creation will start from (1)(i) and end with (n)(i+(n+2)/2) as in equation (2), as shown at the bottom of the next page. As like that, row creation for the vertical screw propagation with an odd number of columns starts with (i)(1) and ends with (i+(n+1)/2)(n) as in the equation (3), as shown at the bottom of the next page. For the vertical screw propagation with an even number of columns, the row creation will start from (i)(1) and ends with (i+(n+2)/2)(n) as in equation (4), as shown at the bottom of the next page. The proposed screw pattern array configuration is applicable for any size of PV arrays such as squared and non-squared PV arrays. Each row is been created with the mathematical equations, by substituting the values of i and n. The value of i represents the number of rows, for row creation of the first row, the value of i will be 1, for the second row the value of i will be 2 and it continues till the end of PV rows. For the m × n PV array, the value of i starts from 1 to the number of rows (m). For example, in the 9 × 9 PV array, the number of row creation will be 9. For the first row, i will be 1, for the second row, i will be 2, and it continues till the ninth row. For
the ninth row, the value of \( i \) will be 9. Also in each equation, another term \( n \) has been used. The values of \( n \) vary from 1 to the number of rows. For the \( 9 \times 9 \) PV array, the number of rows is 9.

The other two variables named ‘a’ and ‘b’ are used in the mathematical equations. The values ‘ab’ denote the position of PV modules. The PV module’s position in the row is denoted by the variable ‘a’ and the position in the column is denoted by ‘b’. For example, the PV module placed in the PV array of the 4\(^{th} \) row and 5\(^{th} \) column is represented as \( P_{45} \), whereas, the value of ‘a’ is 4 and the value of ‘b’ is 5. For the PV module \( P_{73} \), the value of ‘a’ is 7, and the value of ‘b’ is 3. A constraint is also framed for the equation.

In horizontal propagation, the row creation of the first row using the equation (1) gives the result as, \( P_{11} \), \( P_{29} \), \( P_{32} \), \( P_{48} \), \( P_{53} \), \( P_{67} \), \( P_{74} \), \( P_{86} \), and \( P_{95} \). The propagation starts from the first row and ends with the 9\(^{th} \) row. But the second-row propagation starts from the 2\(^{nd} \) row and ends with the 1\(^{st} \) row and for the third-row creation, the propagation starts from the 3\(^{rd} \) row and ends with the 2\(^{nd} \) row. It continues till the 9\(^{th} \) row, where the propagation starts from the 9\(^{th} \) row and ends in the 8\(^{th} \) row. For deriving these modules position mathematically, a constraint is included in the equations as, when the derived value of ‘a’ exceeds the number of rows ‘m’ then the value of ‘a’ is been subtracted from the a and for the ‘b’, when it exceeds the number of columns then the value of ‘b’ is subtracted from the number of columns ‘n’. This constraint allows the mathematical expression to achieve the accurate screw pattern without the repeated modules from the same row.

**TABLE 1. Node creation of the first row for vertical screw propagation.**

| Actual Positions of PV modules | Mathematical Expression | Position of PV modules in proposed PV configurations |
|--------------------------------|-------------------------|----------------------------------------------------|
| \( P_{11} \)                   | \( (i)(i) \)             | \( P_{11} \)                                        |
| \( P_{12} \)                   | \( (2)(i + (n - 1)) \)  | \( P_{29} \)                                        |
| \( P_{13} \)                   | \( (3)(i + 1) \)         | \( P_{32} \)                                        |
| \( P_{14} \)                   | \( (4)(i + (n - 2)) \)  | \( P_{48} \)                                        |
| \( P_{15} \)                   | \( (5)(i + 2) \)         | \( P_{53} \)                                        |
| \( P_{16} \)                   | \( (6)(i + (n - 3)) \)  | \( P_{67} \)                                        |
| \( P_{17} \)                   | \( (7)(i + 3) \)         | \( P_{74} \)                                        |
| \( P_{18} \)                   | \( (8)(i + (n - 4)) \)  | \( P_{86} \)                                        |
| \( P_{19} \)                   | \( (9)(i + 4) \)         | \( P_{95} \)                                        |

For the row creation of first row \( i=1 \) and \( n=9 \)

Both horizontal and vertical screw propagated array configurations is been applied in the \( 9 \times 9 \) PV array. The row creation for each configuration is derived using the mathematical
expression. The first-row creation of the horizontal screw propagation is given in Table 1. The mathematical expression derives the following modules \( P_{11}, P_{29}, P_{32}, P_{48}, P_{53}, P_{67}, P_{74}, P_{86}, \) and \( P_{95} \) for the first row. The pictorial representation of the row creation for the horizontal screw propagation is shown in Figure 2. Each row creation for the \( 9 \times 9 \) PV array has pictorially represented in Figure 2. Screw pattern array configuration of horizontal propagation for the \( 9 \times 9 \) PV array is given in Table 2.

The vertical propagated screw pattern for the \( 9 \times 9 \) PV array is derived by the equation (3). The node creation for the first row is given in Table 3. The mathematical expression derives the following modules \( P_{11}, P_{92}, P_{23}, P_{84}, P_{35}, P_{76}, P_{47}, P_{68}, \) and \( P_{59} \) for the first row of vertical propagated screw pattern array configuration. The pictorial representation of the row creation for the vertical screw propagation is shown in Figure 3(a). The final structure of the vertical propagated screw pattern configuration of the \( 9 \times 9 \) PV array has pictorially represented in Figure 3(b). Screw pattern array configuration of vertical propagation for the \( 9 \times 9 \) PV array is given in Table 2.

The proposed array configuration can be explained with the simple steps as follows

Step - 1: Obtain the actual structure of the PV array.

Step - 2: Consider no of rows as ‘m’ and the number of rows as ‘n’.

Step - 3: Consider the temporary variables ‘a’ and ‘b’ for representing the panel position.

Step - 4: Obtain the PV modules in each row by using the mathematical function

Step - 5: If the values of ‘a’ and ‘b’ are greater than ‘m’ and ‘n’, then

\[
a = a - m \\
b = b - n
\]

Step - 5: In \( 9 \times 9 \) PV array, each corresponding row, the function \( P_{ab} \) has nine PV modules. For example, the first row has the following modules, \( P_{11}, P_{29}, P_{32}, P_{48}, P_{53}, P_{67}, P_{74}, P_{86}, P_{95} \).

Step - 6: Obtain each row using the mathematical function

Step - 7: Check once for the non-repeated PV modules from the same row of conventional configuration

Step - 8: Connect the PV modules in the real-time PV array according to the mathematically obtained results.

### Table 2. Vertical screw propagated configuration pattern for \( 9 \times 9 \) PV array.

| i varies from 1 to 9 & n=9 | \( P_{11} \) | \( P_{29} \) | \( P_{32} \) | \( P_{48} \) | \( P_{53} \) | \( P_{67} \) | \( P_{74} \) | \( P_{86} \) | \( P_{95} \) |
|--------------------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|
| \( P_{11} \) i=1         | \( P_{11} \) | \( P_{29} \) | \( P_{32} \) | \( P_{48} \) | \( P_{53} \) | \( P_{67} \) | \( P_{74} \) | \( P_{86} \) | \( P_{95} \) |
| \( P_{12} \) i=2         | \( P_{11} \) | \( P_{29} \) | \( P_{32} \) | \( P_{48} \) | \( P_{53} \) | \( P_{67} \) | \( P_{74} \) | \( P_{86} \) | \( P_{95} \) |
| \( P_{13} \) i=3         | \( P_{11} \) | \( P_{29} \) | \( P_{32} \) | \( P_{48} \) | \( P_{53} \) | \( P_{67} \) | \( P_{74} \) | \( P_{86} \) | \( P_{95} \) |
| \( P_{14} \) i=4         | \( P_{11} \) | \( P_{29} \) | \( P_{32} \) | \( P_{48} \) | \( P_{53} \) | \( P_{67} \) | \( P_{74} \) | \( P_{86} \) | \( P_{95} \) |
| \( P_{15} \) i=5         | \( P_{11} \) | \( P_{29} \) | \( P_{32} \) | \( P_{48} \) | \( P_{53} \) | \( P_{67} \) | \( P_{74} \) | \( P_{86} \) | \( P_{95} \) |
| \( P_{16} \) i=6         | \( P_{11} \) | \( P_{29} \) | \( P_{32} \) | \( P_{48} \) | \( P_{53} \) | \( P_{67} \) | \( P_{74} \) | \( P_{86} \) | \( P_{95} \) |
| \( P_{17} \) i=7         | \( P_{11} \) | \( P_{29} \) | \( P_{32} \) | \( P_{48} \) | \( P_{53} \) | \( P_{67} \) | \( P_{74} \) | \( P_{86} \) | \( P_{95} \) |
| \( P_{18} \) i=8         | \( P_{11} \) | \( P_{29} \) | \( P_{32} \) | \( P_{48} \) | \( P_{53} \) | \( P_{67} \) | \( P_{74} \) | \( P_{86} \) | \( P_{95} \) |
| \( P_{19} \) i=9         | \( P_{11} \) | \( P_{29} \) | \( P_{32} \) | \( P_{48} \) | \( P_{53} \) | \( P_{67} \) | \( P_{74} \) | \( P_{86} \) | \( P_{95} \) |

### Table 3. Node creation of the first row for horizontal screw propagation.

| Actual Positions of PV modules | Mathematical Expression | Position of PV modules in proposed PV configurations |
|-------------------------------|-------------------------|-------------------------------------------------|
| \( P_{11} \)                   | \((0)\)                 | \( P_{11} \)                                    |
| \( P_{12} \)                   | \((i+(n-1))\)           | \( P_{12} \)                                    |
| \( P_{13} \)                   | \((i+1)\)               | \( P_{13} \)                                    |
| \( P_{14} \)                   | \((i+(n-2))\)           | \( P_{14} \)                                    |
| \( P_{15} \)                   | \((i+2)\)               | \( P_{15} \)                                    |
| \( P_{16} \)                   | \((i+(n-3))\)           | \( P_{16} \)                                    |
| \( P_{17} \)                   | \((i+3)\)               | \( P_{17} \)                                    |
| \( P_{18} \)                   | \((i+(n-4))\)           | \( P_{18} \)                                    |
| \( P_{19} \)                   | \((i+4)\)               | \( P_{19} \)                                    |

### Figure 3. (a) Row creation of vertical propagated screw pattern (b) 9 \times 9 PV array with vertical propagated screw pattern.

### IV. RESULT AND DISCUSSIONS

The simulation of a PV cell is constructed from the single diode model. The single diode model of the PV cell is constructed by a current source with shunt-connected resistance. The circuit diagram, of the single diode model, is shown in figure 4. An equivalent circuit of the PV cell has a current source \( I_{ph} \) and a shunt resistance \( R_{shunt} \). This structure represents the equivalent circuit of a single PV cell. For the PV module and PV array creation ‘n’ a number of PV cells are connected in series. \( I_{max} \) is the maximum current generation from the PV cell model.
The equation for the maximum output current from the Figure.4 can be derived as,

\[
I_{\text{max}} = I_{\text{ph}} - I_{\text{sat}} \left[ \exp \left( \frac{V_{\text{pv}} + I_{\text{max}} R_s}{(nKTA/q)} \right) - 1 \right] - \frac{V_{\text{pv}} + I_{\text{max}} R_s}{R_{\text{shunt}}} \tag{5}
\]

where, 
- \(I_{\text{max}}\) = Maximum output current of PV cell
- \(V_{\text{pv}}\) = Maximum voltage at the load terminal
- \(I_{\text{ph}}\) = Photovoltaic Current
- \(I_{\text{sat}}\) = Saturation Current
- \(K\) = Boltzmann’s constant
- \(R_s\) = Series Resistance
- \(R_{\text{sh}}\) = Shunt Resistance
- \(T_a\) = Ambient Temperature.

For validating the proposed horizontal and vertical screw propagated array configuration, a 9 × 9 PV array is been modeled in the MATLAB/Simulink® as shown in figure.5. Based on the mathematical equation the PV cell is designed and integrated as a 9 × 9 PV array. The specification of PV modules is given in Table 5.

The convention array configurations such as Series parallel, Total Cross Tied, and Sudoku array configurations are
TABLE 4. Horizontal screw propagated configuration pattern for 9 × 9 PV array.

| i varies from 1 to 9 & n=9 | P_{C1} | P_{C2} | P_{C3} | P_{C4} | P_{C5} | P_{C6} | P_{C7} | P_{C8} | P_{C9} |
|---------------------------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| Rows                      |        |        |        |        |        |        |        |        |        |
| P_{H1}                    | i=1    | P_{I1} | P_{I2} | P_{I3} | P_{I4} | P_{I5} | P_{I6} | P_{I7} | P_{I8} | P_{I9} |
| P_{H2}                    | i=2    | P_{I1} | P_{I2} | P_{I3} | P_{I4} | P_{I5} | P_{I6} | P_{I7} | P_{I8} | P_{I9} |
| P_{H3}                    | i=3    | P_{I1} | P_{I2} | P_{I3} | P_{I4} | P_{I5} | P_{I6} | P_{I7} | P_{I8} | P_{I9} |
| P_{H4}                    | i=4    | P_{I1} | P_{I2} | P_{I3} | P_{I4} | P_{I5} | P_{I6} | P_{I7} | P_{I8} | P_{I9} |
| P_{H5}                    | i=5    | P_{I1} | P_{I2} | P_{I3} | P_{I4} | P_{I5} | P_{I6} | P_{I7} | P_{I8} | P_{I9} |
| P_{H6}                    | i=6    | P_{I1} | P_{I2} | P_{I3} | P_{I4} | P_{I5} | P_{I6} | P_{I7} | P_{I8} | P_{I9} |
| P_{H7}                    | i=7    | P_{I1} | P_{I2} | P_{I3} | P_{I4} | P_{I5} | P_{I6} | P_{I7} | P_{I8} | P_{I9} |
| P_{H8}                    | i=8    | P_{I1} | P_{I2} | P_{I3} | P_{I4} | P_{I5} | P_{I6} | P_{I7} | P_{I8} | P_{I9} |
| P_{H9}                    | i=9    | P_{I1} | P_{I2} | P_{I3} | P_{I4} | P_{I5} | P_{I6} | P_{I7} | P_{I8} | P_{I9} |

TABLE 5. PV module specifications.

| S.NO | PARAMETERS          | RATINGS |
|------|---------------------|---------|
| 1    | Short Circuit Current (Isc) | 1.25A   |
| 2    | Open Circuit Voltage (Voc)  | 11.5V   |
| 3    | Maximum Current (Im)      | 1.10A   |
| 4    | Maximum Voltage (Vm)      | 9.09V   |
| 5    | Maximum Power (Pm)        | 10W     |

The power output of the healthier modules is limited by the faulted and partially shaded modules. This phenomenon is known as mismatch loss. Based on the shading level that occurred in the PV array, it can be contained into eight kinds of shading patterns. All kinds of shading levels (minimum to maximum) are coming under these eight kinds of shading patterns. The eight kinds of shading patterns are uneven row shading, uneven column shading, diagonal shading, random shading, short and narrow (SN) shading, short and wide (SW) shading, Long and narrow (LW) shading, and long and wide (WL) shading. Under these eight kinds of classifications. Six shading patterns except for uneven row and uneven column were applied on the proposed horizontal and vertical screw propagated array configuration. Also, the same shading patterns are applied on the conventional array configurations of series-parallel, TCT, and Sudoku array configurations.

The equation for the maximum output current from the figure 4 can be derived as,

\[ \%_{-}\text{of\_mismatch\_Loss} = \frac{P_{R_{\text{max}}} - P_{R_{\text{min}}}}{P_{R_{\text{max}}}} \times 100\% \quad (6) \]

where, \( P_{R_{\text{max}}} \) is the power generation of the maximum power generating row, and \( P_{R_{\text{min}}} \) is the power generation of the minimum power generating row.

The efficiency of the PV system under any circumstances can be measured by the following expression,

\[ \text{Efficiency, } \eta = \frac{P_{\text{ACTUAL}}}{P_{\text{RATED}}} \times 100\% \quad (7) \]

where, \( P_{\text{ACTUAL}} \) is the actual power generation of the PV array, and \( P_{\text{RATED}} \) is the rated power generation of the PV array.

The results of proposed and conventional array configurations are compared and discussed. The six shading patterns are shown in figure 6. The shading level is shown in figure 6(g) on which each color pattern represents the amount of irradiation received by the PV modules. A random shading pattern is created in the 9 × 9 PV array as in figure 6(a). The main causes of random shading are due to internal faults, isolated PV modules, and the shadow of clouds. Figure 6(b) shows the diagonal shading pattern where the PV module position of P11 receives 300W/m², P22 receives 500W/m², P33 receives 600W/m², P44 receives 700 W/m², P55 receives 800 W/m², P66 receives 900 W/m², P77 receives 100 W/m², P88 receives 800 W/m², and P99 receives 900 W/m² as shown in figure 6(b). Diagonal shading pattern is caused by the nearby taller objects such as transmission posts, mobile towers and etc., A short and Narrow (SN) shading pattern is created in the PV array as shown in figure 6(c). In the 9 × 9 PV array, four columns of the first five rows are covered by the shadings for creating the SN shading pattern. For the Short and Wide shading pattern, all columns of the first five rows are shaded as shown in figure 6(d). Generally, short and narrow and short and wide shading patterns are occurred in the PV array due to the clouds, new building constructions nearby the PV plants. A long and Narrow (LN) shading pattern is applied on the
The power output of the conventional and proposed array configuration is given in Table 6 to Table 11. The short circuit current (I_{sc}), power output (P_m) and efficiency under the partial shading conditions of series-parallel (Se-P) configuration, TCT configuration, Sudoku pattern-based configuration, horizontal propagated screw pattern array configuration (Scr_H), and vertical propagated screw pattern array configuration (Scr_V) were presented in the output results. In a
TABLE 9. Performance comparison of under S&W shading.

| S.NO | TOPOLOGY | CURRENT | POWER | EFFICIENCY |
|------|----------|---------|-------|------------|
| 1    | Se-P     | 3.75    | 270   | 33.3%      |
| 2    | TCT      | 6.1     | 432   | 53.3%      |
| 3    | Sudoku   | 7.18    | 504   | 62.2%      |
| 4    | Screw    | 8.13    | 585   | 72.2%      |
| 5    | Screw Vertical | 7.8     | 558   | 68.9%      |

TABLE 10. Performance comparison of under L&N shading.

| S.NO | TOPOLOGY | CURRENT | POWER | EFFICIENCY |
|------|----------|---------|-------|------------|
| 1    | Se-P     | 8.38    | 603   | 74.4%      |
| 2    | TCT      | 8.38    | 603   | 74.4%      |
| 3    | Sudoku   | 8.52    | 612   | 75.5%      |
| 4    | Screw    | 9.13    | 657   | 81.1%      |
| 5    | Screw Vertical | 9.08    | 648   | 80.2%      |

TABLE 11. Performance comparison of under L&W shading.

| S.NO | TOPOLOGY | CURRENT | POWER | EFFICIENCY |
|------|----------|---------|-------|------------|
| 1    | Se-P     | 2.88    | 207   | 25.6%      |
| 2    | TCT      | 6.12    | 432   | 53.3%      |
| 3    | Sudoku   | 6.88    | 495   | 61.1%      |
| 4    | Screw    | 7.54    | 540   | 66.7%      |
| 5    | Screw Vertical | 7.63    | 549   | 67.8%      |

random shading pattern, the Scr_H method generates 6.69A of short circuit current and 481W of power output. Scr_V method generates 6.56A of short circuit current and 472W of power output. The proposed horizontal and vertical methods are superior to the conventional methods of Se-P, TCT, and Sudoku configurations. under this shading condition, the power generations by the conventional method are 243W, 342W, 386W respectively by the Se-P, TCT, and Sudoku configurations. Se-P configuration generates the least output power among others. The power generating capability under the shading conditions shows the ability to create even current generating rows. Almost 35% of shading is created on the PV array in the random shading pattern. The proposed Scr_H configuration generates power with the efficiency of 59.4% with the 65% of available irradiation. On other hand, the proposed Scr_V configuration generates power with the...
efficiency of 58.3% with the 65% of available irradiation. Other configurations of Se-P, TCT, and Sudoku had the efficiency of 40.3%, 42.2%, and 59.4% respectively. The P-V and I-V characteristic curves of all configuration methods under the random shading pattern are shown in figure 7. The proposed Scr_H and Scr_V have smoother P-V and I-V characteristic curves as compared to the conventional configuration.

In the diagonal shading pattern, the performance of the sudoku puzzle pattern is poor than the TCT configuration. The proposed configuration and the TCT generate the equal power output in the diagonal shading pattern as given in Table 5. The P-V and I-V characteristic curves under the diagonal shading pattern are shown in figure 8. In a short and narrow shading pattern, the Scr_V configuration has the maximum power generation of 684W output power, whereas the Scr_H configuration generates 666W of output power. The proposed configurations are generating power nearly equal to each other. The conventional configurations are generating power nearly to others. The proposed Scr_H and Scr_V are better than the conventional configurations. Under the long and wide shading pattern, Scr_H generates 540W power output with the 66.7% of efficiency, and the Scr_V pattern generates 549W of power output. The proposed patterns generate maximum power than the conventional methods also the proposed system had smoother P-V and I-V characteristic curves than others.

The performance of the proposed system has been compared with the L-shape propagated array configuration [23] and spiral pattern array configuration scheme [24]. These two

![Figure 13. Power output comparison chart.](image)
references are discussed about the array configurations for minimizing the mismatch losses as like this proposed method. The performance of these two methods was analyzed and compared with the Series parallel, TCT, and Sudoku array configurations with the eight shading patterns. L-shape propagated array configuration and spiral pattern array configuration method have better performance over the conventional methods. By comparing the percentage of efficiency in power enhancement, these methods are superior to the conventional array configurations. However, the percentage of efficiency of the proposed screw pattern vertical and horizontal propagation method is a little more superior to all other array configuration methods. The comparison result is given in Table 12.

| S.NO | TOPOLOGY         | EFFICIENCY (%) |
|------|------------------|----------------|
| 1.   | Scr-P            | 25.6%          |
| 2.   | TCT             | 53.3%          |
| 3.   | Sudoku          | 61.1%          |
| 4.   | L-Shape [23]    | 61.6%          |
| 5.   | Spiral Pattern [24] | 62.5%     |
| 6.   | Scr_H           | 66.7%          |
| 7.   | Scr_V           | 67.8%          |

V. CONCLUSION

In this paper, a new array configuration for the solar PV system is proposed based on the pattern that follows the screw structure. Screw propagated array configuration is further classified into two classifications based on the direction of propagation as horizontal propagated screw pattern and vertical propagated array configuration. The steps in creating nodes in a screw pattern for any sized PV array is defined with the proper mathematical formulation. The mathematical expressions with the necessary constraints for creating PV rows are defined with the examples in this paper. The proposed Scr_H and Scr_V are designed in the MATLAB/Simulink® software. These Scr_H and Scr_V configurations are tested with the six types of possible shading patterns. The performance of the proposed method is been compared and discussed with the conventional array configurations. For the high long and narrow shading pattern, the conventional methods are generating 207W, 432W, 495W power, whereas the proposed Scr_H and Scr_V methods generate 540W and 549W power. The proposed two methods have almost equal power generation and compared to the conventional methods, the proposed method has superior performance. For observing the performance of each array configuration, P-V and I-V characteristic curves were plotted. The curves of the proposed array configurations are smoother than the conventional methods. The conventional methods are performing well in some shading patterns and performing poorly in others. whereas the proposed array configuration is performing consistently well in all shading patterns. The power output given in the results section shows the consistent performance of the proposed configurations. Also, the shade dispersion rate and ability to adapt over the environment and partial shading condition are better for the proposed array configuration. This array configuration is easy to implement in the PV array with the addition of wires to the conventional methods. The performance of the partial shaded photovoltaic system can be sufficiently enhanced by the proposed Scr_H and Scr_V array configurations.

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