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Research article

Power enhanced solar PV array configuration based on calcudoku puzzle pattern for partial shaded PV system

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ABSTRACT

The power output of solar photovoltaic systems can be affected by environmental factors, such as partial shading. This can lead to a decrease in the power conversion rate of the system. Although existing solutions for this issue are cost-effective and efficient, new solutions could further improve the system's performance by increasing consistency, power generation, and reducing mismatch loss and costs. To address this, a new method for configuring PV arrays was proposed using the calcudoku puzzle pattern. The performance of this new array configuration was evaluated in MATLAB/Simulink® for a 9 × 9 PV array and compared to conventional methods like Series-parallel, Total Cross Tied (TCT), and Sudoku array configurations. The performance was evaluated under eight different shading patterns based on power conversion rate and mismatch losses between the PV rows. The proposed array configuration resulted in 3.9%–13.3% of mismatch losses across the different shading patterns, while other configurations had a minimum of 13.8% to a maximum of 51.9% of mismatch losses. This reduction in mismatch losses directly improved the power conversion rate of the PV array.

1. Introduction

The exhaustion of non-renewable energy sources and the release of carbon emissions can be addressed through the progress made in producing renewable forms of energy [1]. Renewable energy sources with simple harvesting techniques and low costs are favored for further developments. Compared to other sources of renewable energy, solar energy (SEC) and wind energy (WEC) have relatively fewer limitations [2]. While both have their advantages, SEC has simpler implementation and is more suitable for rural electrification. SEC can be categorized into two types: solar thermal conversion and solar photovoltaic (PV) system. For go-green technologies and rural electrification, the solar PV system is a great solution since it converts sunlight into electricity directly [3]. The efficiency of PV cells has improved with the advancements in semiconductor technologies, and they can now be categorized as polycrystalline and mono-crystalline PV cells based on the type of semiconducting material [4]. Over time, newer types of PV cells, including thin-layer PV cells, bifacial PV modules, and PV buildings, have been developed.

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PV array topologies have been developed to group PV cells into PV modules and PV modules into PV arrays for better energy supply management [5]. The power generation of PV cells is largely influenced by environmental factors, particularly irradiation and temperature. The amount of irradiation directly affects the current generation, while the voltage developed in the PV cell is proportional to temperature. The performance of photovoltaic (PV) systems can be influenced by various factors, and among them, mismatch loss stands out as the most significant challenge for solar PV generation [5]. Mismatch loss occurs due to factors such as hotspots, partial shading, degradation, delamination, diode failure, etc., which cause power reduction and mismatch between the rows of the PV array [6,7]. Healthy PV rows in a PV array can operate normally, whereas rows with any of the faults will produce the reduced power output. As a result, some rows generate the rated power, while others produce less, causing a power mismatch between the healthy and faulted rows, leading to mismatch loss. The power output of a PV array depends on the power generation of each individual PV module and PV row, but these factors can cause reduced power output in some rows.

To minimize mismatch losses, several research methods have been proposed like reconfiguration, Maximum Power Point Tracking (MPPT), current compensation and etc., The conventional MPPT methods are Perturb and Observe algorithm-based MPPT and Incremental conductance-based MPPT [8]. PV systems may operate on unsmooth Power (P) – Voltage (V) and Current (I)-Voltage (V) curves under partial shading conditions [9]. These curves contain numerous peaks, which are referred to as local maximum power points (LMPP), and identifying the actual maximum power point, the Global Maximum Power Point (GMPP), can prove to be a challenging task. Conventional MPPT algorithms may not always be efficient in locating the GMPP, hence soft computing methods and

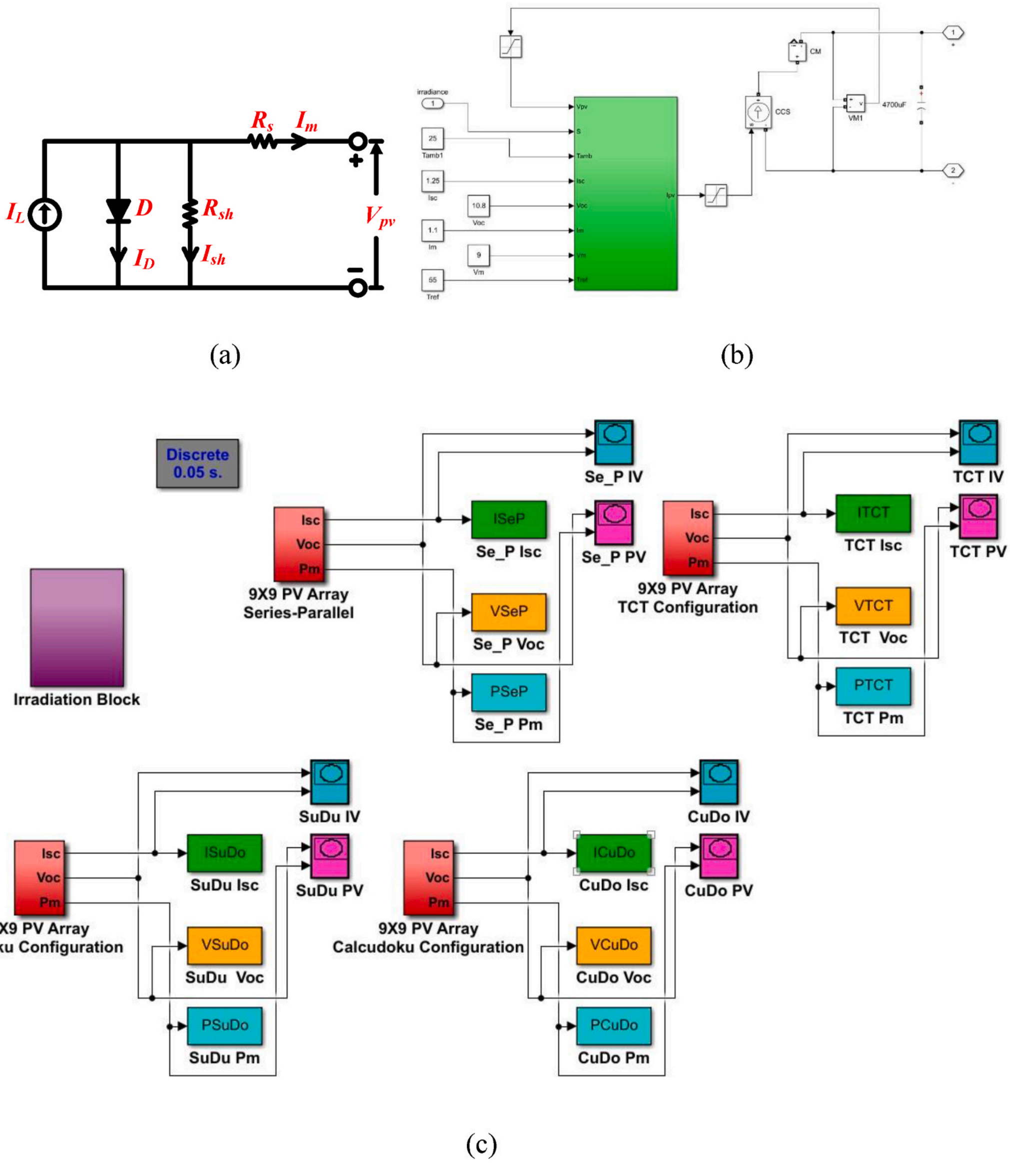

Fig. 1. (a) An equivalent circuit model of PV cell(b) Simulation model of PV cell (c) Various array configurations.

optimization techniques have been incorporated into MPPT techniques to improve their effectiveness [10,11]. Nevertheless, in complex situations, these methods may fail to track the GMPP, and shading that is not uniformly distributed over the PV array is another limitation of MPPT [12].

The bulk power generation technique commonly used is the array configuration technique. Although it is well-known for its power generation abilities, it can also reduce the partial shading effect. Traditional array configuration methods like series parallel are having poor shade dispersion rates. The interconnections between the PV cells/modules can be changed for improving the power output. The total cross-tied (TCT) configuration was initially developed, which connects all panels in series and parallel with neighboring PV modules. This method minimizes the impact of shaded panels in the series connections. When shading accumulates on a single row of array causes more mismatch losses [13,14].

Based on the structure of natural thing such as bridge, honey comb and based on the logics like sudoku, magic square, competence square, futoshiki puzzle and so on, new kind of array configurations were evolved. These configurations are effectively reduces the mismatch losses and improves the power generating ability of PV [15–24]. All of these configurations are using different logics for attaining the new configuration.

Each array configuration has a unique logic for creating the PV array. In the honeycomb array configuration, the interconnection between PV strings resembles a honeycomb. The bridge-linked array configuration uses a unique interconnect, such as a bridge converter, between PV strings. The Futoshiki and Sudoku puzzle pattern configurations follow a number-based puzzle logic system for constructing the PV array. In magic square, the sum of numbers in rows, columns, and diagonals are equal. This logic has been used for building PV array. The dominant square and competence square configurations follow a similar concept with slight modifications. The L-shape propagated array configuration creates rows by the movement of a knight coin of the chess game. In the spiral pattern array configuration, nodes are created to form a spiral shape. These are some of the most commonly used and recently developed array configuration methods. The performance can be furtherly enhanced by introducing new logics or combining two or more for building a new kind of array configuration. A detailed review of the overall outline of PV array configurations developed from earlier days has been provided [25].

In addition to array configuration, the reconfiguration method is another familiar concept for enhancing power generation in partial shading photovoltaic systems. Initially, the physical position of panels are reorganized as per the occurrence of shading. Electrical reconfiguration was developed after the development of semiconducting devices and controllers. The usage of power electronic devices allows to incorporate electrical array reconfiguration methods. A switching circuit is built with switches and sensors and it connected between the PV panels. Based on the values measured by the sensors, the switches rearrange the interconnection of PV panels. This method is more efficient method on the reduction of mismatch loss [26]. The measurements by using sensors are replaced by the image processing [27], that uses image analysis to determine partial shading. The current compensation method was developed later to reduce the presence of partial shading. An external current source compensates for unbalanced current generation caused by partial shade, allowing all PV rows to generate an identical amount of current, thus eliminating the possibility of mismatch losses among PV rows [28,29].

The organization of this article is, Section 2 describes, the mathematical modeling of PV array, section 3 discusses the proposed methodology, section 4 discusses the results and discussion of the proposed methodology and section 5 concludes the proposed work with advantages and disadvantages.

2. Mathematical model of PV cell in MATLAB

The maximum current, I_m, generated by the PV cell's single diode model in relation to diode current (I_D), light current (I_L), and shunt current (I_{sh}) can be written as (1), [30–32]. The equivalent circuit of the PV cell is shown in Fig. 1(a). The MATLAB/Simulink model of the PV cell is developed using equation (1) and it constructed as a PV array configuration as shown in Fig. 1(b) and Fig. (c)

$$I_m = I_L - I_D - I_{sh} \tag{1}$$

Equation (1) can be rewrittenas equation (2) with respect to voltage, number of cells in series, and resistance,

$$I_m = I_L - I_{sat}\left[exp\left(\frac{V + IR_s}{nN_sV_{th}}\right) - 1\right] - \frac{V + IR_s}{R_{sh}} \tag{2}$$

The short circuit current with respect to the irradiation and temperature can be written as equation (3). The equation for calculating the output current of a photovoltaic (PV) cell takes into account various factors, including the rated short circuit current (I_{SC}), actual available solar irradiation (S_a), rated solar irradiance (S_{STC}), actual available temperature (T_a), rated temperature (T_{STC}), and the temperature coefficient of current (μ_{Isc}). The output current can be determined by plugging these values into the equation.

$$I_{SC}(S,T) = (S_a / S_{STC})\left[I_{SC(STC)} + \mu_{ISC}(T_a - T_{STC})\right] \tag{3}$$

The open circuit voltage of the PV cell with respect to the temperature can be derived as equation (4),

$$V_{OC} = V_{OC(STC)} + \mu_{(V_{OC}}\left(T_a - T_{(STC)}\right) \tag{4}$$

where $\mu_{Voc}$is the positive temperature coefficient of voltage. The maximum voltage produced across the PV cell can be derived as equation (5),

$$V_m = \frac{AkT_a}{e}\left(\frac{I_{ph}+I_D+I_m}{I_D}\right) - R_s I_m \tag{5}$$

where $V_m$is the maximum output voltage of the PV cell, I_D is the current flow through the diode, $I_m$is the maximum output current generated by the solar cell, R_s is the series resistance, $R_{sh}$is the shunt resistance.

The maximum power output of the PV cell can be expressed as equation (6),

$$P_m = I_m \times V_m \tag{6}$$

The relation between the maximum voltage, the maximum current and open-circuit voltage, short circuit current can derive as the fill factor as expressed in equation (8) as,

$$FillFactor, (FF) = \frac{Vm \times I_m}{V_{OC} \times I_{SC}} \tag{7}$$

Equation (7) can be modified by equation (6) as,

$$P_m = (V_{OC} \times I_{SC}) \times FillFactor \tag{8}$$

3. Proposed methodology

This work proposes a new type of array arrangement based on the calcudoku puzzle pattern. The concept of the calcudoku puzzle pattern is like the sudoku array configuration, where this array pattern is created by the number logic. In sudoku, there is no conditions except non-repeated numbers for creating the array pattern. But in the calcudoku array configuration, a mathematical relation is there for every location of the PV array as shown in Fig. 2. In Fig. 2, for the position of 55, and 56, there is a mathematical relation as 40×, which means the multiplication of the number in 55 and 56 should be equal to 40. Along with this mathematical relation, it is ruled to maintain the non-repeated numbers in both rows, and columns. The mathematical relations are selected to define the optimal distance of each number from one another. This leads to the solution for the shade dispersion among the PV array.

The calcudoku puzzle pattern for the 9 × 9 PV array is generated as shown in Fig. 2. The selection of the mathematical relations is to select the different numbers from each row and each column. These mathematical solutions are cross-checkedin order to avoid repeated numbers from the same row or the same column. After selecting the numbers based on the calcudoku puzzle pattern, the row creation is processed for converting numbers into PV module positions in PV array. The numbers placed in the first column of the calcudoku puzzle pattern is considered as the first module position for each row as shown in Fig. 3. This process is been continued up to the last panel in the PV row is placed. This PV array configuration has the more resistivity against the shading pattern, because of the usage of mathematical relations. As compared with the sudoku and Sudoku puzzle patterns, this calcukodu puzzle pattern uses puzzle logics and the mathematical relations. This adds the additional advantage over the other puzzle patterns-based array configurations. The present research work conducts a thorough analysis to verify the effectiveness of the proposed array configurations by comparing them with the existing methods of array configurations.

This proposed calcudoku puzzle pattern-based array configuration has certain advantages over other puzzled pattern

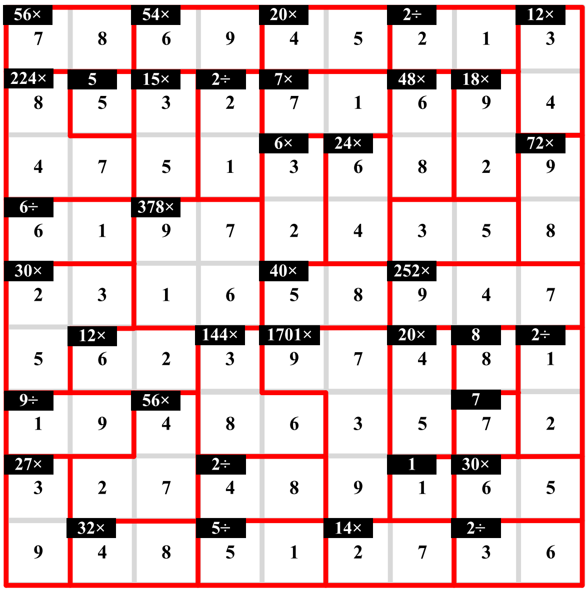

Fig. 2. 9 × 9 Calcudoku puzzle pattern.

71	82	63	94	45	56	27	18	39
81	52	33	24	75	16	67	98	49
41	72	53	14	35	66	87	28	99
61	12	93	74	25	46	37	58	89
21	32	13	64	55	86	97	48	79
51	62	23	34	95	76	47	88	19
11	92	43	84	65	36	57	78	29
31	22	73	44	85	96	17	68	59
91	42	83	54	15	26	77	38	69

Fig. 3. Matrix diagram of 9 × 9 calcudoku puzzle pattern based PV array configuration.

configurations like Sudoku, magic Square, Competence square, and so on. In this array configuration, it can be suitable for both square and non-squared array sizes. Also, the calcudoku puzzle pattern can be attained for a large number of array sizes whereas, the complexity of creation and solvation of puzzles have increased an increase in array size. This array configuration method will be one of the methods for reducing the consequences of mismatch losses.

4. Results and discussions

The proposed array configuration was simulated for the 9 × 9 PV array in the MATLAB/Simulink®. Also, the conventional array configuration are simulated to compare with the performance of proposed method. The efficiency of each array configurations were measured. The efficiency can be state as the ability of PV to convert available solar irradiation into power output. It can be calculated using equation (9)

$$\%\ of\ \eta = \frac{P_{Actual}}{P_{Rated}} \times 100 \tag{9}$$

Equation (10) provides the expression to calculate the percentage of mismatch losses in the PV array based on the power generation difference between rows. This is determined by calculating the ratio between the row which generating minimum power and maximum power. The resulting value represents the percentage of mismatch losses in the PV array.

$$\%\ of\ ML = \frac{P_{Row_{MAX}} - P_{Row_{MIN}}}{P_{Row_{MAX}}} \times 100 \tag{10}$$

The evaluation of PV array configurations can be performed using equations (9) and (10). While partial shading cannot be entirely prevented, its effects can be reduced by evenly distributing shading across the PV array. This results in minimum mismatch losses and increased power conversion rate. To assess the proposed calcudoku puzzle pattern-based array configuration, its performance has been compared to three conventional configurations: Series Parallel, TCT, and Sudoku. The comparison is carried out by power generation, percentage of mismatch losses, and percentage of power conversion efficiency.

The proposed array configuration is been analyzed with the other conventional configurations under the following shading patterns: i). random shading patterns (Fig. 4(a)), ii). Diagonal shading pattern (Fig. 4(b)), iii). Frame shading pattern (Fig. 4(c)), iv). L-Shape shading pattern (Fig. 4(d)), v). short and narrow (SN) shading pattern (Fig. 4(e)), vi). short and wide (SW) shading pattern (Fig. 4(f)), vii). long and narrow (LN) shading pattern (Fig. 4(g)) and viii). Long and wide (LW) shading pattern (Fig. 4(h)). The evaluation of the performance is carried out on 10 W panels and its ratings are given in Table 1.

The occurrence of the random shading pattern is due to the merging of multiple shading patterns, which can result in a lack of a discernible pattern and cause unpredictable shading of PV modules. As a result, the PV system experiences increased power losses. Table 2 presents a comparison of the output between the proposed array configuration and another array configuration. When subjected to this shading pattern, the series-parallel array configuration yielded a power output of 207 W and a short circuit current of 2.88A, resulting in an efficiency of 25.6%. However, the percentage of mismatch losses was high at 72.4%. On the other hand, the TCT and Sudoku array configurations produced significantly higher power outputs of 396 W and 423 W, respectively, with corresponding short circuit currents of 5.5A and 5.88A. The power generation efficiencies of the TCT and Sudoku configurations were similar, at

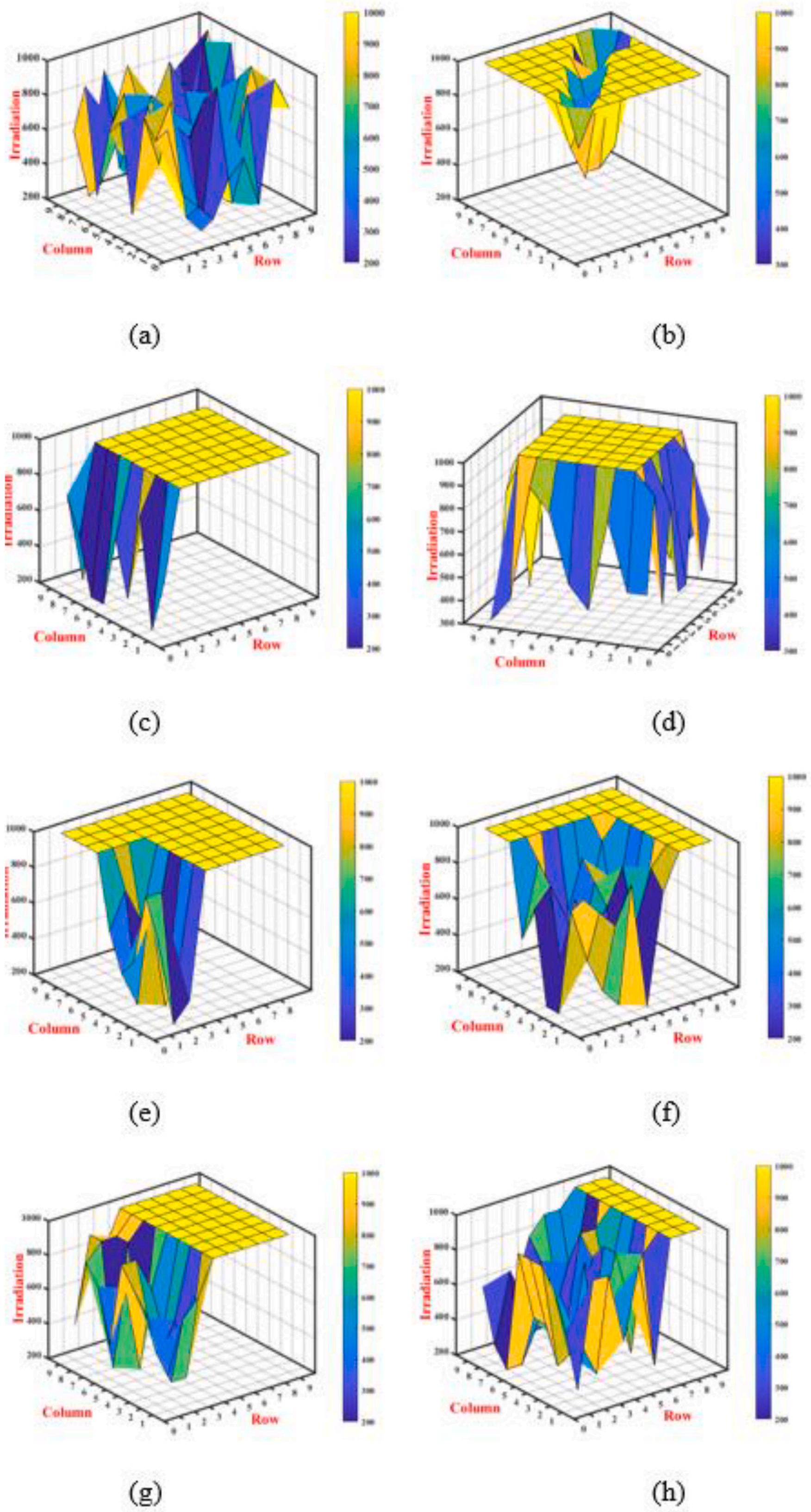

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Fig. 4. Shading patterns (a) Random (b) diagonal (c) Frame (d) L-Shape (e) Short and Narrow (SN) (f) Short and Wide (SW) (g) Long and narrow (LN) (h) Long and Wide (LW) shading pattern.

Table 1
Rated specification of 10 W PV module.

Particulars	Rating
Maximum Power, P_m	10 W
Open Circuit Voltage, V_{oc}	11.5 V
Maximum Voltage, V_m	9.09 V
Short Circuit Current, I_{sc}	1.25 A
Maximum Current, I_m	1.1 A
Fill Factor, FF	1.1
STC Irradiance (G_{STC})	1000 W/m^2
STC Temperature (T_{STC})	25 °C

Table 2
Comparison of results in random shading.

S. No	Type of PV topology	Short Circuit Current (I_{SC})	Maximum CurrentOutput (I_M)	Maximum PowerOutput (P_M)	Power Conversion Efficiency (η)	Percentage of Mismatch Loss
1	Series-Parallel	2.88	2.53	207	25.6%	72.4%
2	TCT	5.50	4.84	396	48.9%	35.3%
3	Sudoku	5.88	5.17	423	52.2%	36.5%
4	Calcudoku	6.75	5.94	486	60.0%	12.9%

48.9% and 52.2%, respectively. In contrast, the proposed calcudoku array arrangement demonstrated the most impressive performance under this random shading pattern, generating a power output of 486 W and a short circuit current of 5.94A.The proposed array configuration exhibits an efficiency of 60% and a relatively low mismatch loss of 12.9%. The reduction in mismatch loss highlights the configuration's ability to distribute shading evenly across the PV array, even in complex shading patterns. This even distribution results in the lowest possible mismatch power loss and increases power output. Fig. 5(a) and Fig. 5(b) illustrate the P–V and I–V characteristic curves of various array topologies under the random shading condition. Notably, the proposed array configuration displays smoother and superior characteristic curves compared to other PV array arrangements.

The proposed array configuration has been tested and validated under diagonal shade patterns created by taller buildings, towers, and other structures adjacent to the PV system. Although the TCT configuration can mitigate partial shading in this pattern, the proposed technique outperforms other array arrangements in suppressing partial shading. Under this shading pattern, the TCT array arrangement generated 630 W of power with a short circuit current of 8.75A, while the proposed calcudoku array layout produced 711 W of power with a short circuit current of 9.88A. The proposed array arrangement demonstrated lower mismatch loss compared to other array configurations. Table 3 summarizes the performance under the diagonal shading pattern, while Fig. 6(a) and Fig. 6(b) present the relevant P–V and I–V characteristic curves. Although both the proposed and TCT array designs have smoother P–V and I–V curves, the proposed array configuration exhibits superior characteristics compared to the other configurations.

The frame shading pattern occurs due to new constructions, porticos, or towers built near the PV array, affecting two complete PV

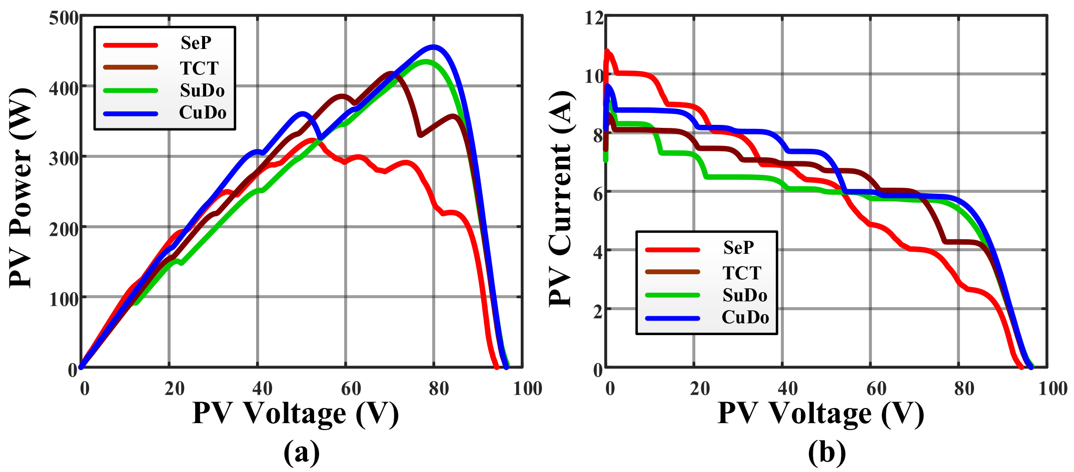

Fig. 5. (a) Power (P) – Voltage (V) (b) Current (I) – Voltage (V) characteristic curves under Random Shading Pattern.

Table 3
Comparison of results in diagonal shading.

S. No	Type of PV topology	Short Circuit Current (I_{SC})	Maximum CurrentOutput (I_M)	Maximum PowerOutput (P_M)	Power Conversion Efficiency (η)	Percentage of Mismatch Loss
1	Series-Parallel	5.88	5.17	423	52.2%	47.8%
2	TCT	8.75	7.70	630	77.8%	21.3%
3	Sudoku	7.25	6.38	522	64.4%	35.6%
4	Calcudoku	9.88	8.69	711	87.8%	12.2%

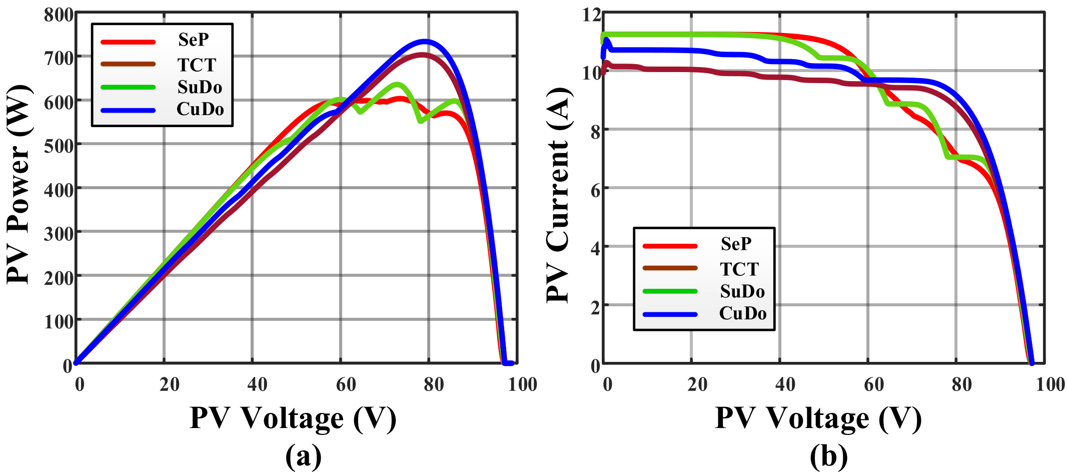

Fig. 6. (a) P–V (b) I–V characteristic curve in diagonal shading.

rows and two complete PV columns. This shading pattern results in significant power loss in Se–P and TCT array configurations. However, the sudoku and proposed calcudoku array configurations disperse shading in the PV array since their PV rows and columns are designed to do so. Table 4 presents the power output of the PV array under the frame shading pattern. The calcudoku array configurations outperform the sudoku configuration by the power generation. While the sudoku array generates 594 W of power with a 46.7% efficiency and a short circuit current of 7.26A, the proposed method produces a 648 W power with a short circuit current of 9A and an efficiency of 80%. Due to the mathematical relationships used in the design of the PV array, the proposed method performs better than the sudoku puzzle pattern. Fig. 7(a) and Fig. 7(b) depict the P–V and I–V characteristic curves. The calcudoku array configuration exhibits a smoother characteristic curve than the sudoku configuration due to its higher dispersion rate.

The L-shaped shade pattern is typically caused by new buildings constructed near the PV array, resulting in shading that covers entire rows and columns of the array. Table 5 presents a comparison of the performance of various array configurations under this shading pattern. The Se–P array design produces the least power output at 477 W, while the TCT array configuration produces 513 W. The Sudoku Puzzle pattern-based array configuration produces 675 W, while the proposed calcudoku array layout generates the highest power output at 720 W. The proposed array arrangement experiences only 8% mismatch losses in the PV array, while the sudoku array configuration has 13.8% mismatch losses. Fig. 8(a) and Fig. 8(b) show the characteristic curves of the different array configurations under the L-shaped shading pattern.

Approximately a quarter of the PV array is affected by a short and narrow shading pattern, covering around 25% of the panel's surface. The PV array's power generation is ranked as follows when subjected to this shading pattern: proposed method, sudoku, TCT, and Se–P. The proposed method yields an efficiency of 88.9% and generates 720 W, while the sudoku pattern produces an efficiency of 81%, TCT generates 78.9%, and series-parallel generates 75%. Output results for the short and narrow shading patterns are presented in Table 6, while Fig. 9(a) and Fig. 9(b) illustrate the characteristic curves. The characteristic curves for the series-parallel and TCT have more than two LMPPs, whereas the Sudoku and proposed methods have fewer peaks due to the high shade dispersion rate.

The SW shading are mostly caused by the nearby buildings that shaded almost 50% panel surface. The sudoku configuration

Table 4
Comparison of results in frame shading.

S. No	Type of PV topology	Short Circuit Current (I_{SC})	Maximum CurrentOutput (I_M)	Maximum PowerOutput (P_M)	Power Conversion Efficiency (η)	Percentage of Mismatch Loss
1	Series-Parallel	5.25	4.62	378	46.7%	51.9%
2	TCT	6.63	5.83	477	58.9%	36.9%
3	Sudoku	8.25	7.26	594	73.3%	18.5%
4	Calcudoku	9.00	7.92	648	80.0%	13.3%

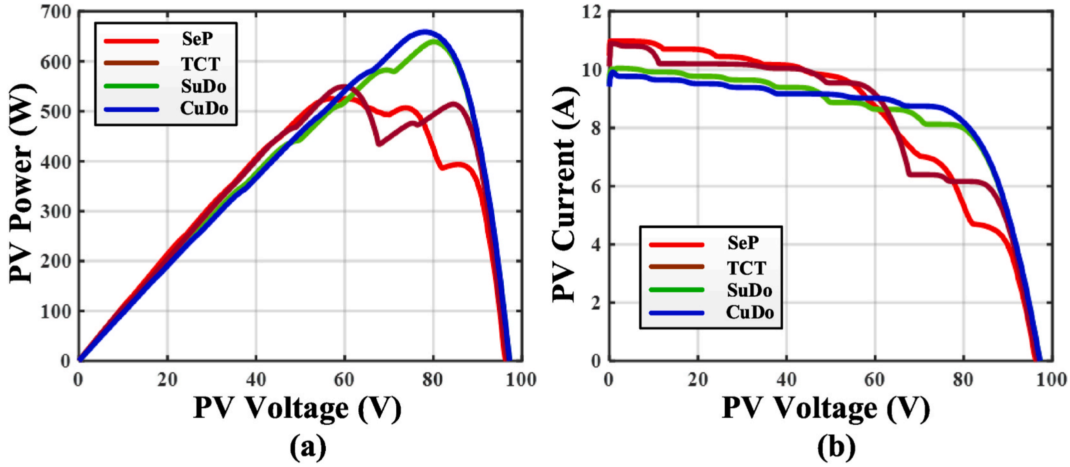

Fig. 7. (a) P–V (b) I–V characteristic curve in frame shading.

Table 5
Comparison of results in L-shape shading.

S. No	Type of PV topology	Short Circuit Current (I_{SC})	Maximum CurrentOutput (I_M)	Maximum PowerOutput (P_M)	Power Conversion Efficiency (η)	Percentage of Mismatch Loss
1	Series-Parallel	6.63	5.83	477	58.9%	40.7%
2	TCT	7.13	6.27	513	63.3%	36.0%
3	Sudoku	9.38	8.25	675	83.3%	13.8%
4	Calcudoku	10.00	8.80	720	88.9%	8.0%

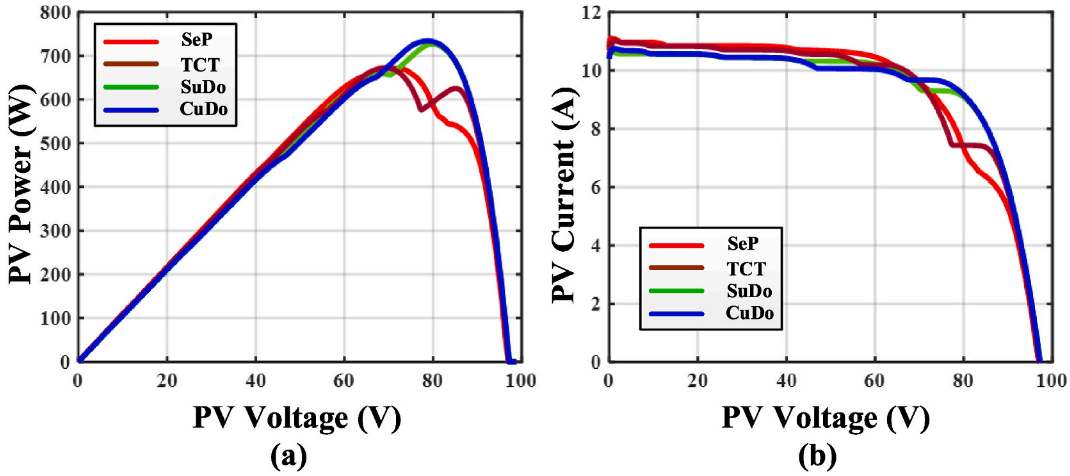

Fig. 8. (a) P–V (b) I–V characteristic curve in L-Shape shading.

Table 6
Comparison of results in SN shading.

S. No	Type of PV topology	Short Circuit Current (I_{SC})	Maximum CurrentOutput (I_M)	Maximum PowerOutput (P_M)	Power Conversion Efficiency (η)	Percentage of Mismatch Loss
1	Series-Parallel	8.50	7.48	612	75.5%	24.4%
2	TCT	8.88	7.81	639	78.9%	21.1%
3	Sudoku	9.13	8.03	657	81.1%	18.9%
4	Calcudoku	10.00	8.80	720	88.9%	11.1%

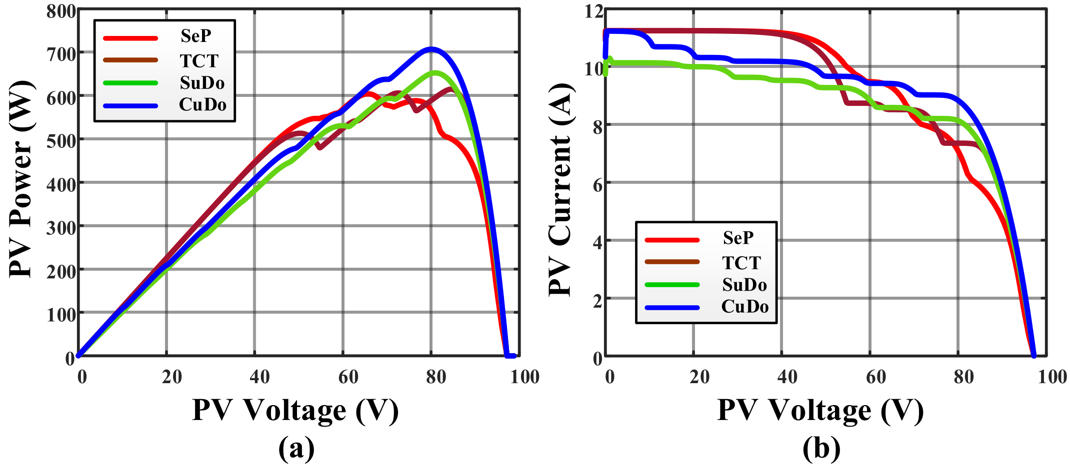

Fig. 9. (a) P–V (b) I–V characteristic curve in SN shading.

Table 7
Comparison of results in SW shading.

S. No	Type of PV topology	Short Circuit Current (I_{SC})	Maximum CurrentOutput (I_M)	Maximum PowerOutput (P_M)	Power Conversion Efficiency (Ƞ)	Percentage of Mismatch Loss
1	Series-Parallel	5.75	5.06	414	51.1%	48.9%
2	TCT	7.38	6.49	531	65.5%	34.4%
3	Sudoku	8.25	7.26	594	73.3%	21.4%
4	Calcudoku	9.13	8.03	657	81.1%	3.9%

generated greater power and had smoother characteristic curves as compared to the Se–P and TCT configurations. However, the proposed array configuration outperforms the sudoku method. The proposed configuration generates more power than the sudoku method since it has just a 3.9% mismatch loss. Table .7 shows the output results for the short and SW shading patterns, and Fig. 10(a) and Fig. 10(b) shows the characteristic curves. When the percentage of mismatch losses is compared, the series-parallel array design has 48.9%, the TCT array has 34.4%, Sudoku has 21.4%, and the proposed calcudoku array configuration has just 3.9%.The shade dispersion rate of the proposed methods is more than the all-other PV configurations, So, the efficiency of the proposed method is also greater than the others.

The LN shading type covers approximately 25–35% of the panel surface. This is considered to be a major or complex pattern. Calcudokku configuration has been evaluated in this type of shade with 7.2% mismatch losses and a power conversion efficiency of roughly 85.5%. Other PV array configurations generate power with an efficiency greater than 75%. Because the shading is considered at the column level in this example, it does not cause additional losses in series-parallel and total cross-linked array arrangements. Long and narrow shadowing in PV rows causes increased power losses in Se–P and TCT. The Se–P array has a power conversion efficiency of

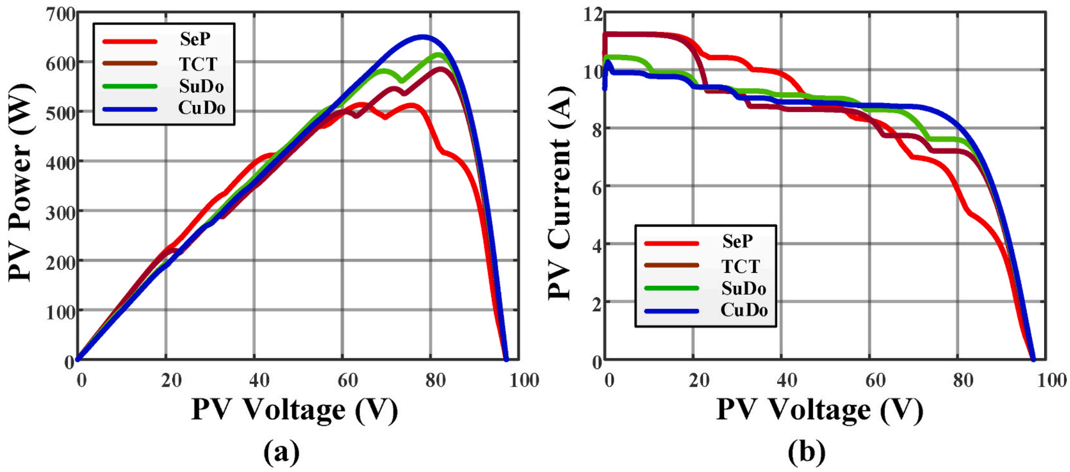

Fig. 10. (a) P–V (b) I–V Characteristic Curve in SW shading.

Table 8
Comparison of results in LN shading.

S. No	Type of PV topology	Short Circuit Current (I_{SC})	Maximum CurrentOutput (I_M)	Maximum PowerOutput (P_M)	Power Conversion Efficiency (η)	Percentage of Mismatch Loss
1	Series-Parallel	8.50	7.48	612	75.5%	23.5%
2	TCT	8.88	7.81	639	78.9%	17.4%
3	Sudoku	9.13	8.03	657	81.1%	14.1%
4	Calcudoku	9.63	8.47	693	85.5%	7.2%

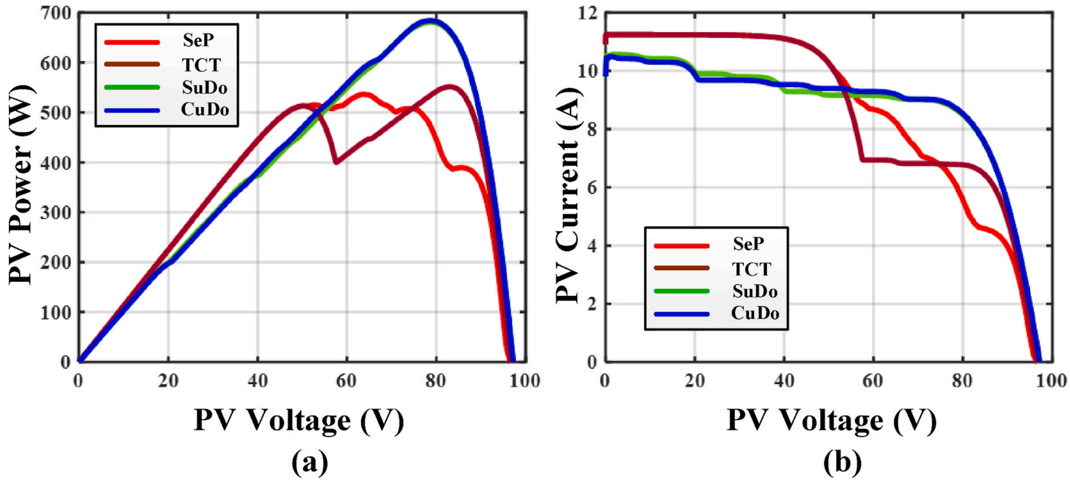

Fig. 11. (a) P–V (b) I–V Characteristic Curve in LN shading.

Table 9
Comparison of results in LW shading.

S. No	Type of PV topology	Short Circuit Current (I_{SC})	Maximum CurrentOutput (I_M)	Maximum PowerOutput (P_M)	Power Conversion Efficiency (η)	Percentage of Mismatch Loss
1	Series-Parallel	5.88	5.17	423	52.2%	45.2%
2	TCT	6.38	5.61	459	56.7%	30.1%
3	Sudoku	7.38	6.49	531	65.5%	15.7%
4	Calcudoku	7.88	6.93	567	70.0%	8.7%

42%, while entire TCT have a power conversion efficiency of 54%. Table 8 shows the output results in LN pattern. Fig. 11(a) and Fig. 11 (b) depicts the characteristic curves under LN pattern.

One of the more complex patterns is the LW shading pattern. This has shaded around 30%–50% of the panel surface. The proposed calcudoku array arrangement has generated a power output of 567 W with a short circuit current of 7.88A, 70% power conversion efficiency, and 8.7% mismatch power loss under this shading pattern. In comparison to the proposed approach, the other configurations generate the least amount of power. The Se–P array arrangement creates the least power, and the TCT array configuration generates the second least power (459 W). Table 9 compares the output of all topologies under the LW patterns. Fig. 12 depicts the typical curves of the PV array configurations. The calukudoku configuration has fewer peaks in the curves than the other PV configurations. Fig. 12(a) and (b) shows the poor shade dispersion rate of a Se–P array arrangement with many peaks.

The proposed calcudoku configuration was compared to the Se–P, TCT and Sudoku. The performance of these connections was evaluated using eight distinct shading patterns. Fig. 13(a) depicts the output power comparison chart of power output ad Fig. 13(b) shows the comparison chart of mismatch loss between existing and proposed array configurations. Among all array configurations, the proposed calcudoku configuration yields more power generateion. The percentage of mismatch losses between PV rows under partial shadowing is also investigated, with the proposed array structure operating the PV array with the minimum mismatch losses. The proposed method's ability to disperse shade is demonstrated by the lower number of mismatch losses.

5. Conclusion

A calcudoku puzzle pattern PV array configuration is proposed in this work to reduce the effect of the partial shade phenomenon. The calcudoku puzzle pattern is similar to the sudoku puzzle pattern, however, this proposed work selects the PV panel places using mathematical relations. Furthermore, the same number is not repeated in the corresponding row and column. The proposed system's performance is validated in a 9 × 9 PV array under the eight possible shading patterns. There are four normal shading patterns and four

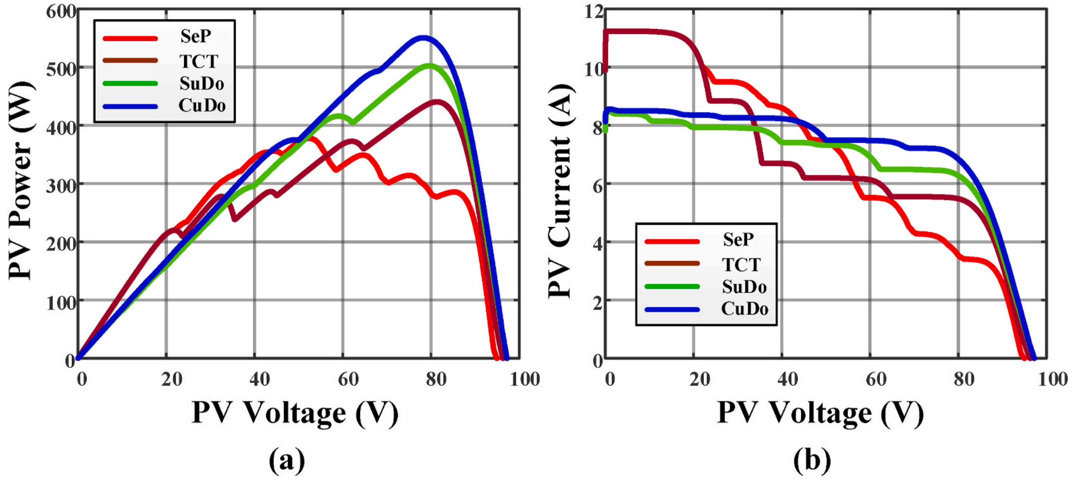

Fig. 12. (a) P–V (b) I–V characteristic curve in LW shading.

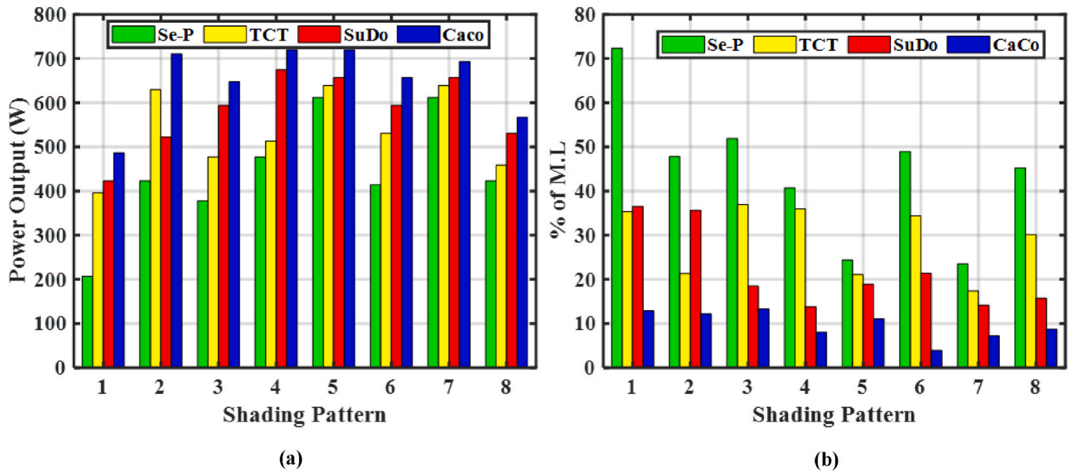

Fig. 13. Performance comparison chart (a) power output (b) mismatch loss.

complex shading patterns among the eight. The proposed array configuration's performance has been compared to existing array configurations such as Se–P, TCT, and Sudoku arrayconfigurations. When comparing the performance of these configuration, thecalcudoku configuration outperform the others. In the normal shading patterns, the TCT and the Sudoku array configurations exhibited the lowest percentage of mismatch losses. However, when applied to a complicated shade pattern, these configurations failed to disperse the shading, resulting in a high percentage of mismatch loss generation. However, the proposed approach performs consistently in all eight shading patterns. The proposed approach has a mismatch loss percentage of 5%–13% in each type of shading pattern. This shows the proposed method's capability in terms of consistent shade dispersal and power generation. The proposed method can be an alternative to series-parallel, TCT, Sudoku, and other array topologies in real-time applications. The proposed array arrangement is also easy and inexpensive to implement.

Author contribution statement

Belqasem Aljafari - conceived and designed the experiments; performed the experiments.
Devakirubakaran S - analyzed and interpreted the data; wrote the paper.
Bharatiraja C - contributed reagents, materials, analysis tools or data; conceived and designed the experiments; wrote the paper.
Praveen Kumar B - conceived and designed the experiments, wrote the paper.
Thanikanti Sudhakar Babu - conceived and designed the experiments, contributed reagents, materials, analysis tools or data.

Data availability statement

No data was used for the research described in the article.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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