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An imperative SuDoKu reconfiguration method for photovoltaic array under partial shading conditions

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Partial shading condition (PSCs) is one of the major affecting problems that downwards the PV array performance. In this context, array reconfiguration is one of the useful techniques that maximize the PV array performance under PSCs. Reconfiguration is an approach to spread the shading effects uniformly over the array. This paper proposed an imperative SuDoKu puzzle reconfiguration connection to reduce the shading impacts on Total-Cross-Tied (TCT) PV array. In this approach, the actual locations of PV modules in the TCT array are modified based on the imperative SuDoKu, thereby the power output of the TCT can be improved. This method is tested on 9×9 array under various grouping shading conditions by obtained performance index parameters. Also, the proposed method validated with the other existed reconfiguration methods under PSCs.

Keywords: PV Modelling, partial shading, reconfiguration techniques, TCT array and SuDoKu.

Introduction

The utilization of conventional energy causes significant damage due to emissions and chemical reagents, thereby making it more relevant to use renewable sources, namely solar, wind, and geothermal. The most common and necessary renewable energy is solar energy because of its ubiquity and abundance in nature[1]. The primary concern of the PV system is a change in the environment, which results in a non-uniform irradiance effect on the PV modules. Non-uniform irradiance or Partial Shading Condition (PSCs) occurs because of the shade of the module area due to several reasons, such as passing clouds, adjacent buildings, and telephone towers. In PSCs, the shaded PV module consuming the power instead of generating; as a result PV system affected by the hot-spot[2]. To avoid the effect of hot-spot, a bypass diode is connected anti-parallel to the shaded module. The parallel connection of a diode exhibits multiple peaks in the output P-V characteristics. The existence of numerous peaks hinders the real global maximum powerpoint (GMMP), this can add an extra loss to the PV system, and a technique is required to decrease PSCs.The literature discusses several solutions to minimize damages arising from PSCs. The PV module interconnection is the most common solution. According to the research reports, PV modules can connect various fashions, which include "simple-series (SS), parallel (P), series-parallel (SP), total-cross-tied (TCT), bridge-link (BL), and honey-comb (HC)[3]".

Modelling and simulation of various 5×5 "SS, P, SP, TCT, BL, and HC PV array interconnections" under the effect of PSCs are reported[4]. In this work, the authors considered different types of shading conditions to assess the performance of each connection. This paper suggested that TCT array has high fill-factor than the other array interconnections under all shadings. A similar paper is presented on to investigate the effect of PSCs on various interconnections performance of 6×6 PV array under different shading patterns using Matlab-Simulink. The array interconnections include "SS, SP, TCT, BL, and HC". The review study concluded that the TCT and BL array interconnections show effective performance under most shading patterns. As per the findings from the literature, the TCT array eliminates the losses due to partial shadings than the other connection schemes. The main problem with the TCT consists of reducing the array current when the number of PV modules is shaded in one row[4]. However, some authors have attempted to reconfigure the TCT PV array to disperse shading effects from one row to multiple rows in order to solve this problem. Reconfiguration is a way to change the structure of exiting array interconnections to disperse PSCs and increase power production. Based on the research reports, it is mentioned to divide the processes of reconfiguration into dynamic and static[5].

In dynamic techniques, to increase power output under PSCs, the locations of PV modules in the array are electrically modified. In[3], presented an adaptive reconfiguration setup to mitigate irradiance mismatch loss in TCT array under PSCs. This technique has fixed and adaptive parts. Under PSCs, the adaptive part modules connected to rows of a fixed part with the help of electrical switches to reduce irradiance drop. To conduct this experiment required various external devices such as irradiance sensors, switches, and separate optimization algorithm. It is a difficult task to communicate these devices under reconfiguration. The existence of these components also complicates the PV system[6].

As compared with the dynamic, the static reconfiguration utilizes the fixed connection structure to gain the power output under PSCs. This method can't change its electrical connections while operating time, means the physical location of PV modules is altered, but their electrical connections are fixed under all effect of shadings[7]. In addition, there is no need for external equipment's such as sensors, electrical switches, and separate algorithms. This method requires an appropriate pattern that reconfigures the modules' physical positions to distribute shading effects around the array. In[7], developed a fixed connection scheme on 3×3 TCT array to reduce PSCs and gain the maximum power. The proposed connection arrangement is done only one time for all shading effects. This work suggested that the proposed connection increased power output as compared to other interconnections like SP and TCT array. In[8], proposed a novel pattern arrangement to relocate the modules position in TCT that can distribute PSCs across the array. In this work, the suggested pattern applied to 4×4 TCT array, and validated with other existing interconnections. This study revealed that the proposed reconfiguration pattern showed better output than the other connections. In[9], introduced a one-time arrangement structure, namely the magic-square pattern for 4×4 TCT array to distribute PSCs. This technique aims to relocate the PV modules position in the array using magic-square without modifying their electrical connections. The results of this paper revealed that the proposed technique enhanced the power generation under PSCs. In[9], proposed SuDoKu puzzle-based reconfiguration to reduce the impact of PSCs on 9×9 TCT array. In this work, the authors considered various shading conditions and parameters to investigate the performance of SuDoKu. This article showed that, in comparison with other reconfigurations, the proposed SuDoKu improved the power output.

However, this article has few drawbacks: (i) The first column of the SuDoKu pattern is not physically relocated, which means the location of modules remains the same even if shading occurs (refer in Fig. 1, highlighted). Thus can reduce the power output of the array and exhibits multiple peaks. (ii) The SuDoKu pattern is ineffective under diagonal shading distribution because of repeated modules connection (example: PV modules are connected in 9th row sequentially shown in Fig. 1). As a consequence, number of shaded modules increases in series and limits the output current. To overcome these issues, this paper proposed an imperative SuDoKu puzzle reconfiguration for the application of TCT PV array to enhance power production under PSCs[10]. The benefit of the proposed pattern is distributed any shading impacts uniformly over the array as compared to SuDoKu. This proposed method is tested on 9×9 array and validated under various grouping shading conditions by obtained the "global maximum power point (GMMP), power loss (PL), fill-factor (FF), and utilization factor (UF)". Also, the proposed method is numerically compared with other existing reconfigurations such as SP, TCT, and SuDoKu under shading conditions.

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

Fig. 1. SuDoKu reconfiguration pattern.

PV System modelling

The PV module generates DC electricity at given standard irradiance based on photovoltaic principle. Typically, a single PV module consists of approximately 20–40 solar cells in a series connection. The power output of a PV module entirely depends on its physical dimensions. To simulate the output characteristics of a PV module modelling is needed[6]. The mathematical modelling of a single PV cell is carried out to study the PV module performance characteristics. The single diode PV cell model is shown in Fig. 2.

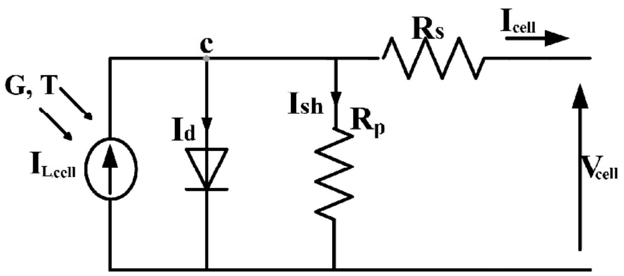


Fig. 2. Single diode PV cell model.

The output current equation of single diode PV cell model can be written as[11],

$$I_{cell} = I_{Lcell} - I_d - I_{sh} \quad (1)$$

Connecting PV cells in a series fashion will reflect the complete structure of the PV module. The output I-V characteristics of PV module can be written as,

$$I_m = I_{ph} - I_d\left[\exp\left(\frac{q(V_m + I_mR_s)}{nkT}\right) - 1\right] - \left(\frac{V_m + I_mR_s}{R_{sh}}\right) \quad (2)$$

The PV module can be built into an array by connecting the PV modules in sequence and parallel. The output functions of the PV array can be summarized as[12],

$$I_a = N_{pp}\left\{I_{ph} - I_o\left[\exp\left(\frac{(V_a + I_aR_s)}{V_tN_{ss}}\right) - 1\right]\right\} - \left(\frac{V_a + I_aR_s}{R_p}\right) \quad (3)$$

The above collection of equations can also be used to display the output characteristics of the PV array under various irradiations and temperatures, as can be seen, respectively, in Figs. 3 and 4. The standard test condition (STC) specifications for the PV module are given in Table 1.

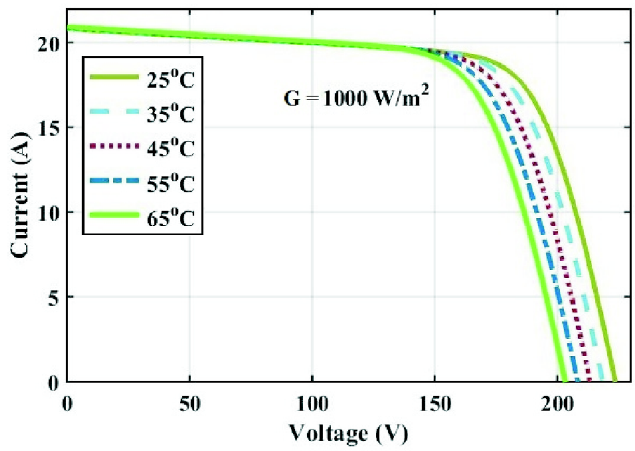


Fig. 3. I-V characteristics of the PV array.

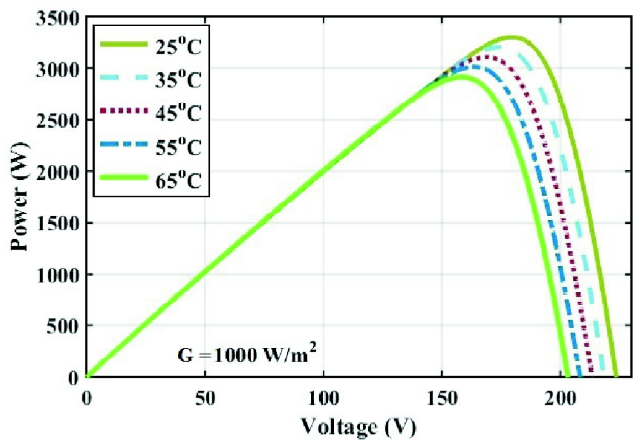


Fig. 4. P-V characteristics of the PV array.

Table 1. PV Data sheet parameters

Parameters	Ratings
Power output (P_{mp})	170.05 W
Nominal voltage (V_{oc})	44.2 V
Nominal current (I_{sc})	5.2 A
Current at MPP (I_{mp})	4.75 A
Voltage at MPP (V_{mp})	35.8 V
PV module area	62.2 inc×31.9 inc

Total-Cross-Tied PV array

TCT is the combination of rows of parallel-connected PV modules, and all of these rows are connected in a series mode called a string (refer in Fig. 5). In this paper, the proposed technique adopted a 9×9 TCT array to investigate the effect of PSCs. The 9×9 TCT consists of 81 PV modules with a rated peak power of a single module is 170 W. Nine rows are connected in series, and each row has nine modules that are connected in parallel. In TCT, connecting modules in parallel, which increase the array output current. This can be found using given eq. (4)[15].

$$V_a = \sum_{i=1}^{9} V_{mi} \tag{4}$$

The TCT array voltage is the number of series-connected row voltages. Each row voltage is equal to the maximum module voltage; this can be found using given eq. (5)[15],

$$I_a = \sum_{j=1}^{9} \left(I_{ij} - I_{(i+1)j} \right) \tag{5}$$

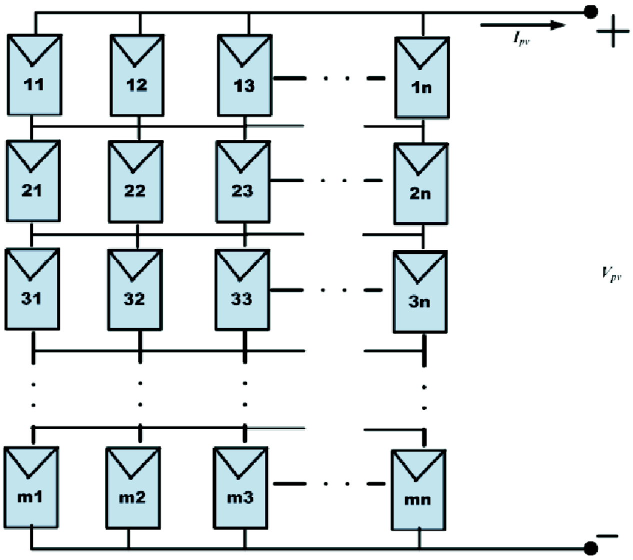


Fig. 5. TCT PV array connection.

Proposed methodology

As per the findings from observation, it is necessary to optimizing power in SuDoKu reconfiguration and therefore is the main scope of this work. This paper suggests a logic puzzle, namely imperative SuDoKu that can overcome the issues found in the SuDoKu. 9×9 imperative SuDoKu has nine 3×3 sub-array matrix, which contains row, column, and diagonal blocks. Two main conditions behind to develop this proposed SuDoKu: (i) The row, column, and diagonal numbers should not be repeated so that shading effects can be distributed equally. (ii) The number in each sub-array size matrix, i.e. 3×3, 4×4 has to be unique that can disperse adjacent shadings between modules. The backtracking algorithm has been used to solve this problem that can satisfy these two conditions. Backtracking is an algorithm for solving higher order computational problems, which in particular limits problems with satisfaction. The proposed algorithm illustrated as follows: (i) Choose partially filled 9×9 matrix as shown in Fig. 6(a). (ii) Assign the number from 1 to 9 in each empty block randomly, see in Fig. 6(b). (iii) Check the conditions of each assigned digit, and try to move forward with recursive checking (refer in Fig. 6(b)). (iv) Otherwise, backtracking undergoes the search and replace the assigned cells so that every row, every column, every diagonal, and every 3×3 matrix only has the same number once (refer in Fig. 6(b)).

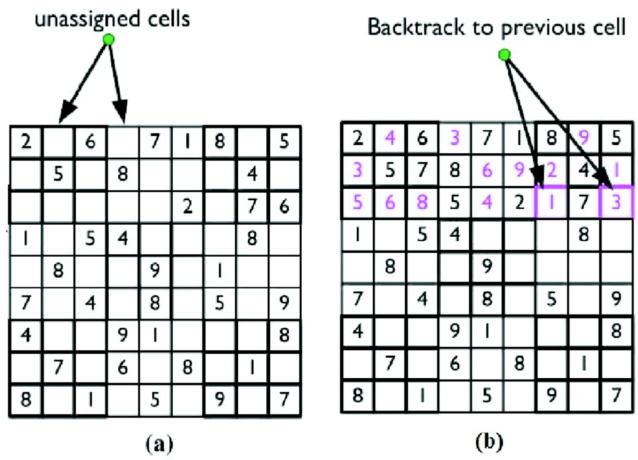


Fig. 6. Formation of proposed puzzle.

This figure shows the puzzle has unique numbers in each row, column, diagonal, and 3×3 sub-array matrix. This puzzle can be transformed into an array pattern as shown in Fig. 7. It shows each column is assigned with numbers 1 to 9 is called the column index. The modules in the TCT array are rearranged using the proposed pattern by shifting their locations physically with fixed electrical connections (refer in Fig.

7). This enables modules affected by shading is distributed uniformly in the PV array from the same row into separate rows. Therefore, for the same shading conditions, the PV array's power output is increased[13].

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

Fig. 7. Imperative SuDoKu puzzle and pattern.

Shading conditions

This article considered three grouping shading conditions into account to verify the proposed method. Grouping is a size of the array subjected to partially shading with different irradiance levels. In each grouping, 4×4 sub-arrays is shaded in the 9×9 array with various irradiance levels. The suggested pattern's efficiency is assessed by obtaining GMPP, fill-factor, power loss, and utilization factor. The mathematical representation of these parameters is given in[9].

Results and discussion

This article proposed an imperative SuDoKu reconfiguration technique to mitigate the effect of partial shadings in TCT array. This technique is tested on 9×9 size of the array under four grouping shading conditions. The position of global peaks in each shade is calculated by measuring each row's output current and voltage using eqs. (4)-(5). The results of the proposed imperative SuDoKu are compared with existing reconfigurations techniques by obtaining the GMPP, power loss, fill-factor and utilization factor[14].

Grouping shading condition-I:

In this condition, a 4×4 sub-array group of modules is affected by PSCs in the bottom-right of 9×9 array with different irradiances is shown in Fig. 8. In this figure, the shading dispersion structure of the proposed SuDoKu method is also shown. Identification of location of the global peak for TCT, SuDoKu, and proposed imperative SuDoKu can be obtained by calculating the current and voltage of each row by using eqs. (4)-(5). After the estimation of voltrage and current of individual rows of the array shows that imperative SuDoKu method provided more power under this shading condition than other techniques. The theoretical calculations can be found[9]. Whereas, the generated global peaks of all the methods are validated through simulation by plotting the I-V, and P-V curves are shown in Fig. 10. In addition to this, the SP array interconnection also simulated for this shading, as shown in Fig. 10. Further, GMPP, power loss, fill-factor, and utilization factor are calculated and graphically reported in Fig. 9. The obtained result defined that the proposed imperative SuDoKu reconfiguration technique enhanced the power output than other methods.

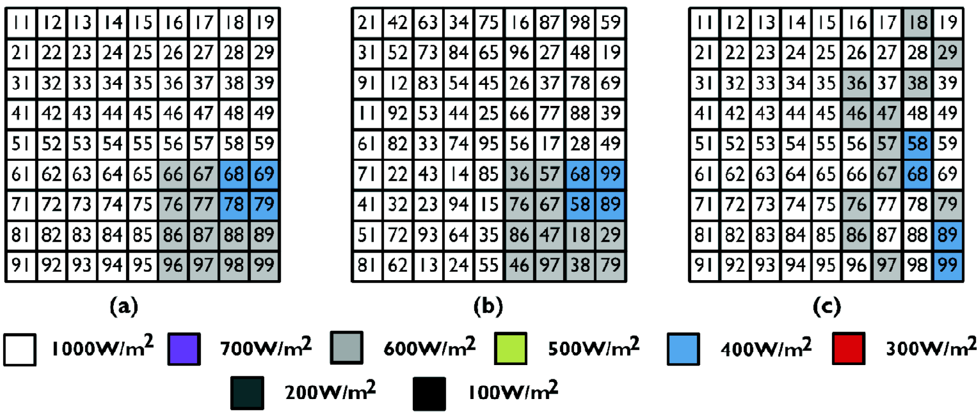


Fig. 8. Grouping shading condition-I.

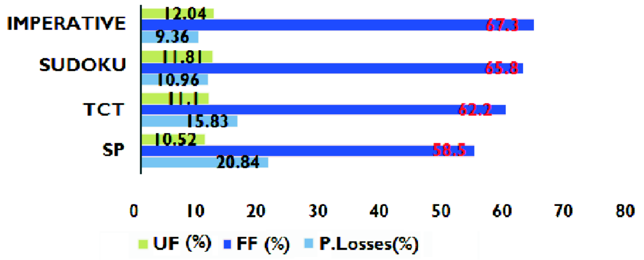


Fig. 9. Obtained parameters for shading-I.

Grouping shading condition-II:

In this condition, a 4×4 sub-array group of modules affected by PSCs in the bottom-left of 9×9 array with lower irradiance is shown in Fig. 11. In this figure, the shading dispersion structure of the proposed SuDoKu method is also shown. Identification of location of the global peak for TCT, SuDoKu, and proposed imperative SuDoKu can be obtained by calculating the current and voltage of each row by using eqs. (4)-(5). After the estimation of voltage and current of individual rows of the array shows that imperative SuDoKu method provided more power under this shading condition than other techniques. Whereas, the generated global peaks of all the methods are validated through simulation by plotting the I-V, and P-V characteristics are shown in Fig. 13. In addition to this, the SP array interconnection also simulated for this shading, as shown in Fig. 13. Further, "GMPP, power loss, fill-factor, and utilization factor" are calculated and graphically reported in Fig. 12. The obtained result defined

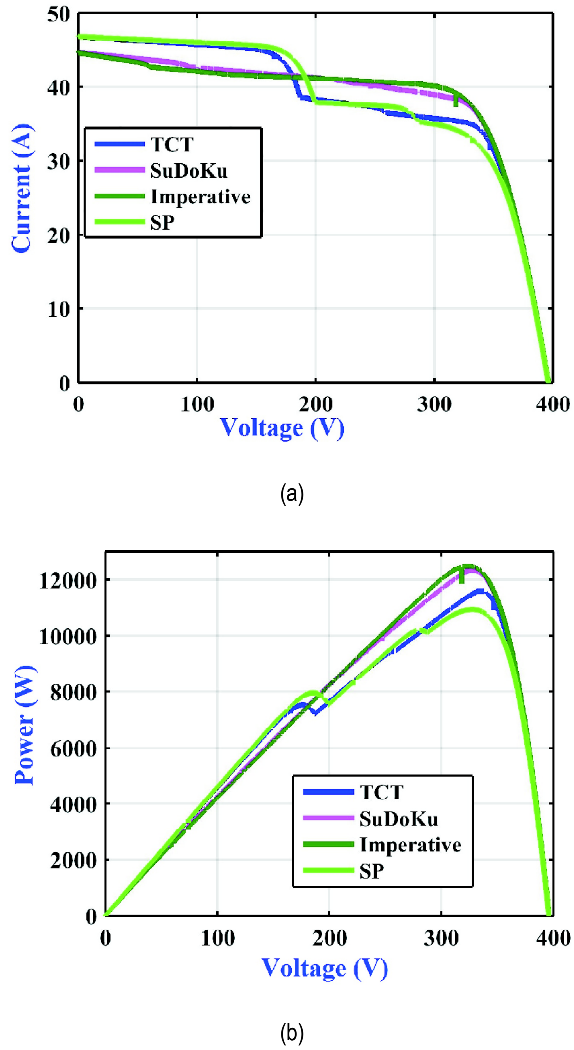


Fig. 10. (a) I-V and (b) P-V curve for shading case-I.

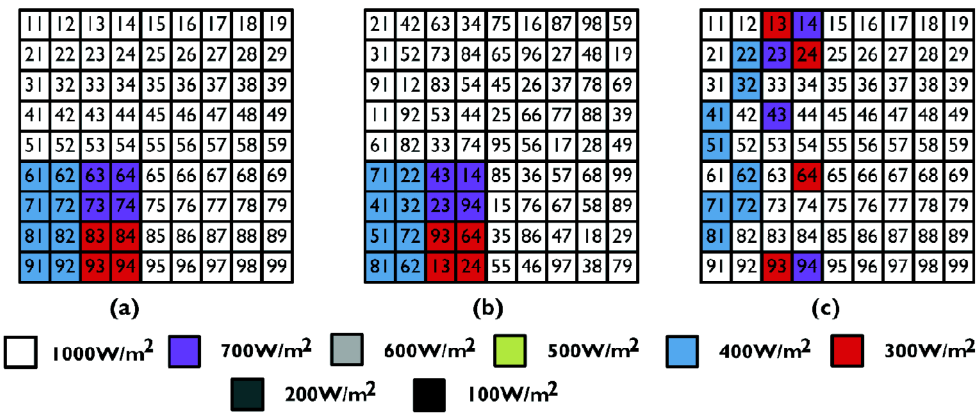


Fig. 11. Grouping shading condition-II.

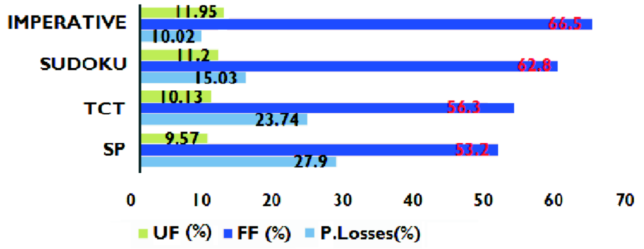


Fig. 12. Obtained parameters for shading-II.

that the proposed imperative SuDoKu reconfiguration technique enhanced the power output than other methods.

Grouping shading condition-III:

In this condition, a 4×4 sub-array group of modules affected by partial shading in the top-right of 9×9 array with lower irradiance is shown in Fig. 14. In this figure, the shading dispersion structure of the proposed SuDoKu method is also shown. Identification of location of the global peak for TCT, SuDoKu, and proposed imperative SuDoKu can be obtained by calculating the current and voltage of each row by using eqs. (4)-(5). After the estimation of voltrage and current of individual rows of the array shows that imperative SuDoKu method provided more power under this shading condition than other techniques. Whereas, the generated global peaks of all the methods are validated through simulation by plotting the I-V, and P-V characteristics are shown in Fig. 16. In addition to this, the SP array interconnection also simulated for this shading, as shown in Fig. 16. Further, “GMPP, power loss, fill-factor, and utilization factor” are cal-

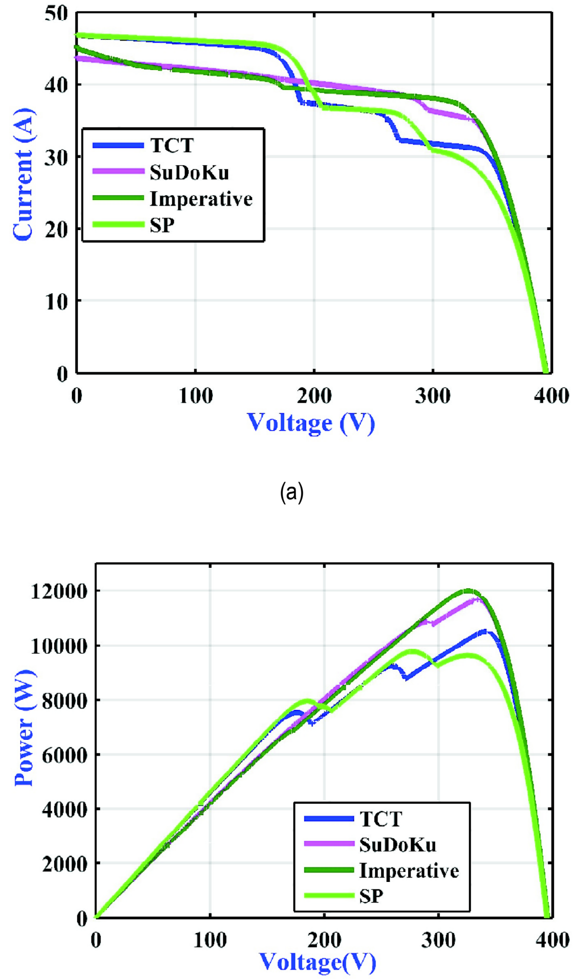


Fig. 13. (a) I-V and, (b) P-V characteristics for shading case-II.

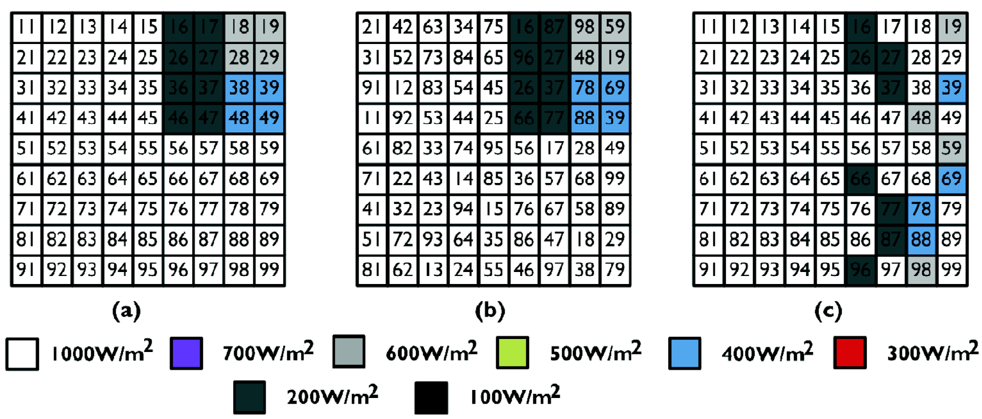


Fig. 14. Grouping shading condition-III.

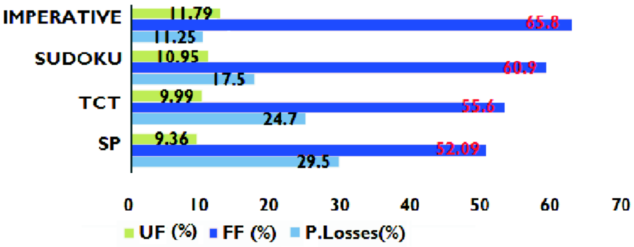
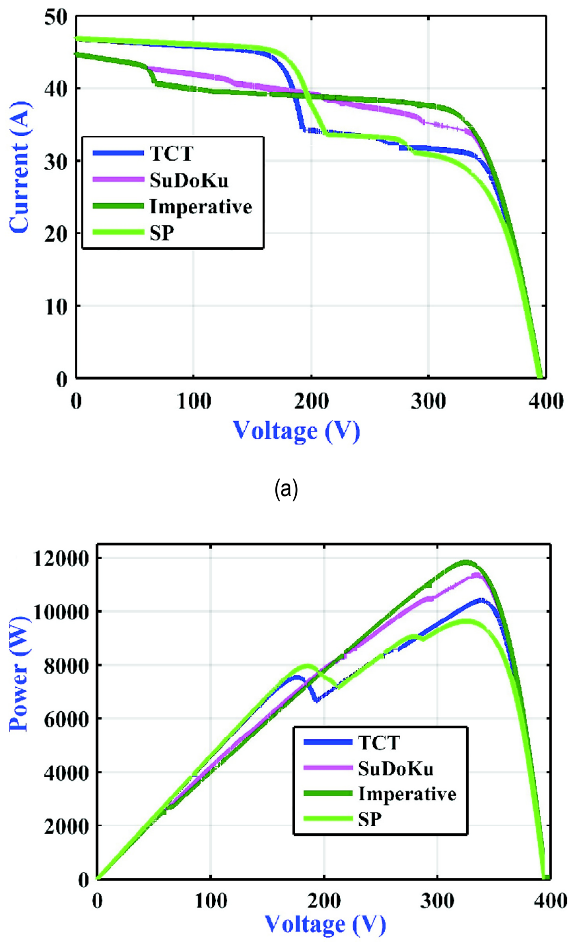


Fig. 15. Obtained parameters for shading-III.



(a)

(b)

Fig. 16. (a) I-V and (b) P-V characteristics for shading case-III.

culated and graphically reported in Fig. 15. The obtained result defined that the proposed imperative SuDoKu reconfiguration technique enhanced the power output than other methods.

Table 2. Power enhanced by imperative SuDoKu (%)

Shadings	SP	TCT	SuDoKu
Shading-I	15.3	9.8	3.8
Shading-II	24.9	19.2	6.9
Shading-III	28.6	18.5	8.8

Table 2 shows the power loss comparison between the proposed technique with other existing "SP, TCT, SuDoKu" methods under shading conditions. This table stated that the imperative SuDoKu reconfiguration method enhanced the power output and utilization factor than the other methods.

Conclusion

In this paper, an imperative SuDoKu reconfiguration technique is proposed for a 9×9 TCT PV array to combat the effect of partial shadings. In this work, without interrupting their electrical connections, the positioning of PV modules in the TCT array is followed based on the proposed technique. Four partial shading scenarios are created to validate this technique by obtained "global maximum power, fill-factor, power loss, and utilization factor". The findings concluded that the imperative SuDoKu connection is better suited to the TCT array to spread shading effects and enhance the power output than other methods of SP, TCT, and SuDoKu. The issue of the proposed method is that if you increase the size of the array will increase the cost of the system as well as voltage drop. Hence, the proposed methodology is limited for average PV array sizes, i.e. 6×6, 7×7 and 9×9.

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