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Twisted two-step arrangement for maximum power extraction from a partially shaded PV array

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***Abstract*—Partial Shading (PS) is one of the biggest challenges in the optimum utilization of photovoltaic panels. occurrence of shade on the front side of panel affects the light transmission completely or partially, leads to its production loss. Hence in this work, to improve the electrical performance of the partially shaded solar panel physical array reconfiguration based novel twisted two-step technique is proposed. The effectiveness of the proposed methodology is verified by utilizing three shade patterns at various locations of the panel. A comparative analysis with various prominent methods in terms of seven critical performance metrics and is carried out. Further, an experimental study conducted on a 3x3 PV array reveals that the output power has increased by 41% post to reconfiguration technique.**

***Index Terms*—Photovoltaics (PV), Partial Shading (PS), Physical Array Reconfiguration (PAR), Twisted two-step arrangement, Power generation enhancement.**

I. INTRODUCTION

POWER generation from renewable energy holds an incredible promise in attaining energy independence. Among the available energy resources such as solar, wind, geothermal and hydro, solar energy plays a pivotal role in the worlds transition towards sustainable energy future. Yet its complete utilization is frequently constrained by predominantly occurring Partial Shading (PS) phenomenon. Further, lack of a unique methodology in dispersing the shade aggravated the issue, thereby presenting a new challenge in the growth of solar PV [1]. The root causes, and effects, as indicated in Fig.1, include buildings, tree shadow, dust accumulation, bird droppings, etc. [2].

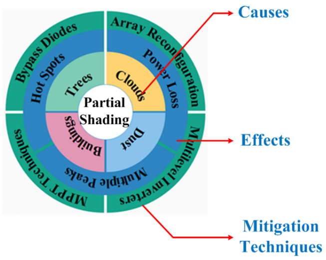

Fig. 1: Causes and effects of Partial Shade (PS) in PV.

To resolve the PS issue, many possible solutions have been proposed that include use of appropriate converters, Maximum Power Point Tracking (MPPT) techniques and Array Reconfiguration methods [2]. Among them, the simplest and inexpensive one that offers a prominent solution is array reconfiguration . The MPPT methods also handle the problem of PS in a PV array; even many meta-heuristic basd approach like Salp-Swarm Optimization [3], Henry gas solubility [4], Bat algorithm [5] are popular. However, these methods only attempts to track any of the power peaks that occur in the PV curves. Nevertheless, those methods alters the PV curve to minimize the number of power peaks. Furthermore, the process of rearranging the panel positions by altering the electrical connection or physical positions disperses the shade effectively ;thus reduces the number of power peaks [6]. These techniques are mostly tested on any of the following PV array interconnections: 1. Series, 2. Series-Parallel (SP), 3. Total Cross Tied (TCT), 4. Bridge Linked (BL), 5. Honey Comb (HC) and 6. SP-TCT, 7. BL-TCT, and 8. HC-TCT [6].

Recently Electrical Array Reconfiguration (EAR) techniques to disperse the shade used Marine Predator algorithm [7], Grey wolf optimization [8], and PSO [9] methods. Though useful in shade dispersion and produce higher power, the methodology is prone to the following drawbacks: 1. Array size linearly increases switches and sensors quantity, 2. Incur additional investment cost when implemented for larger PV plants, 3. Raises the possibility of fault occurrences, and 4. Necessitates high-end processors hence expensive [10]. Alternatively, Physical Array Reconfiguration (PAR) techniques are exempted from electrical wiring alterations, thus alleviates the usage of switches, sensors, hence more economical than EAR techniques [6] On survey, the recently developed Su Do Ku reconfigured BL-TCT [11], and well-established Su Do Ku [12], Optimal Su Do Ku [13][6], Improved Su Do Ku [14] disperses shade uniformly with lesser power loss. However, its random arrangement of panels during reconfiguration requires puzzle-solving skills for every 3x3 matrix increases the complexity when array size increases. Besides Su Do Ku based techniques, other reconfiguration techniques such as Odd-Even [15], Dominance Square [16] have been attempted to unlock the full potential of the shaded PV array. In addition, a zig-zag technique for reconfiguring the shaded panel follow tedious reconfiguration steps is proposed [17] . Nevertheless,its adoption for all shade cases is restrained because of its versatility is exhibited only for fewer shade cases. Since most of the existing techniques suffer minor setbacks, the vast potential of the solar PV remains untapped. Moreover, the limitations of these techniques, as indicated, hastened the researchers to find an efficient method for effective shade dispersion. Hence, to utilize the full potential of a partially shaded PV array, a Twisted two-step repositioning technique for effective shade dispersion is proposed. This new approach undoubtedly pose a significant challenge to the results of various existing methods. Further, the multiple contributions made in this article are

- Two-step, one-time physical reconfiguration based twisted repositioning technique is proposed for a shaded PV array.

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- The proposed technique's prophecy is validated for three different shades with six performance parameters cases via theoretical and simulation.
- The proposed technique has shown its versatility in all shade cases and surpassed every technique for the considered performance parameters.
- Further, the Su Do Ku based techniques follow a random procedural steps and its result varies accordingly. However, the proposed method follow a standard procedure to reconfigure the PV array that makes the method as a more reliable option.

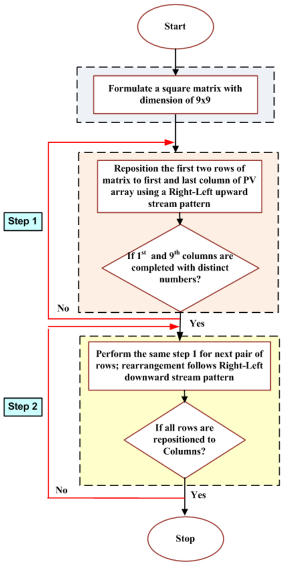


Fig. 3: Flow chart for the proposed method.

II. TWISTED TWO-STEP ARRANGEMENT FOR ARRAY RECONFIGURATION

An accurate PV panel shade dispersion technique needs to incur attributes such as simple steps, maximum power generation, economical, minimal row currents difference, and less power loss. The proposed twisted two step method principally follows a simple procedure that is easy to implement. This method positions the panel anywhere within the array for row current minimization, unlike shade dispersion within the column. Further, it made incredible progress in power output with all shade cases considered and established itself as an advanced self-sustaining versatile technique.

***Step 1**: Panel positioning in an upward stream pattern:* The proposed method follows a unique "Z" pattern panel position for every row of the original square matrix. The unique feature is the involvement of a dual step, which suits for both symmetric and asymmetric arrays, as well as for any array size. The procedure adopted is explained with the help of TCT connected 9x9 PV matrix shown in Fig. 2(a). Initially, the 9th row panels occupy the 5th column in a upward stream and is illustrated in Fig. 2(b). The actual repositioning start with the first row, i.e., panels numbered $(11...to...19)$ initially positioned as row matrix is now repositioned column-wise with every two panels in the row is sequentially arranged in "Z" sequence starting from the bottom right in an upward stream fashion . Likewise, the elements of the remaining row panels in the array are repositioned. To be precise, odd-numbered row panel starts from bottom right position and even-numbered row panels begins repositioning from bottom left position onwards to the right and left of the middle column respectively and is shown in Fig. 2(d & e) .

***Step 2**: Flip-Flop panel positioning:* For effective shade dispersion, the even numbered columns of previous rearranged matrix swapped with respect to midpoint as shown in Fig. 2(f). Thus following the above 2 steps, the entire panel can be relocated in a effective way.

Thus, complete reconfigured matrix adopting Right Left upward stream pattern for the panel arrangement in a PV array is indicated in Fig. 2(g). It is significant that the PV panels are diversely situated such that widespread shade dispersion is achieved. The comprehensive procedural steps are illustrated via flow diagram in Fig. 2(h).

III. RESULTS AND DISCUSSIONS

To assess the performance of the proposed methodology, three different shade patterns are considered. In every case, a maximum 4x4 array of TCT 9x9 PV matrix is exposed to the irradiances ranging from $100W/m^2$ to $700W/m^2$ respectively. The shading patterns considered for analysis are: Shade Pattern 1: Top Right Corner (TRC); Shade Pattern 2: Top Left Corner (TLC); Shade Pattern 3: Bottom Right Corner (BRC). To showcase the consistency and competence of the proposed methodology, the PV parameters such as Fill Factor (FF), Power Loss (P_{Loss}), MM loss, Capacity Factor (CF), Capture Loss (C_{Loss}) and Execution Ratio (ER) are estimated for three different reconfiguration technique. Further, a shred of objective evidence comprising of comparison results with alternative three prominent methodologies like TCT, Sud., and OP. SUD. is also presented. It is noteworthy to mention that all simulations are achieved in MATLAB/SIMULINK environment with changing insolation and constant temperature (25^0C) constraints. The impact of each shade condition on PV array power generation is described using row current analysis and its Power-Voltage and Current-Voltage characteristics.

A. Shade Pattern 1: Top Right Corner shade (TRC)

In this case, a 4x4 subarray occupying the upper half right corner is exposed to an irradiance of $600W/m^2$, $400W/m^2$, and $200W/m^2$ respectively. The panel position relocated diagrams of conventional and proposed methods are illustrated in Fig. 3(a-d). Multiple insolation results in different row currents, this pattern exhibits two different row currents with three power peaks for conventional TCT pattern. The calculation of row currents for TCT shade patterns shown in Fig. 4(a) is explained as follows: In this case, the last five rows of the panel I_{R5}, I_{R6}, I_{R7}, I_{R8}, I_{R9} is subjected to an irradiance of $900W/m^2$; wherein, the rows I_{R1}, I_{R2} and I_{R3}, I_{R4} receives an irradiance of $200W/m^2$, $600W/m^2$ and $400W/m^2$ contributing a current of $8.1I_m$,$6.1I_m$ and $5.7I_m$ respectively. Here the maximum current limit of each panel considered is $0.9I_m$. For better understanding, the row currents estimated for the TCT method is expressed as follows: Similarly, the row currents calculated for shade dispersed pattern using proposed method is expressed as follows:

$$\left.\begin{aligned}
I_{R1} &= (1*(0.2*I_m))+(2*(0.6*I_m)) \\
&\quad +(7*(0.9*I_m)) = 7.71I_m \\
I_{R1} &= I_{R2} \\
I_{R3} &= (2*(0.2*I_m))+(7*(0.9*I_m) \\
&\quad +(2*(0.4*I_m)) = 7.5I_m \\
I_{R3} &= I_{R4} \\
I_{R5} &= (9*(0.9*I_m)) = 8.1I_m \\
I_{R5} &= I_{R6,7,8,9}
\end{aligned}\right\} \qquad (1)$$

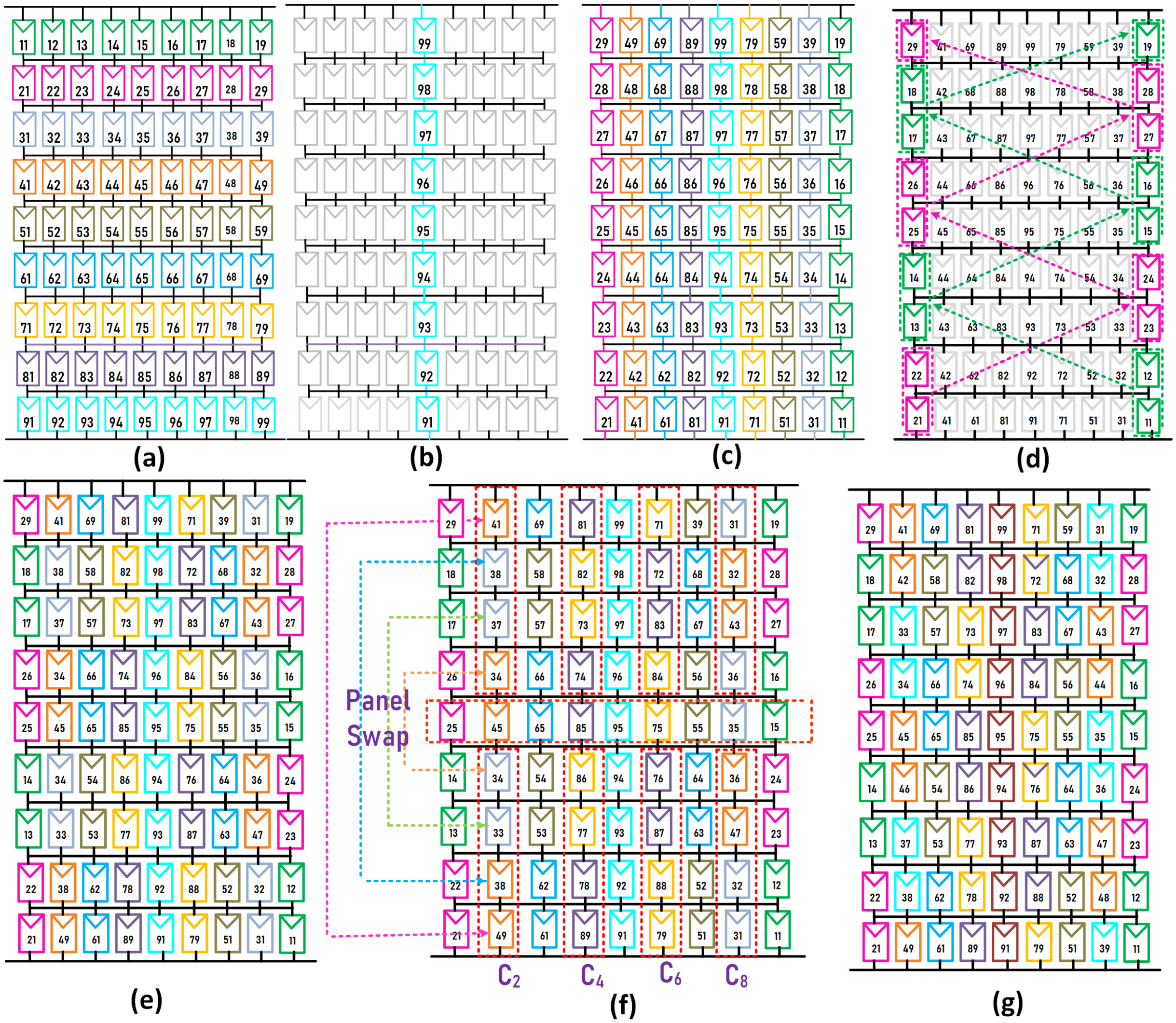


Fig. 2: Reconfiguration procedure of twisted Two Step arrangement (a) TCT connected PV array, (b & c) Row to column shift, (d & e) Upward stream panel positioning,(f) Flip-Flop Panel positioning, (g) Final reconfigured Matrix

Even though the TCT produced only two bypasses, the difference between the global and local power peak is quiet higher when compared to the proposed technique. The PV arrangements before and after panel repositioning is illustrated in Fig. 3(a-d). The row current calculation pertinene to the methods are provided elaborately in Table 1. The analysis indicates that proposed method has a minimum number of 4 bypasses when compared to SUD. Further, the power generated by the proposed approach is $60.3 V_m I_m$ which is the highest among methods. Thus, the findings of row current analysis have strengthened our conviction that the proposed technique is highly efficient in relocating panels completely.

Further, to validate the observations made in Table 1, the I-V and P-V curves of TRC shade pattern for all the four methods are plotted and presented in Fig. 6(a and b).The maximum power attained with TCT, SUD., OP. SUD. and the proposed method are 4620W, 5032W, 5103W, and 5200W, respectively. Further, the curves obtained with the proposed technique is smoother with a lesser number of peaks. Thus, the findings from characteristics analysis offer a piece of unprecedented vital evidence for the usefulness of the proposed technique.

B. Shade Pattern 2: Top Left Corner shade

In this shade pattern, 16 cells residing in the top left portion of a 9x9 PV array comprising R_1, R_2, R_3, R_4 is exposed to the irradiation of $100W/m^2$, $200W/m^2$, $300W/m^2$, $500W/m^2$ and $900W/m^2$ respectively. Fig. 4 (a-d) illustrates the PV array before and after shade dispersion by various methodologies. The row current analysis of all the methods for shading pattern 2 is tabulated in Table 2. It is observed that the minimum current and maximum power attained with the proposed method is $6.7 I_m$ and $60.3 V_m I_m$, which is significantly higher than other existing peer techniques regardless of the intensity of the shade. Further, the number of bypasses that occurred with the proposed technique is 5, which is notably lesser than SUD. methods. Fundamentally, the number of bypasses decides the number of peaks in the power curve , which is shown in Fig. 6 (c and d); an essential factor defines the efficiency of the array reconfiguration techniques. The highest power of 5097 W with lesser number of power peaks picturize the importance of the proposed technique in solving partial shading issue.

C. Shade Pattern 3: Bottom Right Corner shade pattern

As shown in Fig. 5(a), a 4x4 subarray residing in the right corner portion of a 9x9 PV array comprising R_6, R_7, R_8, R_9 receives an irradiation of $400W/m^2$ and $600W/m^2$ respectively. The shade dispersion obtained with SUD., OP. SUD. is shown in Fig. 5(b and c). Similar to the previous shade cases, the row current and P-V and I-V characteristics-based analysis are performed for this shade pattern. The findings from row current analysis given in Table 3 confirm once again the proposed method provided an unrivalled performance by providing the highest power of $63.9V_mI_m$ and a minimum number of bypasses against other finest techniques compared.Eventhough the performance of OP. SUD. is equally good for this shade case, the method complexity of proposed technique is far lesser than OP. SUD. method.

IV. PERFORMANCE ANALYSIS

Performance metrics analysis underline the progress achieved with the proposed methodology and illuminate the path ahead. Many factors that impact the energy production of a solar PV includes Fill Factor (FF), % Power Loss, Mismatch Loss (MMLoss), Capacity Factor (CF), Capture Loss (CL), Execution Ratio (ER). But without a strong understanding of these factors, arriving at an accurate estimate can be challenging. Hence a precise estimation of essential parameters in evaluating the performance of the solar PV is presented in this section. The performance analysis is performed on methodologies, including TCT, Su Do Ku (SUD), Optimal Su Do Ku (OP. SUD.), and proposed method

Fill Factor(FF): The most prevalent measurement of solar performance growth is Fill Factor. It is estimated by comparing maximum power extracted form solar PV to the product of voltage and current obtained during open and short circuit conditions. FF is expressed as follows

$$FF = \frac{P_{max}}{V_{oc} * I_{sc}} \tag{2}$$

Power Loss: Power loss is a primary component in evaluating the conversion capability of a solar cell. It is the dividing the power difference attained at STCs and PSCs by Maximum Power Point conquered at STC.

$$\%Powerloss = \frac{GMPP_{STC} - GMPP_{PSCs}}{GMPP_{STC}} \tag{3}$$

Mismatch Loss: When solar cells having different electrical characteristics are interconnected together, then it leads to mismatch loss. It can be estimated by finding the difference between the power extracted during STC and PSCs. Higher the mismatch loss, lesser the efficiency and power output of solar PV. It is defined as follows:

$$MismatchLoss = Power_{STC} - Power_{PSCs} \tag{4}$$

Execution ratio (ER): It is estimated by dividing the highest power attained at PSC (P_{PSC}) and power attained at STC (P_{STC}). As the ER increases, the efficacy of the solar cell also increases.

$$ER = \frac{(V_{MPP} * I_{MPP})_{PSC}}{(V_{MPP} * I_{MPP})_{STC}} \tag{5}$$

A. Analysis based on performance metrics

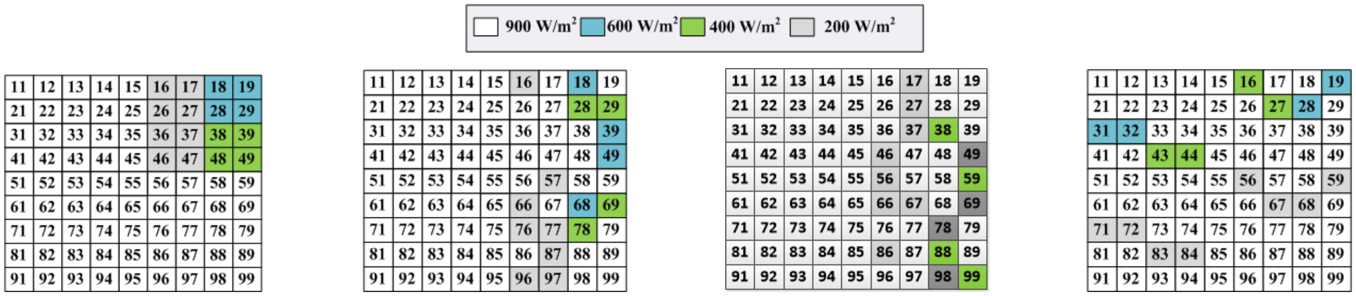
The effect of various metrics on the performance of the solar PV is studied by changing the shade pattern is explained in Table 4. Among the methodologies compared, the proposed shows the ultimate performance having the highest FF, % Power Loss, Mismatch Loss, CF, C_L and ER values. Measured and computed values of performances metrics are depicted in Fig. 7 (a-f) and the same in Table 4; wherein the proposed technique values is highlighted for better understanding. It is obvious from the results that the proposed method yields satisfied results compared to all techniques compared. Further, the discussion on estimated parameters, for various shade patterns indicate that the proposed technique has the potential in producing highest values for all the metrics considered for the study. Hence, it can be concluded that the performance of the proposed method is superior compared to existing techniques for all the shade cases considered. If sustained, stronger investment in machinery and equipment could underpin stronger productivity growth over the medium-term.

V. QUALITATIVE COMPARATIVE ANALYSIS

A qualitative comparative analysis on the existing and proposed method is performed by considering the following vital factors such as circuit arrangement, Number of reconfiguration steps, Number of bypasses, Number of Power peaks, Power generation capability and Revenue Generated respectively. The complete set of data pertinent to the analysis is provided in Table 5, and the same is illustrated in Fig. 9 for better understanding. The diagram can be understood by the fact that the larger the area covered, the higher the drawback of the method. For instance, the TCT method in Fig. 8(a), covers the largest wheel area; hence the method performance level is poorer compared to other methods; whereas only a lesser portion is covered in case of the proposed method and it is shown in Fig. 9(d). Thus, it can be concluded that the proposed method outperformed all methods in every case considered for the analysis.

VI. EXPERIMENTAL ANALYSIS OF TWISTED TWO STEP ARRANGEMENT IN MITIGATING PARTIAL SHADING EFFECT

Rigorous tests, performance analysis conducted so far indicate that twisted two step technique achieves the highest shade dispersion among all with highest row current difference minimization. However, it would be conducive evaluating the method performance in real-time before final implementation. Therefore, experiments are conducted in actual environmental condition at Vellore Institute of Technology, India (79.1559 longitude East, 12.9692 latitude North) during summer month of April 2021. Two typical TCT connected photovoltaic arrays with 9 panels of 20W each are installed on the photovoltaic scaffolds. These panels are operated at a maximum irradiance of 900W/m2 as per IEC 60904 for experimentation. The power attenuation rate of the 3x3 PV array under the partial shading is studied; wherein the shade is artificially created using polythene sheet with commercial grade thickness of 200 micron. Before experimentation, the impact of polythene sheet on the PV panel performance is analysed by observing the amount of current generated from the panel. Upon full irradiance i.e., zero shade, it generates 1.284A; while current generated by the panel drops by 10.9% i.e., 1.144A with an artificial shade of a polythene sheet. Likewise, when the shading intensity increases, the current generation capacity of panel reduces

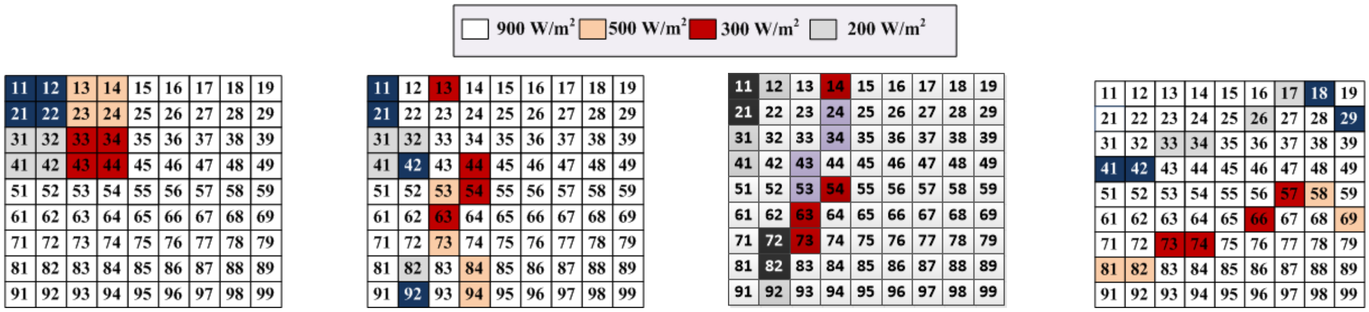


(a) (b) (c) (d)

Fig. 4: Top Right Corner (TRC) pattern: a) TCT [12] , (b) SUD. [6], (c) OP. SUD, [12] (d) Proposed method

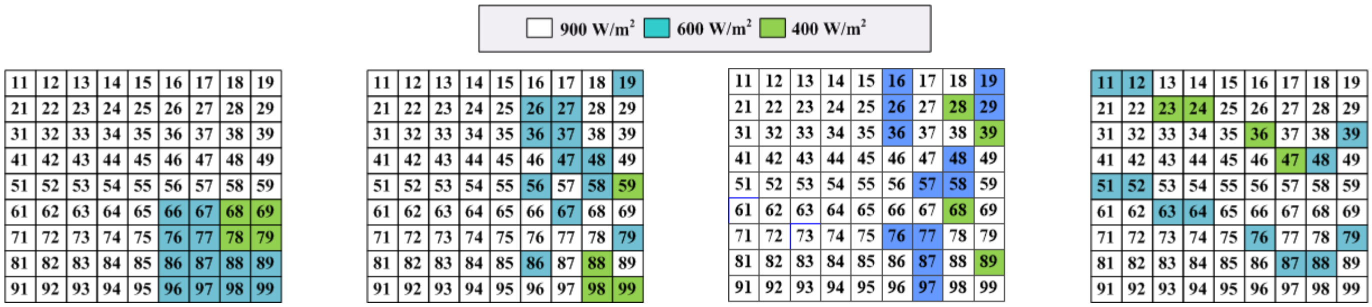
TABLE I: Row current calculations of Top Right Corner (TRC) type for existing TCT, SUD., OP. SUD. and proposed method

TCT [12]				SUD.[19]				OP. SUD. [20]				PROP.			
	Current I_m (I_A)	Voltage V_m (V_A)	Power $V_m I_m$ (P_A)		Current I_m (I_A)	Voltage V_m (V_A)	Power $V_m I_m$ (P_A)		Current I_m (I_A)	Voltage V_m (V_A)	Power $V_m I_m$ (P_A)		Current I_m (I_A)	Voltage V_m (V_A)	Power $V_m I_m$ (P_A)
IR_3	$5.7I_m$	$9V_m$	$51.3P_A$	IR_7	$6.2I_m$	$9V_m$	$55.8P_A$	IR_6	$6.4I_m$	$9V_m$	$57.6P_A$	IR_5	$6.7I_m$	$9V_m$	$60.3P_A$
IR_4	$5.7I_m$	-	-	IR_6	$6.6I_m$	$8V_m$	$52.8P_A$	IR_3	$6.9I_m$	$8V_m$	$55.2P_A$	IR_6	$6.7I_m$	-	-
IR_1	$6.1I_m$	$7V_m$	$42.7P_A$	IR_9	$6.7I_m$	$7V_m$	$46.9P_A$	IR_5	$7.1I_m$	-	-	IR_7	$6.7I_m$	-	-
IR_4	$5.7I_m$	-	-	IR_1	$7.1I_m$	$6V_m$	$42.6P_A$	IR_6	$7.1I_m$	-	-	IR_8	$6.7I_m$	-	-
IR_5	$8.1I_m$	$5V_m$	$40.5P_A$	IR_2	$7.1I_m$	-	-	IR_8	$7.1I_m$	-	-	IR_4	$7.1I_m$	$5V_m$	$35.5P_A$
IR_6	$8.1I_m$	-	-	IR_5	$7.4I_m$	$4V_m$	$29.6P_A$	IR_4	$7.3I_m$	$4V_m$	$29.2P_A$	IR_1	$7.3I_m$	$4V_m$	$29.2P_A$
IR_7	$8.1I_m$	-	-	IR_8	$7.4I_m$	-	-	IR_1	$7.4I_m$	$3V_m$	$22.2P_A$	IR_2	$7.3I_m$	-	-
IR_8	$8.1I_m$	-	-	IR_3	$7.8I_m$	$2V_m$	$15.6P_A$	IR_9	$7.4I_m$	-	-	IR_3	$7.5I_m$	$2V_m$	$15P_A$
IR_9	$8.1I_m$	-	-	IR_4	$7.8I_m$	-	-	IR_7	$7.6I_m$	$1V_m$	$7.6P_A$	IR_9	$8.1I_m$	$1V_m$	$8.1P_A$



(a) (b) (c) (d)

Fig. 5: Top Left Corner (TLC) pattern TCT [18] , (b) SUD. [19], (c) OP. SUD [20],(d) Proposed method



(a) (b) (c) (d)

Fig. 6: Bottom Right Corner (BRC) pattern: a) TCT [18] , (b) SUD. [19], (c) OP. SUD [20], (d) Proposed method.

proportionately. For instance, when covered with 10 layers the current generation capacity falls up to 60.90%.

For authenticity, the recordings are carried out at the same time instant. Moreover, for cross verification of the study Pyrometer

TABLE II: Row current calculations of Top Left Corner (TLC) type for existing TCT, SUD., OP. SUD. and proposed method

TCT [12]				SUD.[6]				OP. SUD. [12]				PROP.			
	Current	Voltage	Power		Current	Voltage	Power		Current	Voltage	Power		Current	Voltage	Power
	I_m (I_A)	V_m (V_A)	$V_m I_m$ (P_A)		I_m (I_A)	V_m (V_A)	$V_m I_m$ (P_A)		I_m (I_A)	V_m (V_A)	$V_m I_m$ (P_A)		I_m (I_A)	V_m (V_A)	$V_m I_m$ (P_A)
IR_3	$5.5I_m$	$9V_m$	$49.5P_A$	IR_4	$6I_m$	$9V_m$	$54P_A$	IR_1	$6I_m$	$9V_m$	$54P_A$	IR_4	$6.5I_m$	$9V_m$	$58.5P_A$
IR_4	$5.5I_m$	-	-	IR_1	$6.7I_m$	$8V_m$	$53.6P_A$	IR_7	$6.7I_m$	$8V_m$	$53.6P_A$	IR_1	$6.6I_m$	$8V_m$	$52.8P_A$
IR_1	$5.7I_m$	$7V_m$	$39.9P_A$	IR_3	$6.7I_m$	-	-	IR_2	$6.9I_m$	$7V_m$	$48.3P_A$	IR_2	$6.6I_m$	-	-
IR_2	$5.7I_m$	-	-	IR_9	$6.9I_m$	$6V_m$	$41.4P_A$	IR_3	$7I_m$	$6V_m$	$42P_A$	IR_3	$6.7I_m$	$6V_m$	$40.2P_A$
IR_5	$8.1I_m$	$5V_m$	$40.5P_A$	IR_8	$7I_m$	$5V_m$	$35P_A$	IR_4	$7I_m$	-	-	IR_7	$6.9I_m$	$5V_m$	$34.5P_A$
IR_6	$8.1I_m$	-	-	IR_5	$7.1I_m$	$4V_m$	$28.4P_A$	IR_5	$7.1I_m$	$4V_m$	$28.4P_A$	IR_5	$7.1I_m$	$4V_m$	$28.4P_A$
IR_7	$8.1I_m$	-	-	IR_2	$7.3I_m$	$3V_m$	$21.9P_A$	IR_8	$7.3I_m$	$3V_m$	$21.9P_A$	IR_6	$7.1I_m$	-	-
IR_8	$8.1I_m$	-	-	IR_6	$7.5I_m$	$2V_m$	$15P_A$	IR_9	$7.4I_m$	$2V_m$	$14.8P_A$	IR_8	$7.3I_m$	$2V_m$	$14.6P_A$
IR_9	$8.1I_m$	-	-	IR_7	$7.7I_m$	$1V_m$	$7.7P_A$	IR_6	$7.8I_m$	$1V_m$	$7.5I_m$	IR_9	$8.1I_m$	$1V_m$	$8.1P_A$

TABLE III: Row current calculations of Bottom Right Corner (BRC) type for existing TCT, SUD., OP. SUD. and proposed method

TCT[12]				SUD.[6]				OP. SUD. [12]				Proposed			
	Current	Voltage	Power		Current	Voltage	Power		Current	Voltage	Power		Current	Voltage	Power
	I_m (I_A)	V_m (V_A)	$V_m I_m$ (P_A)		I_m (I_A)	V_m (V_A)	$V_m I_m$ (P_A)		I_m (I_A)	V_m (V_A)	$V_m I_m$ (P_A)		I_m (I_A)	V_m (V_A)	$V_m I_m$ (P_A)
IR_6	$6.5I_m$	$9V_m$	$58.5P_A$	IR_5	$7I_m$	$9V_m$	$63P_A$	IR_2	$7I_m$	$9V_m$	$63P_A$	IR_2	$7.1I_m$	$9V_m$	$63.9P_A$
IR_7	$6.5I_m$	-	-	IR_9	$7.1I_m$	$8V_m$	$56.8P_A$	IR_3	$7.3I_m$	$8V_m$	$58.4P_A$	IR_3	$7.3I_m$	$8V_m$	$58.4P_A$
IR_8	$6.9I_m$	$7V_m$	$48.3P_A$	IR_8	$7.3I_m$	$7V_m$	$51.1P_A$	IR_8	$7.3I_m$	-	-	IR_4	$7.3I_m$	-	-
IR_9	$6.9I_m$	-	-	IR_2	$7.5I_m$	$6V_m$	$45P_A$	IR_1	$7.5I_m$	$6V_m$	$45P_A$	IR_1	$7.5I_m$	$6V_m$	$45P_A$
IR_1	$8.1I_m$	$5V_m$	$40.5P_A$	IR_3	$7.5I_m$	-	-	IR_5	$7.5I_m$	-	-	IR_5	$7.5I_m$	-	-
IR_2	$8.1I_m$	-	-	IR_4	$7.5I_m$	-	-	IR_7	$7.5I_m$	-	-	IR_6	$7.5I_m$	-	-
IR_3	$8.1I_m$	-	-	IR_1	$7.8I_m$	$3V_m$	$23.4P_A$	IR_6	$7.6I_m$	$3V_m$	$22.8P_A$	IR_7	$7.5I_m$	-	-
IR_4	$8.1I_m$	-	-	IR_6	$7.8I_m$	-	-	IR_4	$7.8I_m$	$2V_m$	$15.P_A$	IR_8	$7.5I_m$	-	-
IR_5	$8.1I_m$	-	-	IR_7	$7.8I_m$	-	-	IR_9	$7.8I_m$	-	-	IR_9	$8.1I_m$	$1V_m$	$8.1P_A$

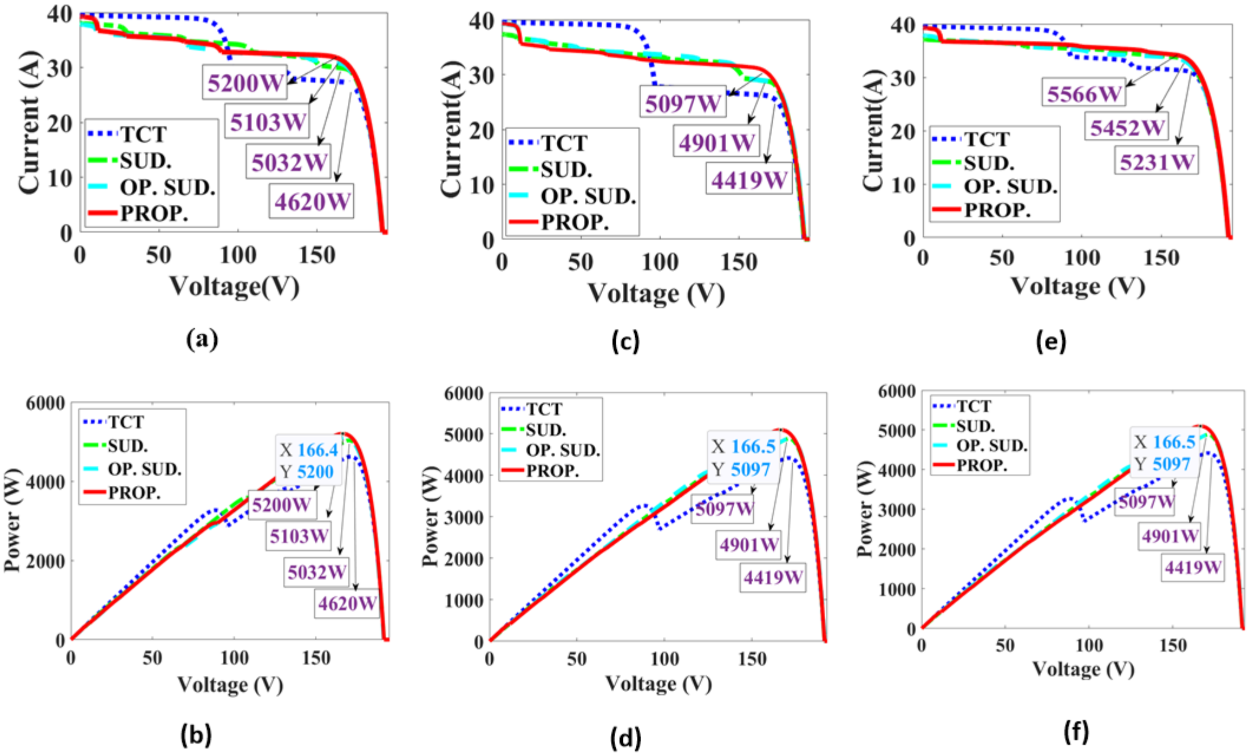
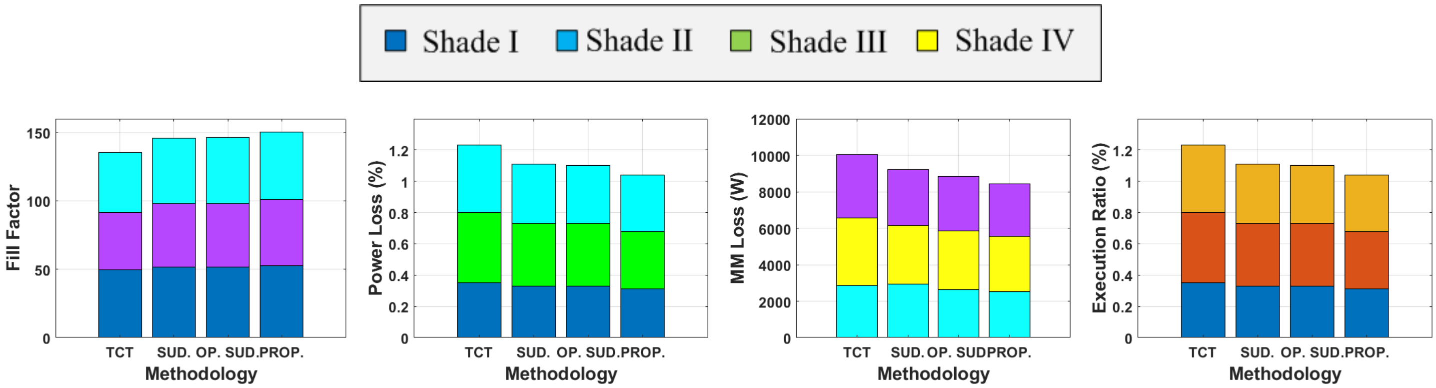
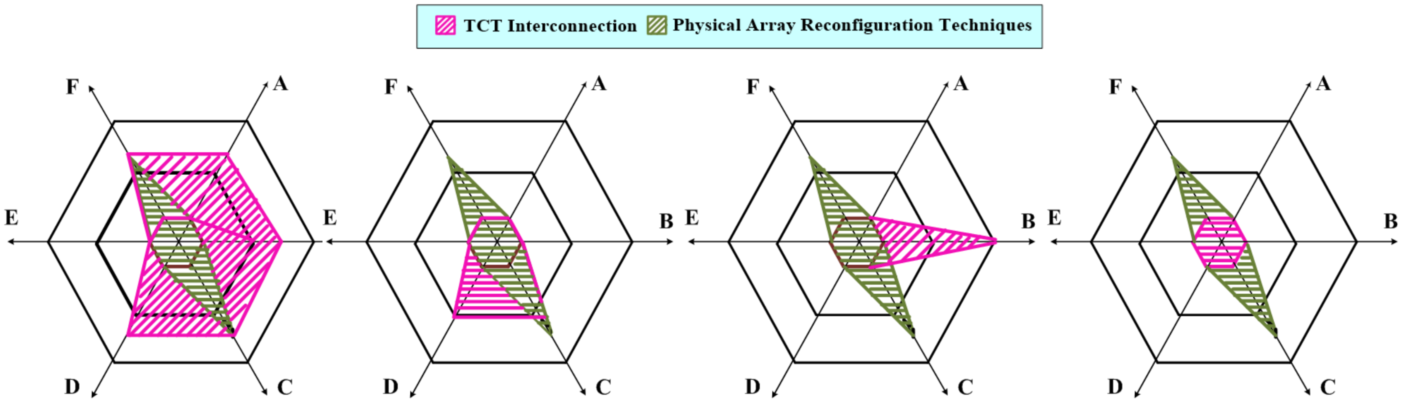


Fig. 7: I-V and P-V characetristics of (i) TRC(a&b),TLC (c&d),BRC (e&f),



(a) (b) (c) (d)

Fig. 8: Performance analysis based on (a) Fill Factor, (b) Power Loss, (c) Mismatch Loss (MM Loss), (d) Execution Ratio.



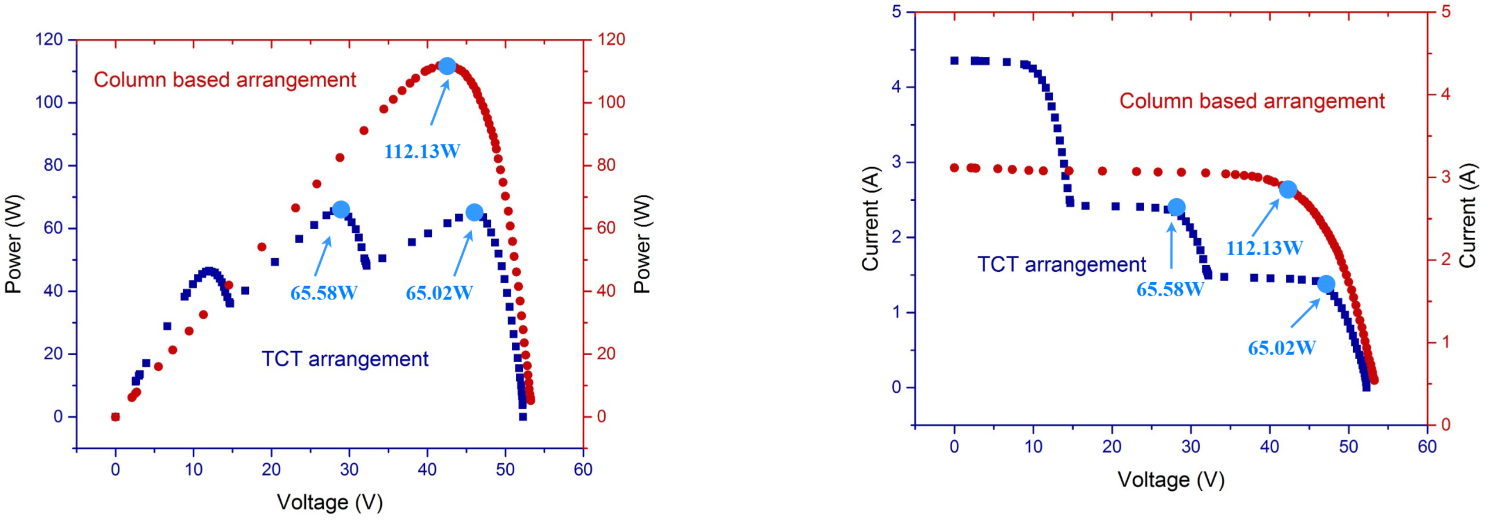
(a) (b) (c) (d)

Fig. 9: Qualitative comparison of proposed method with Existing methods (a) TCT (b) Su Do Ku(c) Optimal Su Do Ku (d)Proposed technique.(A-Circuit Arrangement, B- Reconfiguration steps, C-No. of Bypasses, D- No. of Power Peaks, E- Power Generation Capability, F-Revenue Generated).

(a) (b)

Fig. 10: Hardware setup (a) Conventional TCT arrangement, (b) Reconfigured arrangement using proposed method.

as well as solar power meter (PVW 210) is used for continuous and instantaneous irradiance measurements. The panel used for



(a) (b)

Fig. 11: Characteristics of TCT and proposed method (a) P-V and (b) I-V characteristics.

TABLE IV: Qualitative comparison of proposed method with Existing methods (a) TCT (b) Su Do Ku(c) Optimal Su Do Ku (d)Proposed technique.

Parameters	TCT	SUD.	OP. SUD.	PROP.
Circuit Arrangement Quality	✓	✓	✓	✓
No. Reconfiguration Steps	X	✓	X	✓
No. Of bypasses	X	X	✓	✓
No. of Power Peaks	X	X	✓	✓
Power Generation Capacity	X	✓	✓	✓
Revenue Generated	X	✓	✓	✓

TCT connection is a WAAREE polycrystalline of 20 W. In order to avoid any discrepancy in measurement and avoid mismatch during the experimental study, power output of both the setup are recorded using high precision IV curve tracer (solar-4000 analyser) and multimeter (Fluke 289). The test arrangement consists of 2 TCT connected PV array of size 3x3. Keeping one shaded TCT connection as reference the other is reconfigured using proposed rearrangement. The shade applied is a conventional short-wide shade case with last rows shaded with 5 and 10 layers of polythene sheets respectively; while first row of the panel is left unshaded. The shade selection imitates dust accumulation; since the modules are inclined such that the lower row of panels receives highest deposition. The experimental arrangement of shaded panels and its respective dispersion using proposed reconfiguration strategy is clearly illustrated in Fig. 9(a) and Fig. 9(b) For easy understanding, the highest power attained under both cases are highlighted in graphs as shown in Fig. 10(a) and Fig. 10(b); wherein the fixed TCT and reconfigured setup generated a power of 65.58 W and 111.083 W respectively. From the obtained GMPP values, it is apparent that the reconfigured soiled panels delivered more power with a significant power difference of 45.503W.

Moreover, reconfigured setup produced a smoother I-V and P-V curve with higher MPP voltage and current. Furthermore, the fixed shade set has more number of LMPPs while the proposed column method produced zero LMPP for same intensity of shade; providing a solid evidence for the finest performance of proposed technique in dispersing the shade. Thus, combined effect of the above-mentioned reasons paved the way for considering the reconfiguration technique as one of the prominent solution for extracting higher power from a shaded solar PV.

VII. CONCLUSION

To be an effective shade dispersion technique, the ability to reduce the power loss, minimizing the row current difference and economical is critical. Many existing array reconfiguration techniques are efficient at the cost of less power generating capability and the high complexity in implementation. But starting from shade pattern 1 until 4, the power generation capability of the proposed method is high when compared to the existing methods such as TCT, SUD., and OP. SUD.. The comparative results are highly substantial and also provides an in-depth explanation about the adverse effects of shades in the performance of PV. The highlights of the proposed method are listed below

- For shade pattern 1, the proposed approach outperformed all the benchmarking techniques and sustained its first with the position with significant power enhancement. The output power of the proposed method is 11.3%, 3.2%, 2.3 % higher compared to TCT, SUD., OP. SUD., respectively.
- For shade 2 and 3 the power enhancement percentage of proposed technique with respect to TCT, SUD., and OP. SUD., are 13.3%, 4.2%, 2.0% and 8.0% 5.0%, 0% and 11.2% 1.4%, 1.4% respectively Thus, an incomparable sequence of uninterrupted solid power generation growth has been recorded with the proposed twisted technique for all 4 shade cases.

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