Power Enhancement in Partial Shaded Photovoltaic System Using Spiral Pattern Array Configuration Scheme

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ABSTRACT Partial shading causes mismatch losses in the solar PV system. In the PV array, the power output from the healthy PV modules is gone in vain due to the mismatch losses. The PV array construction with the high resistivity to the mismatch loss generation is the progressing research work in the research field. In this work, a new kind of array configuration scheme is framed for the PV system for overcoming the effect of partial shading. The proposed array configuration has a high resistivity to the mismatch loss generation over the other conventional array configuration methods. The array configuration is framed in a pattern that is similar to the spiral step pattern. Each row of the PV array is constructed with the PV modules from each row of the conventional Total Cross Tied configuration with the optimized distance. This row construction allows the system to uniformly disperses the partial shading over the PV array. The simulation analysis is carried out by applying various shading patterns in MATLAB/Simulink®. The performance of the proposed array configuration is also analyzed in the experimental setup and the results were presented.

INDEX TERMS Array configuration, mismatch loss, maximum power point (MPP), partial shading, PV array reconfiguration, total cross tied (TCT), spiral pattern, sudoku pattern.

I. INTRODUCTION

Photovoltaic (PV) system accelerates its development in the global energy market in recent years because of its eco-friendly characteristics, reliability, and renewability.

Population growth and the depletion of fossil fuels paves the way for utilizing non-conventional energy resources for the world's energy demand. The feasibility of solar energy attracts the energy market for utilizing it. The solar photovoltaic (PV) system is firstly introduced in 1954 by the Bells Laboratory in the United States. The first PV cell is fabricated with the impurities of silicon which directly converts

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the sunlight into electricity by the photovoltaic effect. The efficiency of the first PV cell is around 4% that is developed to 24% in recent years by various researches [1]–[8]. There are various factors such as partial shading, hotspots, diode failure, etc., were affecting the efficiency of the solar PV system. Partial shading is the most common issue in the PV system which cannot be predicted and avoided. This partial shading causes mismatch losses in the PV system, which vainer the power generation of unshaded healthy PV modules [9]–[14]. Many research works approach the various ways of mitigating the consequences of partial shading. Earlier the bypass diode method is been introduced in [13], [15], [16] which extracts the power output of the unshaded healthy cells at the load terminal by bypassing the faulted or shaded or mismatch loss
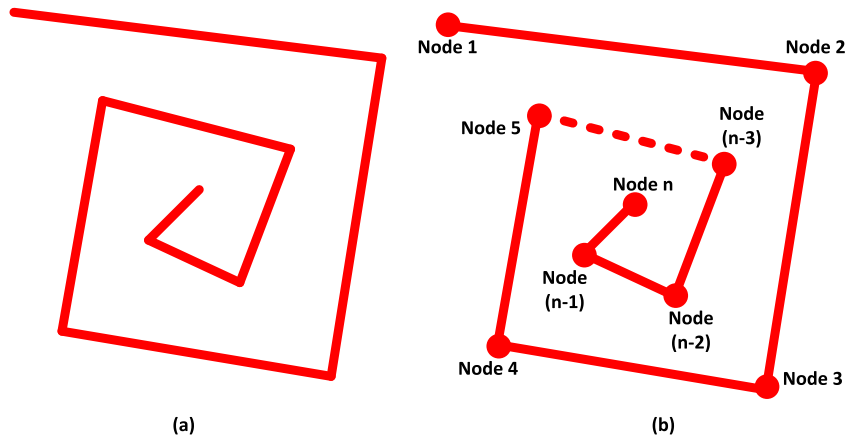
FIGURE 1. (a) Actual spiral pattern (b) node creation (row creation) of spiral pattern.

FIGURE 2. Row creation of spiral configuration scheme.

causing PV cells. However, this approach enhances the power output of the PV system, it failed to extract maximum power due to the isolation of shaded or faulted modules.

The maximum power point is the point at where the system can generate the maximum power at that instant. The maximum power point can be obtained from the P-V characteristic curves. Under the partial shading condition, the P-V characteristic curve had more than one peak point. These points are called local maximum power points. The objective of the maximum power point tracking method is to track the maximum power point under the many local maximum power points. Based on the maximum power transfer theorem of an electrical circuit, Maximum Power Point Tracking (MPPT) [17]–[22] based converter topology is been used for extracting maximum power. Two conventional MPPT algorithms such as perturb and observe (P&O) and incremental conductance algorithm (InC) been used earlier in the PV system which alters the operating point forward and backward accords to the power generation. Under the partial shading conditions, the PV system operates with many local maximum power points, which restricts the MPPT algo-

rithms in achieving global MPPT. For enhancing the performance of the MPPT technique, the optimization algorithms such as neural network (NN), Particle Swarm Optimization (PSO), Ant Colony optimization, etc., were incorporated with it. MPPT methods with optimization algorithms have more efficiency than conventional methods. These techniques also failed to achieve the maximum power point in some cases. Later, the power output is been enhanced by altering the physical interconnection between the PV modules. In earlier days, the array connection is formed by the series, parallel and series-parallel configurations. The power enhancement is achieved by changing array configurations.

In [23]–[26], Total Cross Tied (TCT) configuration is proposed which combines the series-parallel connection. This TCT array configuration highly reduces the effect of partial shading. The performance of TCT configuration is further enhanced by the new array configuration such as Bridge Linked (BL), Honey Comb (HC), Sudoku Puzzle Pattern. Bridge-Linked array configuration is achieved by creating a link with the PV modules in nearby columns for creating a PV row with distinct PV modules. Likewise, the honeycomb array configuration is achieved by creating the link between the modules as the honeycomb structure. The Sudoku puzzle pattern creates each row of PV array with distinct PV modules from the normal TCT configuration by following the rules of the sudoku puzzle game. This never allows the repeated PV modules in the row creation of sudoku from any rows of conventional TCT. These array configurations have higher efficiency than the conventional array formation. The objective of the evolution of these array configurations is to disperse the shading uniformly over the PV array. The TCT configuration can disperse the partial shading more than the series-parallel array configurations, whereas the sudoku is further superior to the TCT configuration. The objective of this proposed work is to enhance the power output more than the all-conventional array configurations.

For improving the shade dispersion capability of the PV array, a new approach of reconfiguration method is been
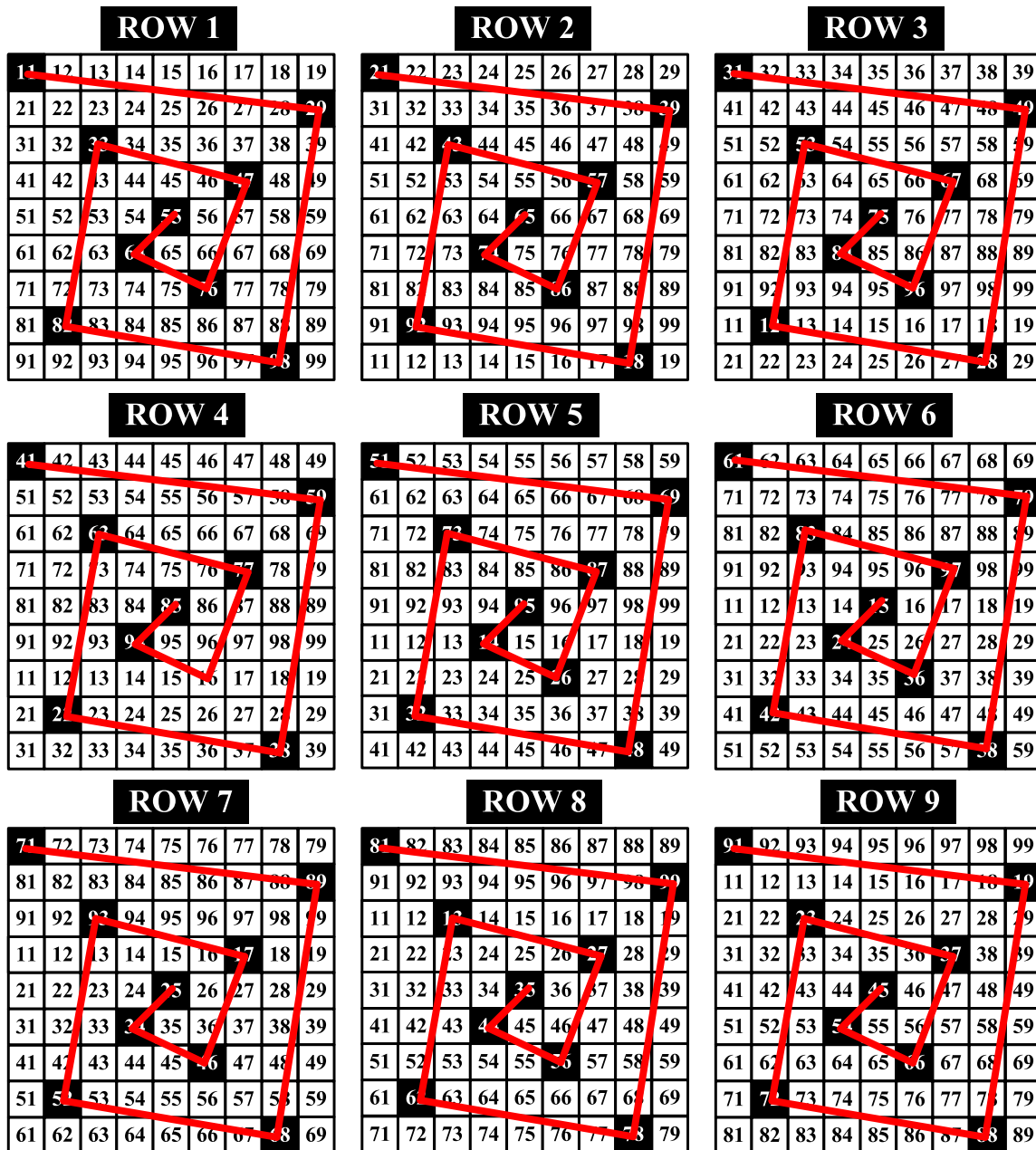
FIGURE 3. Spiral propagation (Row creation) for 9 × 9 PV array.

proposed. The reconfiguration technique rearranges the connection between the PV modules based on the power generation. In [27] the entire PV array is been splitter into two parts such as fixed and adaptive and connected via switching matrix circuit. Based on the current generation a factor called Current Variation Index (CVI) is measured. The reconfiguration controller frames the reconfiguration pattern based on the CVI and executing it through the switching matrix circuit. The data measurements, CVI calculation takes more time in achieving the reconfiguration time. For overcoming these issues, a new kind of reconfiguration algorithm is proposed in [29], where also the PV array is split into two parts as male

and female parts. The current generation of each row of male and female parts is measured by the current sensing units and the controller couples the male part row with the female part row through the switching circuit. The coupling is obtained by a maximum current generating row of the male part is coupled with the minimum current generating row of the female part, which allows all the PV rows to operate with the even current generation. The same method is proposed in [30], where the switching operation is done in two steps. In the first step, the PV system is allowed to operate in its actual array size and when it is affected by the partial shading or any faults, the system will be switched into the second step. This method

achieves maximum power generation which is more than the couple matching method. However, the usage of switches and electrical measurements increases the complexity and the implementation cost. Also, the time period between the establishment of the reconfiguration pattern, a blackout will be in the PV system where the entire PV array is isolated from the load. This also causes power loss in the PV system.

In [31], the current injection method is been proposed and validated in various kinds of array topologies. A current source is a connected parallel with each row of the PV array. When the current generation of the row is been affected by the partial shading then the current source injects the reduced current to the row and made all the PV rows operate with the even current generation. However, the current source, reduced current measurement, converter across each current source increases the cost of the system, also it requires frequent maintenance to avoid the hazards.

In this proposed work, a new kind of static array configuration scheme is proposed. Like the sudoku puzzle pattern, this method follows the spiral pattern for creating the PV rows. The sudoku pattern acquires the rows with the nearby panel at the diagonal position, so that it will be vainer when the shading occurs diagonally or the shading occurs on any two nearby rows. For the performance-enhanced PV array, the system needs a method to generate maximum power when it experiences any kind of shading pattern. This proposed spiral array configuration method achieves the objective of generating maximum power by creating the even current generating rows. The row creation of the proposed method and the mathematical formulation are derived mathematically in this work.

Dynamic array reconfiguration techniques are changing the interconnection between the PV modules to equally disperse the effect of shading. Normal array configuration limits the shade dispersing rate of this technique for some shading patterns [15], [16], Where the proposed array configuration has high resistivity to the partial shading effect. The reconfiguration technique requires more sensors, where the reconfiguration method used in this work requires fewer number sensors. In this work, an L-shaped array configuration with a dynamic reconfiguration method is proposed for uniformly dispersing all kinds of shading patterns. The proposed array configuration can disperse the maximum amount of shading in the PV array. The remaining shading effect in the PV array can be completely or nearly nullified by the dynamic reconfiguration algorithm. This array reconfiguration algorithm does not require more data or sensors like the existing electrical array reconfiguration techniques. The current measurement is the only required data for measuring the shade dispersion rate and performing the reconfiguration algorithm. A switching circuit is incorporated with the PV array is executing the reconfiguration pattern which is generated by the algorithm. The work is simulated in MATLAB/Simulink© and implemented in the hardware. The performance, shading dispersion rate, mismatch loss analysis, and the percentage of

error of the proposed work have been compared and analyzed with the other configurations such as TCT, Sudoku, and FPP.

The rest of the paper is organized as follows. Section II presents the description of the proposed array configuration and its structure. Section III presents the overview of the simulation, test models of the proposed configuration, the overall simulation flowchart, and the results obtained from the simulation. Section IV summarizes and concludes the paper.

II. DESCRIPTION AND MATHEMATICAL FORMULATION OF PROPOSED CONFIGURATION

The ultimate objective of the proposed array configuration is creating PV rows with the PV modules from the distinct rows of conventional TCT. The spiral pattern creates the nodes, with the possible long distance from the distinct PV rows. It never chooses more than one node from a single PV row of conventional TCT. where

$$
\begin{aligned}
if \quad p > m \quad then \quad p = p - m \\
if \quad q > n \quad then \quad q = q - n
\end{aligned}
$$

A proper mathematical expression is framed for the spiral pattern propagation for the mXn PV array. The mathematical expression is given in the following equation (1), as shown at the bottom of the next page.

The expression frames the spiral pattern in the row creation. PV_{ROWi} representing the PV rows of the spiral pattern, i varies from 1 to the number of rows. Ppq is the panel position i.e., the placement of modules in which row and which column, and this can be found by the expression. If the expression gives the value for pq as 23, then it represents the PV module in the 2nd row of the 3rd column will be chosen in the new row formation. If p-value is greater than the number of rows, then the p-value will be subtracted from the number of row(m), and the new p value will be considered as the module number to be selected. Likewise, if the q value is greater than the number of columns(n), then the p-value will be subtracted from the number of columns(n), and the new q value will be considered as the module number to be selected.

The node creation (row creation) is achieved by the equation as follows

Node1 will be $i(n - (n - 1))$

Node 2 will be $(i + 1)n$

Node 3 will be $(i + (n - 1))(n - 1)$

Node 4 will be $(i + (n - 2))(n - (n - 2))$

And the node 'n' will be $(i + (\frac{n-1}{2})(n - (n - (\frac{n+1}{2}))))$

The actual spiral pattern and row creation in the first row are shown in Figure.2. The node propagation follows the mathematical expression and it propagates up to n as shown in figure.2. The node creation for 1st row is calculated and given in Table 1. The PV system with a 9 × 9 array size is considered for the calculation of row creation. The values of i for the 9 × 9 PV array will be varied from 1 to 9. For the first row, the value of i will be 1 and for the ninth row, the value of

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

FIGURE 4. Spiral configuration pattern for 9 × 9 PV array.

FIGURE 5. Equivalent circuit of solar cell single diode model.

FIGURE 6. I-V and P-V characteristics under random shading pattern.

'i' will be 9. The values of n for this 9 × 9 array are 9, where n is the number of columns in the PV system. The pictorial representation of first-row creation is shown in figure.2.

For the 9 × 9 PV array, the row creation of the first row is explained in detail above. The row creation for the balance rows is given in Table 2. and its pictorial representation is shown in fig. The propagation is continued to the 9th node of the mathematical expression. The first row to the ninth row for the spiral pattern configuration scheme is calculated as shown in the table. For the 9 × 9 PV array, the value for the n is equal to 9 (i.e., the number of columns). The value of i is varied from 1 to the number of rows. For the first row, the i value will be 1, for the second row the i value will be 2 and i will be 9 for the ninth row. The entire row creation is achieved by the above values with the mathematical expression. The pictorial representation of each row is shown in figure.3. The final structure of the spiral pattern array configuration scheme is shown in figure.4.

III. RESULT AND DISCUSSIONS

The proposed work is validated in a 9 × 9 PV array which is designed in the MATLAB/Simulink® software as shown in figure 7. The work is also been validated in the experimental setup of a 4 × 4 PV array. The Simulink model of the PV module is designed in MATLAB by the single diode model of the PV cell. The mathematical expression of the single diode model of PV cell is shown in figure.5.

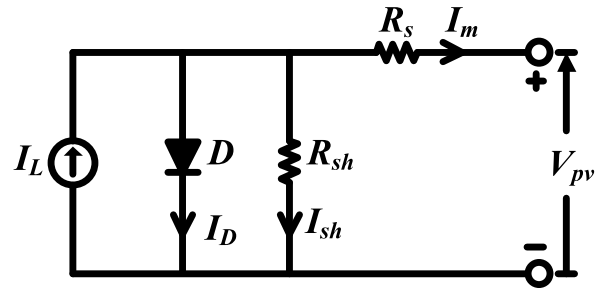An equivalent circuit of the PV cell has been constructed with a current source (Iph) connected by a shunt resistance (Rsh) as shown in Fig.1. There is n number of PV cells are connected in series and parallel to frame a PV module. The output current equation of the PV module can be written as,

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

where I_m is the maximum current generation of PV module, Vm is the maximum voltage generation of PV module, Iph is the photoelectric current, Isat is the saturation current, n is the no of PV cells connected in series, K is the Boltzmann's constant, R_s is the series resistance, R_{sh} is the shunt resistance, T is the temperature of PV module.

Based on the single diode model of PV cell, a 9 × 9 PV array is constructed in MATLAB/Simulink®. The simulation is been validated under the six-kind shading pattern such as random shading, diagonal shading, short and narrow shading, short and wide shading, long and narrow shading, and long and wide shading patterns. The specification of the PV module modeled in simulation and used in hardware setup is given in Table 3. A 10W PV module is used for the validation and analysis of the spiral pattern array configuration scheme. The six kinds of shading created in the PV system as shown in figure.8.

The uneven irradiation on the PV array surface causes mismatch loss in the PV system. PV modules in the PV array

$$PV_{ROW_i} = [P_{pq}] = [i(n-(n-1)) \quad (i+1)n \quad (i+(n-1))(n-1) \quad (i+(n-2))(n-(n-2))$$
$$(i+2)(n-(n-3)) \quad (i+3)(n-2) \quad (i+(n-3))(n-3) \quad (i+(n-4))(n-(n-4))$$
$$(i+4)(n-(n-5)) \quad \ldots\ldots\ldots\ldots \quad (i+\left(\frac{n-1}{2}\right)\left(n-\left(n-\left(\frac{n+1}{2}\right)\right)\right))] \qquad (1)$$

TABLE 1. First row creation of spiral pattern configuration.

FIRST ROW	MATHEMATICAL EXPRESSION	CALCULATION	MODULE NUMBER	MODULE TO BE PLACED
P11	$= i\big(n-(n-1)\big)$	= 1 (9-(9-1)) =1(9-8)	= 11	P11
P12	$= (i+1)n$	= (1+1) 9	= 29	P29
P13	$= \big(i+(n-1)\big)(n-1)$	= (1+(9-1)) (9-1)	= 98	P98
P14	$= \big(i+(n-2)\big)\big(n-(n-2)\big)$	= (1+(9-2)) (9-(9-2))	= 82	P82
P15	$= (i+2)\big(n-(n-3)\big)$	= (1+2) (9-(9-3)	= 33	P33
P16	$= (i+3)(n-2)$	= (1+3) (9-2)	= 47	P47
P17	$= \big(i+(n-3)\big)(n-3)$	= (1+(9-3)) (9-3)	= 76	P76
P18	$= \big(i+(n-4)\big)\big(n-(n-4)\big)$	= (1+(9-4)) (9-(9-4))	= 64	P64
P19	$= (i+4)\big(n-(n-5)\big)$	= (1+4) (9-(9-5))	= 55	P55
		For the row creation of first row i=1 and n=9		

TABLE 2. Spiral propagation and row creation for 9 × 9 PV array.

For 9X9 PV array, n=9 & i = 1 to 9		Pi n-(n-1)	Pi+1 n	Pi+(n-1) (n-1)	Pi+(n-2) n-(n-2)	Pi+2 n-(n-3)	Pi+3 (n-2)	Pi+(n-3) (n-3)	Pi+(n-4) n-(n-4)	Pi+4 n-(n-5)
PROW1	i=1	P11	P 29	P 98	P 82	P 33	P 47	P 76	P 64	P 55
PROW2	i=2	P 21	P 39	P 18	P 92	P 43	P 57	P 86	P 74	P 65
PROW3	i=3	P 31	P 49	P 28	P 12	P 53	P 67	P 96	P 84	P 75
PROW4	i=4	P 41	P 59	P 38	P 22	P 63	P 77	P 16	P 94	P 85
PROW5	i=5	P 51	P 69	P 48	P 32	P 73	P 87	P 26	P 14	P 95
PROW6	i=6	P 61	P 79	P 58	P 42	P 83	P 97	P 36	P 24	P 15
PROW7	i=7	P 71	P 89	P 68	P 52	P 93	P 17	P 46	P 34	P 25
PROW8	i=8	P 81	P 99	P 78	P 62	P 13	P 27	P 56	P 44	P 35
PROW9	i=9	P 91	P 19	P 88	P 72	P 23	P 37	P 66	P 54	P 45

TABLE 3. Specifications of PV module.

S.NO	PARAMETERS	RATINGS	UNITS
1	Short Circuit Current (Isc)	8.95	Ampere
2	Open Circuit Voltage (Voc)	37.23	Volts
3	Maximum Current (Im)	8.42	Ampere
4	Maximum Voltage (Vm)	29.7	Volts
5	Maximum Power (Pm)	250	Watts

receives the different irradiation level, that causes the uneven current generation in the PV rows. In the series connection, the different current sources limited the power output. The minimum current source limits the current output of the maximum current source. The uneven current generating rows limit the power output of the healthy PV rows. The mismatch loss can be defined as the difference of the maximum power generating row and the minimum power generating row. The percentage of mismatch loss can de be expressed as,

The PV system with the spiral pattern array configuration can generate maximum power in the all-shading patterns. The irradiation is not uniform over the day. It dynamically

changed concerning the time. The most possible shading patterns are framed as random, diagonal, short and narrow, short and wide, long and narrow, and long and wide. These shading patterns are applied in the conventional and proposed array configurations and the performance of these configurations is validated. The results were compared in the output analysis section which shows that the performance of the proposed method is better than the conventional methods. The change in shading patterns in the whole day can be classified into the six kinds of shading patterns that are evaluated in this work. The performance of conventional and proposed array configurations has been measured and compared with others. The Series parallel is the conventional and most common array configuration used in commercial applications. TCT and Sudoku array configurations are used in the places where the partial shading occurred more frequently. the proposed array configuration can be used in any commercial application for the enhanced performance of PV systems.

The random shading pattern is created as shown in figure.8(a). This kind of shading pattern will be occurred mostly due to the passing clouds and the nearby trees. The random
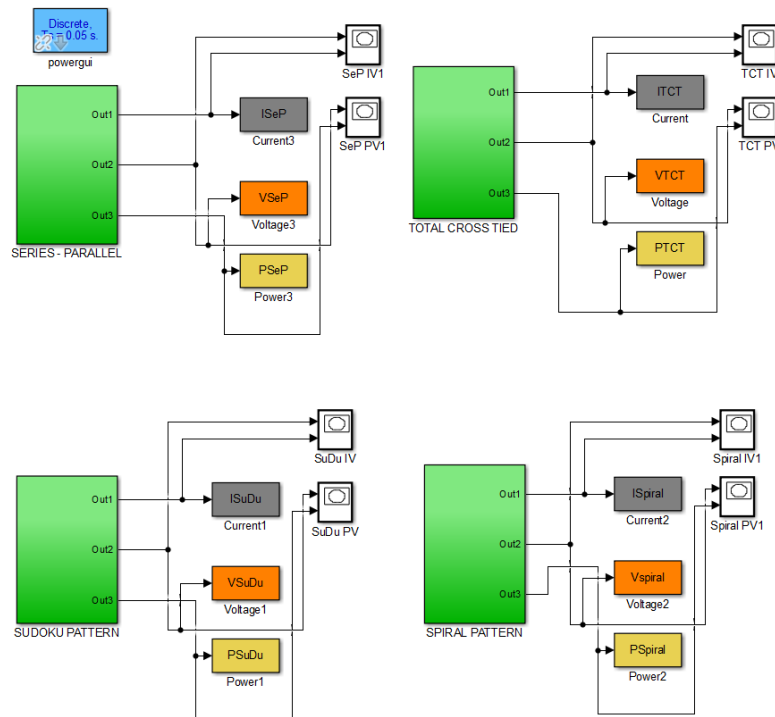
FIGURE 7. Simulation Diagram for validating the P-V and I-V characteristics.

shading pattern is not unique, it occurred randomly in any place of the PV array. This shading pattern level may vary from minimum level to maximum level. The power loss is depending on the number of shading presents in the PV system. Under the random shading condition, the series-parallel array configuration generates 315W power output. The TCT and Sudoku array configurations are generating the power output of 450W and 477W respectively. The proposed array configuration generates more power of 549W which is higher than the existing array configurations. The P-V and I-V characteristic curves are shown in figure.6. This curve shows the performance enhancement of the PV system. The characteristic curves of the existing array configuration have uneven spikes and many LMPP. The characteristic curve of the proposed configuration has smoother curves that show the level of shade dispersion and power enhancement.

The diagonal shading is the most possible shading pattern due to the nearby taller objects such as towers, taller buildings. This shading pattern is applied to the PV system as shown in the figure. 8. (b). The sudoku array configuration chooses the PV modules in diagonal progression in row creation which makes this configuration inefficient in this diagonal shading patterns. The objective of the new configuration is to disperse the shading level uniformly over the PV array. But in sudoku, the shading will be accumulated in a single row that causes poor performance. The TCT configuration has good power generation as compared with the series-parallel and sudoku methods. The proposed spiral

array configuration is still superior to the other configurations on shade dispersion for the diagonal shading pattern. The series-parallel configuration and Sudoku array configuration generate the power output of 369W and 522W respectively. The TCT array configuration generates the power output of 612W with 23.6% of mismatch loss. The spiral array configuration scheme generates the power output of 711W with 12.2% of mismatch losses. The reduction in the mismatch loss generation shows the shade dispersion rate. When all rows of PV array have the even power generation, it shows the even dispersion rate with enhanced power output. Among the four array configurations discussed in this work, the proposed configuration has the minimum mismatch loss generation (i.e., even shade dispersion) than the other three array configurations. The P-V and I-V characteristic curves under the diagonal shading pattern has shown in figure.9. The proposed array configuration has smoother characteristic curves than the other array configurations.

In the short and narrow (SN) shading pattern, the power output of each array configuration is given in Table. 4. Generally, this kind of shading condition is caused by nearby objects, trees, or buildings. This pattern affects any quarter portion of the PV array on any side. The series-parallel array configuration has poor performance in this shading condition. TCT and Sudoku configurations had the same rate of shade dispersion and generate almost equal power output. The proposed spiral array configuration scheme has the 5.8% of mismatch loss whereas it has the 729W output power which is

FIGURE 8. Shading patterns (a) Random shading (b) Diagonal shading (c) Short and narrow shading (d) Short and wide shading (e) Long and narrow shading (f) Long and wide shading.

greater than the other three configurations. The replacement of sudoku over the TCT configuration is not preferred for the diagonal shading, short and narrow shading, and long and narrow shading. Because the shade dispersion rate is almost similar in these shading patterns. But the proposed spiral array configuration scheme can be a solution to the PV system which is frequently affected by the partial shading by these shading patterns. The P-V and I-V characteristic curves of the various configurations are shown in figure.10. The Series parallel, TCT, and Sudoku array configurations had uneven characteristic curves with multiple spikes on them. The pro-

posed spiral array configuration scheme had smoother P-V and I-V characteristic curves that show its effectiveness on power enhancement.

Short and wide shading patterns are caused in the PV system due to the nearby buildings or trees. It almost covers 60% area of the PV array by partial shading. In this kind of shading, the series-parallel and TCT array configurations were failed to disperse the shading evenly over the PV array. That causes a high mismatch loss between the PV rows. The sudoku array configuration has performed well on this shading pattern and it generates 531W power output with

$$\% \ of \ Mismatch \ Loss = \frac{Maximum \ power \ Generating \ Row - Minimum \ Power \ Generating \ Row}{Maximum \ power \ Generating \ Row}$$
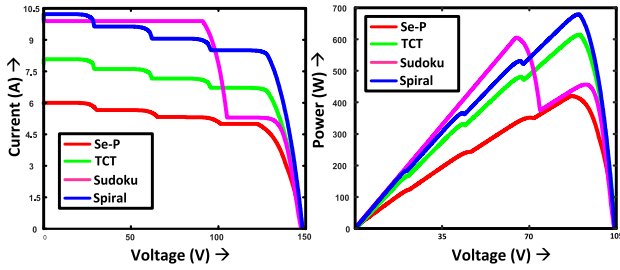
FIGURE 9. I-V and P-V characteristics under diagonal shading pattern.
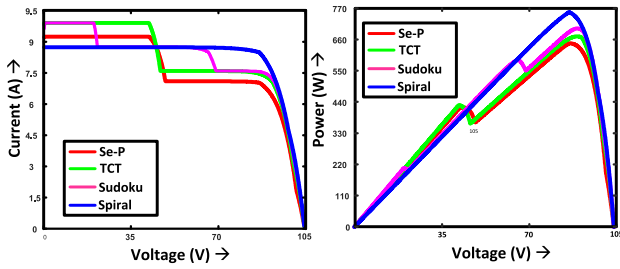

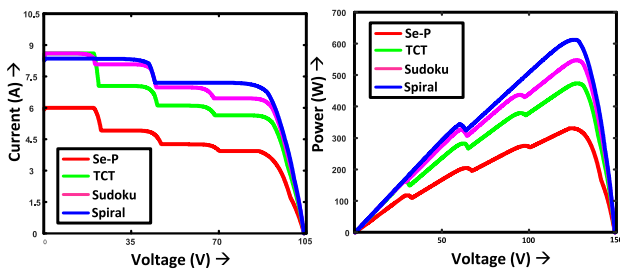**FIGURE 10.** I-V and P-V characteristics under short and narrow shading pattern.

FIGURE 11. I-V and P-V characteristics under Short and Wide shading pattern.

FIGURE 12. I-V and P-V characteristics under long and narrow shading pattern.
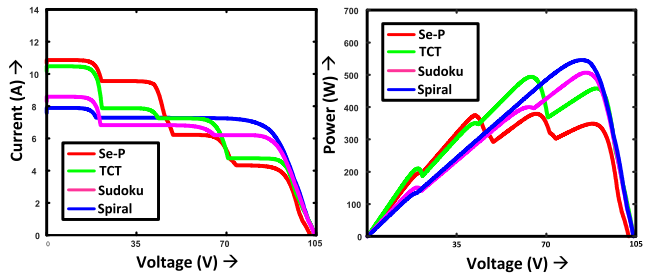
FIGURE 13. I-V and P-V characteristics under Long and wide shading pattern.

25.3% of mismatch losses. The Series parallel and TCT array configurations had mismatch losses of 60.1% and 44.4% respectively. Whereas, the proposed spiral pattern array configuration had the power generation of 624W output which is higher than the other array configurations. The mismatch loss between the rows of the spiral array configuration is around 4.2% which is very lesser than the other configuration methods. In the P-V and I-V characteristic curves, the spiral array configuration scheme has the smoother curve with one spike, whereas other configuration schemes had multiple spikes on the characteristic curves as shown in figure.11.

Under the long and narrow shading pattern, the series-parallel, TCT, and sudoku configuration methods are generating an almost equal power output of 603W, 639W, and 657W power. Whereas the proposed spiral configuration method generates the power output of 702W power. The difference in power output is not much different from other configurations in this array configuration. The high-power output indicates the capability of configuration methods in dispersing the shading evenly over the PV array. In the narrow shading
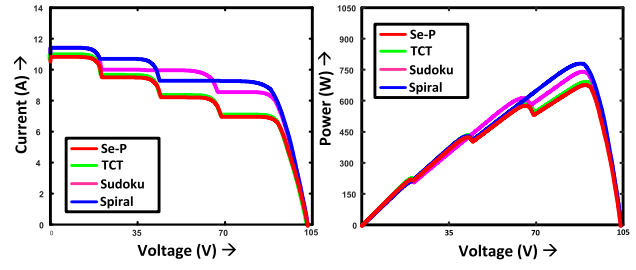
patterns, the Sudoku performs better than the series-parallel and TCT configurations. Because the PV rows are created with distinct PV modules from each row of TCT. Whereas in wide shading patterns the Sudoku performance is similar to the TCT configuration method. But the proposed spiral array configuration scheme had a good performance in both narrow and shading patterns. The P-V and I-V characteristic curves of the array configurations are shown in figure.12. The spiral array configuration method has a smoother characteristic curve, whereas the other three configuration methods have an uneven characteristic curve with multiple spikes. The spiral array configuration scheme is superior to the other configuration methods in these long and narrow shadow conditions.

In long and wide shading patterns, the series-parallel array configuration method has a poor performance than the other three configuration methods. The TCT generates a power output of 450W and the sudoku array configuration method generates 486W power output. The proposed spiral array configuration method generates the power output of 540W. The spiral configuration schemes operate the PV system with 7.7% of mismatch loss whereas the TCT, and sudoku configuration methods had 27.5% and 23.9% of mismatch loss. The spiral configuration method had a higher performance than the other configuration methods. The P-V and I-V characteristic curves of the spiral pattern array configuration method as in figure 13 have the smoother curve with the maximum power point whereas, other methods had the curves with multiple spikes. The spiral configuration efficiently disperses the shading of long and wide shading conditions.

The experimental setup for analyzing the spiral pattern array configuration scheme is validated in the 4 × 4 PV

TABLE 4. Simulation results of 9 × 9 PV array under various shading patterns.

S.NO	SHADING TYPE	ARRAY CONFIGURATION	IM	PM	MISMATCH LOSS	BEST GENERATION
1.	Random	Se-P	3.85	315	-	Spiral Pattern
		TCT	5.5	450	33.3%	
		Sudoku	5.83	477	28.4%	
		Proposed	6.71	549	15.3%	
2.	Diagonal	Se-P	4.51	369	-	Spiral Pattern
		TCT	7.48	612	23.6%	
		Sudoku	6.38	522	35.6%	
		Proposed	8.69	711	12.2%	
3.	Short and Narrow	Se-P	7.37	603	-	Spiral Pattern
		TCT	8.14	666	17.8%	
		Sudoku	8.25	675	16.7%	
		Proposed	8.91	729	5.8%	
4.	Short and Wide	Se-P	3.08	252	-	Spiral Pattern
		TCT	5.5	450	44.4%	
		Sudoku	6.49	531	25.3%	
		Proposed	7.59	624	4.2%	
5.	Long and Narrow	Se-P	7.37	603	-	Spiral Pattern
		TCT	7.81	639	16.3%	
		Sudoku	9.1	657	13.1%	
		Proposed	9.75	702	3.7%	
6.	Long and Wide	Se-P	4.51	369	-	Spiral Pattern
		TCT	5.5	450	27.5%	
		Sudoku	5.94	486	23.9%	
		Proposed	6.6	540	7.7%	
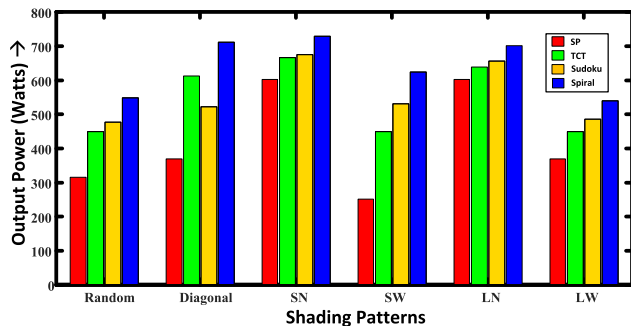
FIGURE 14. Simulation output of 9 × 9 PV array under various shading pattern.

FIGURE 15. Spiral propagation (Row creation) for 4 × 4 PV array.

FIGURE 16. Photograph of 4 × 4 PV array used for spiral pattern array configuration.

creation of the 4 × 4 PV array is shown in figure.15. For the 4 × 4 PV array, the value of i will be varied from 1 to 4. For the 1st row, the value of i is 1, 2 for the 2nd row, 3 for the 3rd row, and 4 for the 4th row. The value of n for the 4 × 4 PV array will be 4. The row creation of the 4 × 4 PV array is given in table.5.

The series-parallel array configuration has poor shade dispersion capability. Performance can be improved by the total cross-tied array configuration and sudoku array configurations. However, these configurations are not consistent in all shading patterns. The proposed array configuration can perform consistently in all kinds of shading patterns. The shade dispersion diagram of the array configurations under the random shading pattern has shown in the figure. Each

array and the photograph of the experimental setup is shown in figure.16. The 10W panel with the specification given in table 3 is used for the experimental validation. The row

TABLE 6. Experimental results of 4 × 4 PV array under various shading patterns.

S.NO	SHADING TYPE	ARRAY CONFIGURATION	IM	PM	MISMATCH LOSS	BEST GENERATION
1.	Random	Se-P	1.98	72	-	Spiral Pattern
		TCT	2.31	84	34.4%	
		Sudoku	2.42	88	29.1%	
		Proposed	2.75	100	7.4%	
2.	Diagonal	Se-P	1.54	56	-	Spiral Pattern
		TCT	2.86	104	23.5%	
		Sudoku	1.98	72	55.2%	
		Proposed	3.08	112	30.4%	
3.	Short and Narrow	Se-P	2.64	96	-	Spiral Pattern
		TCT	2.86	104	35.1%	
		Sudoku	3.08	112	30.3%	
		Proposed	3.52	128	15.8%	
4.	Short and Wide	Se-P	2.42	88	-	Spiral Pattern
		TCT	2.53	92	28.1%	
		Sudoku	2.64	98	25.4%	
		Proposed	2.86	106	7.1%	
5.	Long and Narrow	Se-P	2.42	88	-	Spiral Pattern
		TCT	2.53	92	28.1%	
		Sudoku	2.75	100	24.2%	
		Proposed	3.14	117	3.6%	
6.	Long and Wide	Se-P	1.98	72	-	Spiral Pattern
		TCT	2.2	82	35.5%	
		Sudoku	2.42	89	31.3%	
		Proposed	2.75	100	3.9%	

TABLE 5. Spiral propagation and row creation for 9 × 9 PV array.

For 4X4 PV array, n=4 & i = 1 to 4		Pi n-(n-1)	Pi+1 n	Pi+(n-1) (n-1)	Pi+(n-2) n-(n-2)
PROW1	i=1	P11	P 24	P 43	P 32
PROW2	i=2	P 21	P 34	P 13	P 42
PROW3	i=3	P 31	P 44	P 23	P 12
PROW4	i=4	P 41	P 14	P 33	P 22

series string of the series-parallel array configuration will bring the power output of minimum power-generating PV modules. In TCT array configuration, the minimum current generating row will be the power output of the PV array. The shade dispersion diagram of the TCT configuration is shown in figure 17 (b). the irradiation received by each rows are 2800W/m^2, 2100 W/m^2, 3200 W/m^2, and 2100 W/m^2. Each row had generated a short circuit current of 3.5A, 2.625A, 4A, and 2.625A. The third row of the PV array generating the short circuit current of 4A. The second row and fourth row were generating 2.625A of short circuit current. The difference between the maximum current generating row and the minimum current generating row shows the ability of the shade dispersion. TCT array configuration has a poor shade dispersion rate that reflects in the short circuit current generation PV rows. The shade dispersion diagram of the proposed spiral pattern has shown in figure 17 (c). The shade dispersion and short circuit current generation of each PV row is as follows, 2600 W/m^2 with 3.25A, 2500 W/m^2 with 3.125A, 2700 W/m^2 with 3.375A, and 2500 W/m^2 with 3.125A. The difference between the maximum and minimum current generating rows is very less as compared to the conventional methods. That shows the enhanced shade dispersion capabil-
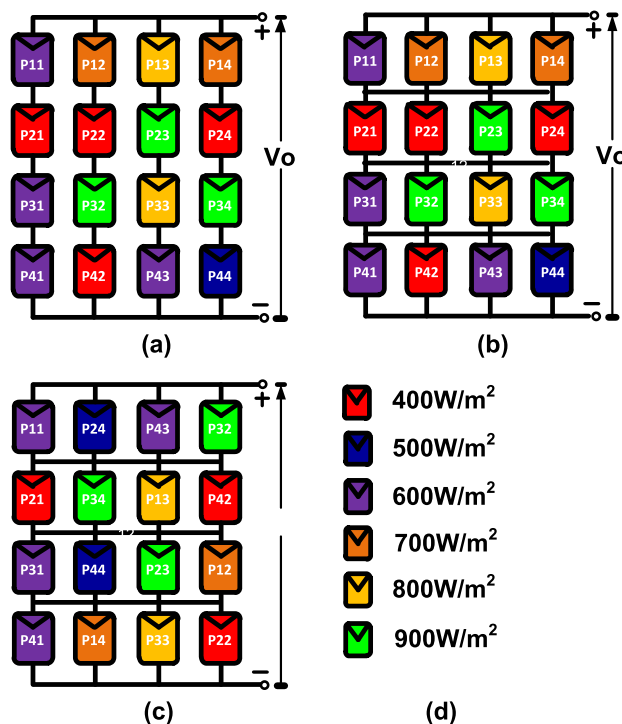

FIGURE 17. Shade dispersion diagram of (a) Series Parallel configuration (b) TCT configuration (c) Spiral pattern configuration (d) Shading Level.

ity of the proposed method. The enhanced shade dispersion capability is the achievement of the proposed configuration in power enhancement of PV array by minimizing the mismatch losses between the PV rows.
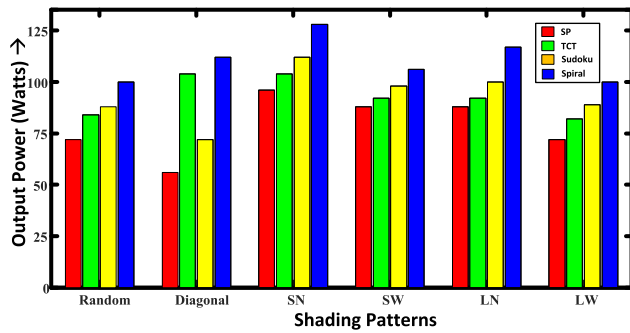
FIGURE 18. Experimental output of 4 × 4 PV array under various shading patterns.

Six kinds of shading patterns used in the simulation are applied in the hardware setup. The irradiation value has been measured by the solar power meter which gives the irradiation date in watts/m2. The experimental validation is carried out during the 12 o'clock daytime. During this time, the system receives around 900W/m2 to 1020W/m2. The shading pattern is been created in the PV array by covering the module surface with cardboard sheets. The performance of the system under the partial shading condition is been measured by the current sensing module ACS758 with the Arduino controller. The power output of the spiral pattern array configuration and the existing methods has given in table.6. The spiral pattern is the superior method in power generation under the all-shading patterns. The power output and mismatch loss generation of each configuration is given in Table 6. In a random shading pattern, the proposed array configuration generates 100W of power output whereas the second-highest power generation is 88W by the sudoku puzzle pattern. The TCT configuration and Se-P configuration generate the power output of 84W and 72W. The mismatch loss between the PV rows of the proposed array configuration is 7.4% but the conventional methods had above 30% of mismatch losses. In the diagonal shading pattern, the proposed method had the 112W power output, where the least power output is 56% by the Se-P array configuration. In the S&N, S&W, L&N, and L&W shading patterns, the proposed configuration method generates the power output of 128W, 106W, 117W, and 100W respectively. In every shading pattern, the proposed method has the highest power generation, which shows the efficient rate of shade dispersion under partial shading conditions. The output power comparison chart is shown in figure.17.

The conventional configurations such as TCT, Se-P, and Sudoku pattern has been compared with the proposed spiral array configuration scheme. Six kinds of possible shading patterns are applied to the PV array. TCT configuration is superior to the Se-P configuration in all the shading patterns and it is superior to the sudoku puzzle pattern in the diagonal shading pattern. The sudoku configuration method has performed well in the all-shading patterns except the diagonal shading. The result comparison proves that the proposed spiral array configuration can generate maximum power than the all-conventional shading patterns. As per the literature

survey, the sudoku puzzle pattern-based array configuration can generate the maximum power theoretically and practically. The proposed array configuration generates each row with the distinct PV modules as in the Sudoku. But this spiral pattern overcomes the limitations of the sudoku pattern and also generates maximum power in all kinds of shading patterns.

IV. CONCLUSION

In this paper, a new kind of PV array configuration scheme called spiral pattern configuration has been proposed for enhancing the performance of PV systems under partial shading conditions. A proper mathematical formulation is expressed based on the number of rows and number of columns and it can be applied to any size of the PV system. The row creation for the spiral pattern array configuration is been demonstrated in this paper. The proposed array configuration is been analyzed in simulation using MATLAB/Simulink® and in the experimental setup. The performance of the spiral pattern configuration scheme is validated with the other array configurations of series-parallel, Total Cross Tied, and Sudoku puzzle patterns by applying the six possible shading patterns. The power output is compared with the conventional configuration methods which state that the proposed spiral configuration scheme is superior to the other configurations in all kinds of shading patterns. In both simulation and hardware results, the spiral pattern has the enhanced performance with minimum mismatch losses. The proposed array configuration method is easy to implement and does not require any additional devices or sensors or controllers. This method will be very efficient for any size of PV system for enhancing the performance under faulty or partial shaded conditions.

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