Hardware Implementation of Sudoku, Optimal Sudoku, Sky-Scrapper, Novel Shade Dispersion and Magic Matrix Shifting PV Reconfiguration Techniques With MPPT Algorithm to Enhance Maximum Power

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***Abstract*—This research paper investigates the performance of reconfiguration methods by integrating the MPPT algorithm. This study examines the performance of various PV array reconfiguration techniques based on power extraction, efficiency, and reliability. The effectiveness of reconfiguration methods has been evaluated through simulation, followed by hardware experimentation under partial shading cases. The methodology involves implementing and testing conventional TCT and other physical PV array reconfiguration methods by integrating the P&O MPPT algorithm with each reconfiguration method, and the performance of the combined system is evaluated under voltage and current curves, power extraction, MPPT tracking efficiency, and % steady state oscillations. Hardware experiments validate the proposed approach using a PV system prototype.**

***Index Terms*—Maximum power point, novel shade dispersion and magic matrix shifting PV reconfiguration techniques, optimal Sudoku, shading conditions, sky-scrapper, Sudoku.**

I. Introduction

THE photovoltaic (PV) system is a potential renewable energy technology for electricity production. However, solar radiation, temperature, and partial shade may substantially impact their effectiveness. Due to the difference in power output between shaded and unshaded modules within a PV array, partial shading circumstances, in particular, may result in significant power losses.

Different strategies have been devised to minimize the negative impacts of partial shade and improve the power generation from PV arrays. Reconfiguration is one solution to enhance power extraction through shade dispersion. Under shading circumstances, using MPPT tends to make the PV system work at its maximum power point (MPP). The Perturb and Observe (P&O) algorithm is a popular MPPT algorithm for its efficiency, simplicity, and compatibility. The static reconfiguration approach includes reconfiguring the panel position of PV modules to distribute shade.

MPPT algorithms significantly increase the efficiency of PV systems by continuing to monitor and maintain the PV array's MPP. The researcher discusses various MPPT methods, like input variables based on conventional MPPT methods, intelligent MPPT methods, optimization-based MPPT methods and hybrid MPPT methods by combining two or more MPPT methods. The performance of MPPT integration is compared based on their tracking speed, control of external variations, power efficiency, algorithm complexity, implementation cost, etc. [1]−[2]. The MPPT system extracts the maximum obtainable power by adjusting the operating point to ensure maximum energy extraction, compensating for changes in temperature, shading, and other environmental factors. The P&O algorithm is comprehensively researched and employed to track maximum power in PV systems.

The research in [3] combines fractional short-circuit current measurement with the P&O technique to enhance the accuracy and efficiency of MPPT. It offers improved tracking performance and eliminates the need for additional sensors to develop a cost-effective solution for PV systems. Authors in [3] introduce an improved adaptive P&O method focusing on enhancing the performance of the power tracking by incorporating adaptive step size and modified perturbation strategies. It aims to achieve faster and more efficient MPPT under varying environmental circumstances. [4] explores the integration of an improved P&O algorithm with artificial bee colony optimization to enhance the P&O method's effectiveness in tracking the extreme power under shading situations. The research in [5] aims to assess the impact of PSC on the P&O algorithm's performance and provides insights into mitigating cross-coupling effects for efficient MPPT operation in PV systems. Therefore, this P&O method has been selected for research.

The PV array reconfiguration static and dynamic reconfiguration approaches for mitigating partial shading influence

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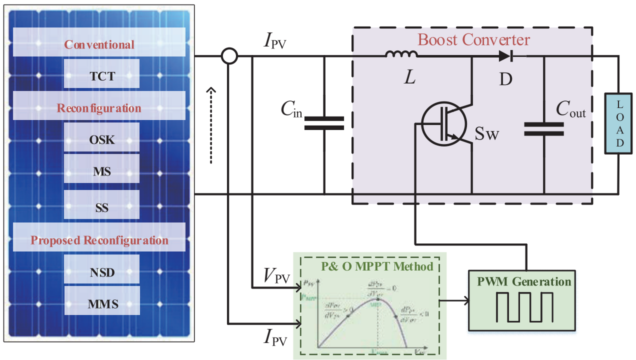

Fig. 1. The architecture of the PV array reconfiguration with MPPT.

process pertain to modifying the spatial arrangement of photovoltaic modules in an array [6]. It can be done electrically or physically. The number of modules and configuration depend on the desired system capacity and available space. There are various sensor-less PV array reconfiguration methods like shifting-based reconfiguration, Sudoku (SK) [6] optimal Sudoku (OSK) [7], [8] improved versions of Sudoku methods [9]−[11] square puzzle-based reconfigurations, dominance square (DS) [12], competence square (CS) [13] magic square puzzle based [14] and other reconfigurations, skyscraper reconfiguration (SS) Lo Shu technique [15] recently proposed reconfigurations[11], [16], [17], novel shade dispersion method (NSD) [18], [19], magic matrix shifting (MMS) [20] etc. The above-mentioned concept presents many potential advantages, including optimizing energy generation by redistributing the shading effect. For conventional configuration, conventional MPPT fails under partial shading conditions. Therefore, in recent years, reconfiguring a PV array by integrating the MPPT algorithm with an available PV system has attracted substantial interest in improving power extraction under partial shade situations.

This work has focused on designing and optimizing reconfiguration circuits, creating control algorithms, and assessing reconfigured PV system performance when connected to MPPT under various shading patterns.

The research objective is to investigate the performance of the conventional TCT configuration and static PV array reconfiguration techniques when integrated with perturb and observe the P&O MPPT algorithm. The study aims to evaluate the effectiveness of different static reconfiguration techniques in enhancing the power output and the effect of reconfiguration on the performance of the P&O MPPT algorithm. The results of this research will help to understand how to effectively use static PV array reconfiguration strategies for maximizing power extraction efficiency in actual applications.

This work proposed two novel methods (MMS and NSD) to reconfigure the 4×4 PV array to extract the maximum power under partial shading conditions. The novelty of work is:

1. Dynamic performance of reconfiguration has been examined through hardware implementation validation and analysis of I-V and P-V curves for all considered reconfiguration methods.

2. This work is implemented using the 8-bit AVR microcontroller, which is an effective solution for practical implementation compared to other microcontrollers like DSP or FPGA.

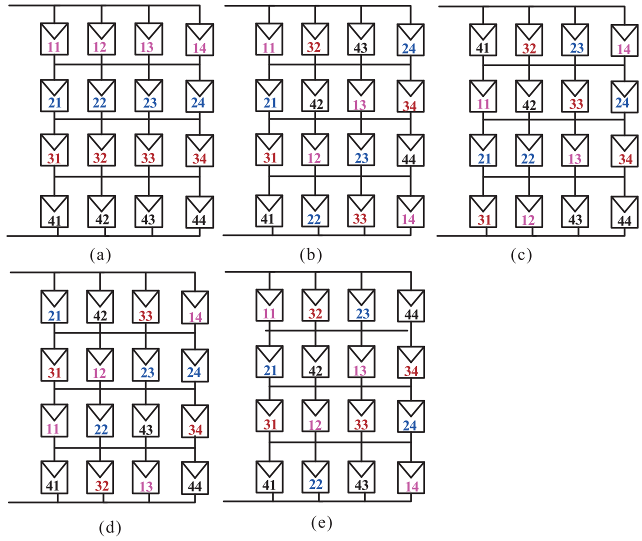

Fig. 2. PV array topology under Case-I shading condition. (a) TCT, (b) OSK, (c) SS, (d) NSD, (e) MMS.

II. Modeling of PV System

Fig. 1 shows the reconfigured PV array with the MPPT algorithm to provide the pulse to boost converter which transfers power to the load. MPPT optimizes the power output of the PV module. This paper focuses on the various techniques used in a PV array reconfiguration with different shading conditions that integrate the MPPT algorithm.

A. Reconfiguration of Photovoltaic Array

In this paper, a sensor-less PV array reconfiguration has been deliberated. Panels are exchanged according to OSK, SS, and the recently proposed MMS reconfiguration. For comparison, the proposed methods with a conventional TCT configuration have been used. The panel position for all the methods is shown in Fig. 2. Table I contains the comparison and required formula for MPPT integration. For NSD and MMS reconfiguration, algorithms are given below:

Step 1: Submatrix Dimensions (NSD and MMS)

m *is* number of rows, n is number of columns, and a *is* total number of elements such that $a = m \times n$.

Thus, the matrix M is an $m \times n$ matrix.

Initially, $M_{i,j}$=0,

Where, $1 \leqslant i \leqslant m$ and $1 \leqslant j \leqslant n$

For NSD: $m < n$

For MMS: $m > n$

Step 2: Filling the submatrix (NSD and MMS):

Start at the first position $M_{1,1}$ and begin placing numbers from 1 to a, incrementing the row and column indices. Feed-forward rule: After placing number k in position $M_{i,j}$,

TABLE I
COMPARASION OF VARIOUS RECONFIGURATION WITH MPPT INTEGRATION

Array Topology	Theoretical Basis	Key Formulas	Reconfiguration with MPPT Integration
TCT	Interconnects PV modules in a mesh-like structure to improve current sharing and reduce mismatch losses.	Current sharing: $I_{\text{tied}}=\frac{\sum_{k=1}^{n} I_k}{n}$ Voltage remains constant: $V_{\text{tied}}=V_{\text{module}}$	Total array power is: $P_{\text{array}}=I_{\text{tied}}\times V_{\text{tied}}$ MPPT adjusts for optimal power: $\eta_{\text{MPPT}}=\frac{P_{\text{MPP}}}{P_{\text{array}}}$
OSK	Ensures a unique arrangement of PV modules to minimize mismatch losses and balance power under fixed shading conditions.	Minimize mismatch loss: $L=\sum_{i=1}^{m}\sum_{j=1}^{n}(P_{\text{avg}}-P(i,j))^2$	The total array power is calculated as: $P_{\text{array}}=\sum_{i=1}^{m}\sum_{j=1}^{n}P(i,j)$ MPPT ensures: $\eta_{\text{MPPT}}=\frac{P_{\text{MPP}}}{P_{\text{array}}}$
SS	Maximizes visibility of PV modules to sunlight by placing taller or unshaded modules in strategic positions.	Maximize visibility: $P_{\text{visible}}=\sum_{i,j}Visible(i,j)\times P(i,j)$	Visibility impacts total power: $P_{\text{array}}=P_{\text{visible}}$ MPPT adjusts to optimize power as: $\eta_{\text{MPPT}}=\frac{P_{\text{MPP}}}{P_{\text{array}}}$
NSD	The submatrix structure equalize the row currents. Modules are repositioned physically, and shading is dispersed logically within a column.	Row current equalization: $I_{\text{row}}=\frac{\sum_{i=1}^{n} I_{i,j}}{n}$ Achieves logical shifting of rows to satisfy magic constant 21 for 2×3 submatrix structure	The total array power is calculated as: $P_{\text{array}}=\sum_{i=1}^{m}\sum_{j=1}^{n}P_{\text{Reconfigured }i,j}$ MPPT extracts maximum power by dynamically tracking: $\eta_{\text{MPPT}}=\frac{P_{\text{MPP}}}{P_{\text{array}}}$
MMS	The submatrix-based approach uses logical shifts and horizontal folds (HF) to reposition PV modules.	Submatrix formation: $m\times n=a$ where a is the total matrix size. Row current equalization is achieved using submatrix shifts to satisfy the magic number	After reconfiguration, power is: $P_{\text{array}}=\sum_{i=1}^{m}\sum_{j=1}^{n}P_{\text{Reconfigured }i,j}$ MPPT ensures maximum power extraction: $\eta_{\text{MPPT}}=\frac{P_{\text{MPP}}}{P_{\text{array}}}$

place number k+1 in the next row and next column. If $m < n$ when placing the next number after filling a column, skip one column. Position for number k: Let k be the number to be placed,
where, $1 \leqslant k \leqslant a$

For each k value update the row and column indices as:

$$i_k=\left|\frac{k-1}{n}\right|+1, \tag{1}$$

$$j_k=k-1 \mod n+1 \tag{2}$$

Step 3: Skipping columns (NSD and MMS) (*if m < n*)

If $m < n$, then after filling the matrix by moving to the next column, we skip one column.

If $j_k \geqslant n$, then instead of moving to j_k+1, we place the next number in j_k+2.

$$j_k=\begin{cases} j_k+1 & \text{if } j_k<n \\ j_k+2 & \text{if } j_k\geqslant n \end{cases} \tag{3}$$

Step 4: Matrix Completion

We continue placing numbers from $k=1$ to $k=a$.

B. Maximum Power Point Tracking (MPPT) Algorithm

The P&O MPPT involves introducing perturbations to the voltage or current during operation, in the P-V curve of the solar panel, at maximum power, the slope of the curve is zero ($\frac{dP_{\text{PV}}}{dP_{\text{PV}}}=0$). The real-time measurement of the voltage and current of the PV panel is done to calculate the slope of the curve. Changes in the power (ΔP_{PV}) and voltage (ΔV_{PV}) are calculated using (4) and (5):

$$\Delta P_{\text{PV}}=P_{\text{current}}-P_{\text{previous}} \tag{4}$$

$$\Delta V_{\text{PV}}=V_{\text{current}}-V_{\text{previous}} \tag{5}$$

The decision of duty ratio change of the boost converter is made by calculating the slope and region of the P-V curve. If ΔP_{PV} is greater than zero and $\Delta V_{\text{PV}}>0$, V_{PV} will increase by ΔV_{step}. If $\Delta V_{\text{PV}}<0$, V_{PV} will reduced by ΔV_{step}. If ΔP_{PV} is less than zero and $\Delta V_{\text{PV}}>0$, V_{PV} will decrease by ΔV_{step} to achieve MPP. If $\Delta V_{\text{PV}}<0$, V_{PV} will increased by ΔV_{step} to achieve MPP. The converter output voltage depends on the duty cycle of the converter. For the boost converter, if the duty cycle is increased then, the output voltage will reduced. In order to transfer the maximum power from PV to load, the load impedance and source impedance should be equal. To match the impedances, a boost converter is used between the source and load.

$$Z_{\text{in}}=(1-d)^2\, Z_{\text{out}} \tag{6}$$

where Z_{in} is the input impedance of the boost converter d is the duty ratio of the converter switching pulse applied to the switch, and Z_{out} is the output impedance of the converter. It is observed from (6) that input impedance depends on the duty cycle.

The sensors sense the voltage and current of PV, and the processed signal is given to the ADC (10-bit) of the AVR microcontroller calculates the output power P_{PV}, and compares it

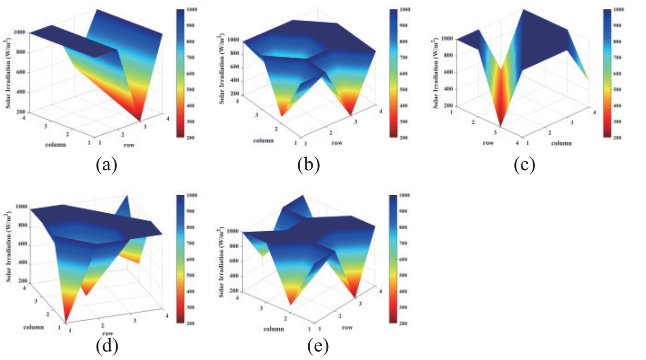

Fig. 3. Case-I shading condition and shade dispersion for (a) TCT, (b) OSK, (c) SS, (d) NSD, (e) MMS.

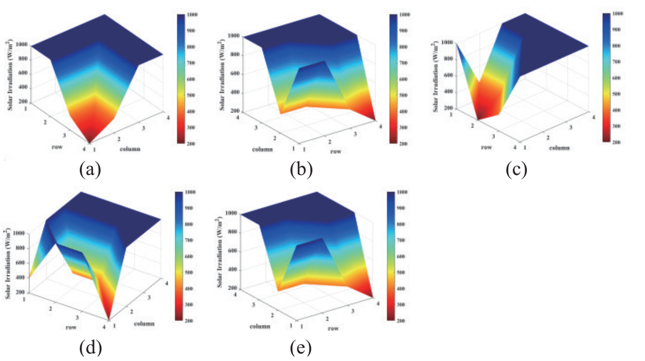

Fig. 4. Case-II shading condition and shade dispersion for (a) TCT, (b) OSK, (c) SS, (d) NSD, (e) MMS.

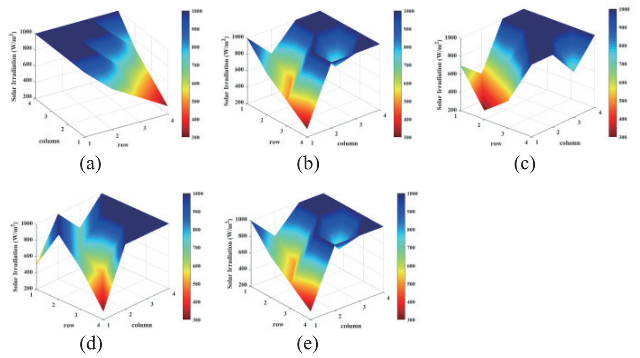

Fig. 5. Case-III shading condition and shade dispersion for (a) TCT, (b) OSK, (c) SS, (d) NSD, (e) MMS.

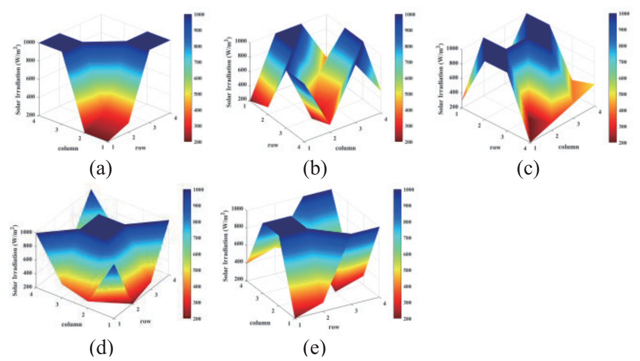

Fig. 6. Case-IV shading condition and shade dispersion for (a) TCT, (b) OSK, (c) SS, (d) NSD, (e) MMS.

to $P_{previous}$. Suppose that $P_{current} > P_{previous}$, the PWM duty cycle is raised to maximize PV panel power. If $P_{current}$ is smaller than $P_{previous}$, the duty cycle is lowered to restore extreme capacity.

C. DC-DC Converter

DC-DC converters reconfigure the PV module connections and voltage levels within the array. These converters enable optimal power transfer by adapting the voltage and current levels to match the load impedance to the source impedance to transfer the maximum power from source to load.

Overall, the PV array reconfiguration with MPPT system architecture aims to maximize the energy output of the PV array by dynamically optimizing the module connections and adjusting the operating point to track the MPP under varying environmental conditions.

III. Partial Shading Conditions and Shade Pattern

In PV array reconfiguration, specific shading conditions such as Case-I, Case-II, Case-III, and Case-IV are selected to evaluate and optimize system performance under various real-world scenarios. Case-I shading simulates typical shadows from horizontal obstructions like buildings and trees, while Case-II shading assesses edge effects and performance impacts from shadows at array corners. Case-III shading represents irregular shading patterns from non-uniform obstructions, and Case-IV shading simulates unpredictable, real-world shading from clouds, debris, and temporary obstructions. These real-world shading conditions improve the PV array to minimize the mismatch power loss, hence improving efficiency.

This paper considers four realistic shading conditions. First is Case-I, shown in Fig. 3, which has five irradiance levels: 200 W/m^2, 300 W/m^2, 400 W/m^2, 500 W/m^2, and 1000 W/m^2. Second Case-II shading in Fig. 4 has three levels of irradiation: 200 W/m^2, 400 W/m^2, and 1000 W/ m^2.

Case-III shade condition consists of four irradiance levels: 300 W/m^2, 500 W/m^2, 700 W/m^2, and 1000 W/m^2, and RM PSC with five irradiance levels: 200 W/m^2, 300 W/m^2, 400 W/m^2, 500 W/m^2 and 1000 W/m^2. In Fig. 3 to Fig. 6(a), subfigures portray the PSC for TCT configuration and (b), (c), (d), and (e). Gives the shade dispersion for OSK, SS, NSD, and MMS methods for considering four shading cases.

The performance of the reconfiguration is investigated with the P&O MPPT method based on power tacked by the MPPT algorithm, % tracking efficiency of the MPPT algorithm, and steady-state power oscillations in percent. The performance is investigated and discussed in section four.

IV. Results and Discussion

The performance of various panel placement topologies

TABLE II
MPPT ALGORITHM PERFORMANCE FOR DIFFERENT PV ARRAY TOPOLOGIES UNDER SHADE CASE-I

Array Topology	GMPP at STC	V_{oc}	I_{sc}	V_{mp}	I_{mp}	P_{mp}	V_{mppt}	I_{mppt}	P_{mppt}
TCT	40	29.17	1.86	17.23	1.66	28.67	23.44	0.90	21.11
OSK	40	29.04	1.62	24.24	1.37	33.14	25.49	1.31	32.30
SS	40	29.17	1.62	24.35	1.31	31.78	21.73	1.35	29.25
NSD	40	29.17	1.58	24.12	1.35	32.63	25.43	1.21	30.85
MMS	40	29.04	1.62	24.24	1.37	33.14	24.49	1.35	32.49

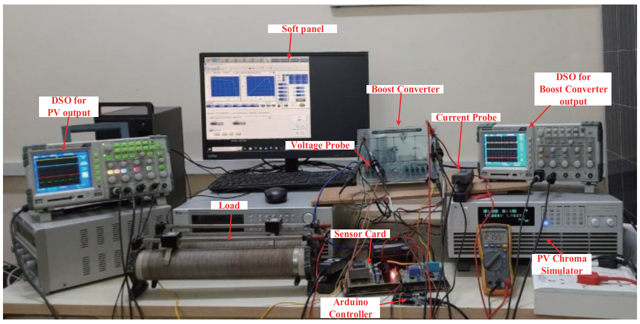

Fig. 7. Experimental prototype to evaluate the performance of reconfiguration techniques.

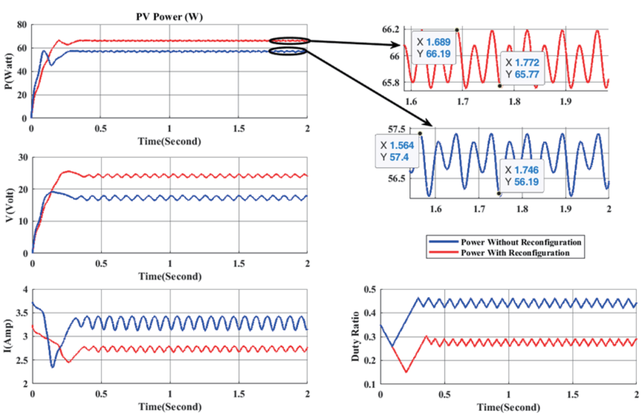

Fig. 8. Simulated PV system power, voltage, and current for conventional TCT and OSK, SS, and MMS reconfiguration methods with P&O MPPT under Case-I shading.

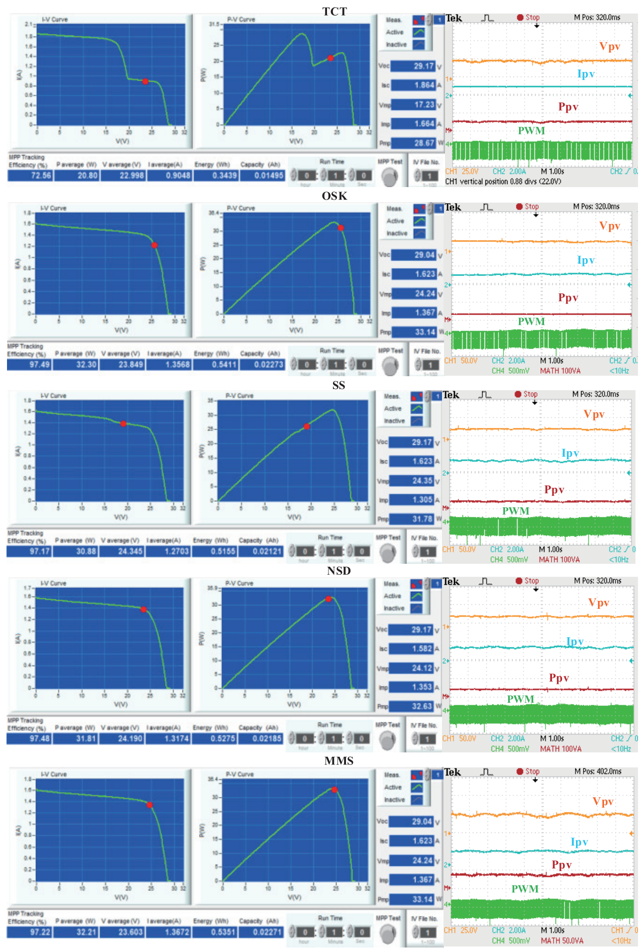

Fig. 9. Experimental result under Case-I shading condition for TCT connection, OSK, SS, NSD, and MMS reconfiguration.

named TCT, OSK, SS, NSD, and MMS has been investigated with conventional P&O MPPT under PSC. The performance is analyzed in both MATLAB simulation and real-time hardware implementation as shown in Fig. 7.

The tests are carried out using a PV panel with an operational voltage of 6 V±5%, an operating current of 833 mA±5%, and an open circuit voltage of 7 V±5%, and a short circuit current of 916 mA±5%. It is used for PV chroma, with the highest PV power on Chroma solar array simulation soft panel 62000 H series being used for 80 W. Chroma has limitations for current. Therefore, the scaling factor 0.5 is employed, resulting in a short circuit current of 1.83 A and output power of 40 W at STC.

A. PSC-Case-I

As shown in Fig. 8, all the reconfiguration methods work efficiently, and reconfiguration improves by 8.79 with 1% of reduced steady-state oscillations in power output. The corresponding experimental result validation is given in Table II. Fig. 9 shows I-V and P-V curves, and performance evaluation is given in Fig.10. It shows that with MPPT integration, MMS is the best reconfiguration with the highest power tracking efficiency of 97.49%, and output power 32.49 W power and least 4.47% power oscillations.

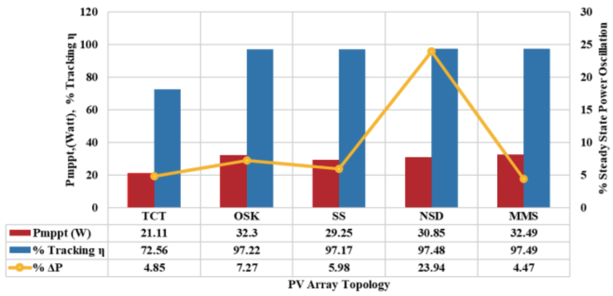

Fig. 10. Performance evaluation under Case-I shade.

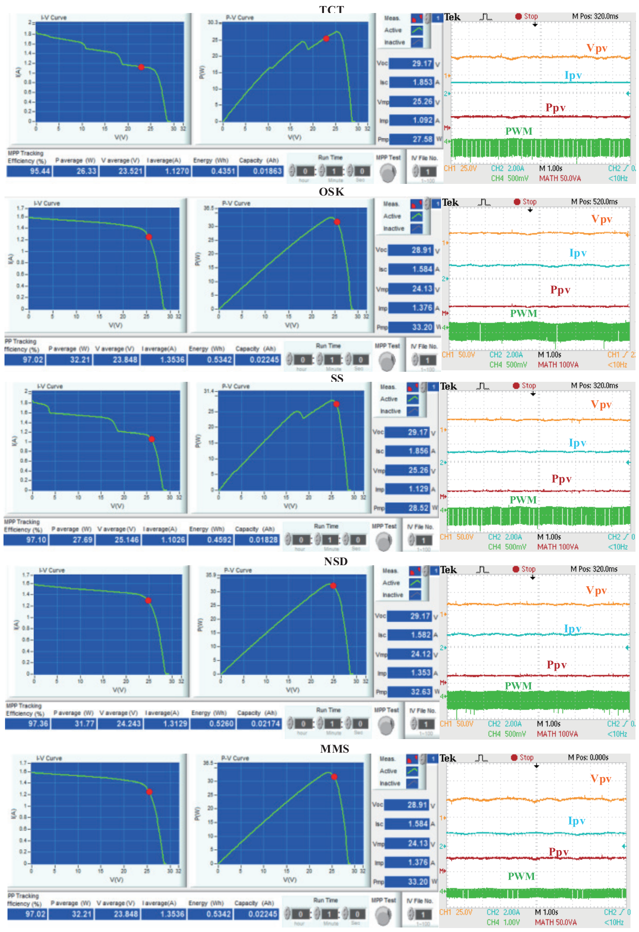

Fig. 11. The experimental result under Case-II shading condition for TCT connection, OSK, SS, NSD, and MMS reconfiguration.

B. PSC-Case-II

The corresponding experimental result validation is given in Table III and Fig. 11. In Fig. 12, simulation results show that under Case-II, MMS and OSK give the highest power of 66 W and the least steady-state power oscillations of 0.2% with the P&O algorithm. For other reconfigurations and TCT, there are 1.3% of steady-state power oscillations and an average of 56.5 W of power generation.

The performance assessment depicted in Fig. 13 reveals that when integrated with MPPT, MMS is the most optimal reconfiguration for power tracking efficiency. This configuration

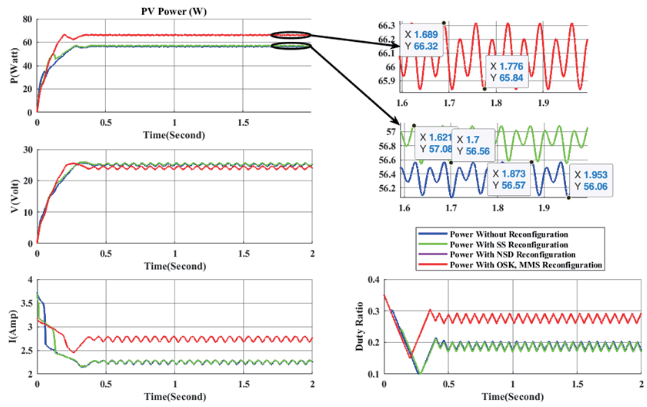

Fig. 12. Simulated power, voltage, and current of PV system for conventional TCT, OSK, SS, NSD, and MMS reconfiguration methods with P&O MPPT under Case-II.

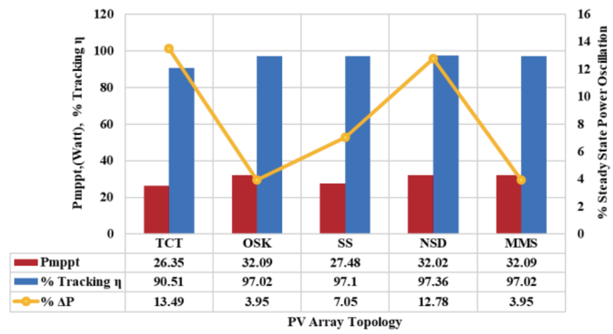

Fig. 13. Performance evaluation under Case-II shade.

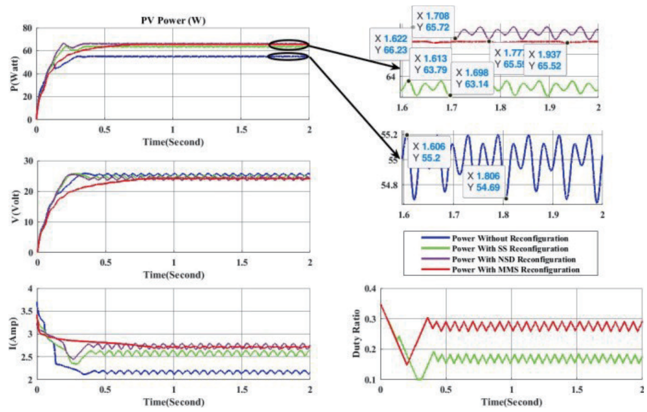

Fig. 14. Simulated PV system power, voltage, and current for conventional TCT and OSK, SS, NSD, and MMS reconfiguration methods with P&O MPPT under Case-III shading.

achieves an impressive 32.09 W power output, corresponding to 97.02% efficiency. Additionally, this configuration exhibits the lowest level of power oscillations, at a mere 4.47%.

C. PSC-Case-III

Fig. 14 shows the simulation results under Case-III, with P&O power point tracking. NSD gives the highest power, oscillating between 65.7 W and 66.23 W. MMS is beside it, giving 65.52 W

TABLE III
MPPT ALGORITHM PERFORMANCE FOR DIFFERENT PV ARRAY TOPOLOGIES UNDER SHADE CASE-II

Array Topology	GMPP at STC	V_{oc}	I_{sc}	V_{mp}	I_{mp}	P_{mp}	V_{mppt}	I_{mppt}	P_{mppt}
TCT	40	29.17	1.85	25.26	1.09	27.58	25.24	1.09	26.35
OSK	40	28.91	1.58	24.13	1.38	33.20	25.20	1.27	32.09
SS	40	29.17	1.86	25.26	1.13	28.52	25.95	1.06	27.48
NSD	40	29.17	1.58	24.12	1.35	32.63	24.69	1.31	32.02
MMS	40	28.91	1.58	24.13	1.38	33.20	25.20	1.27	32.09

Fig. 15. Experimental result under Case-III shading condition for TCT connection, OSK, SS, NSD, and MMS reconfiguration.

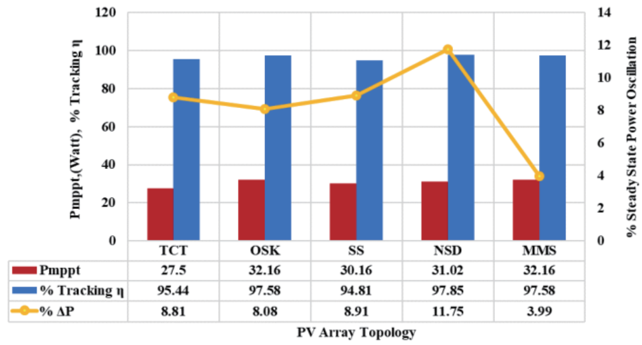

Fig. 16. Performance evaluation under Case-III shade.

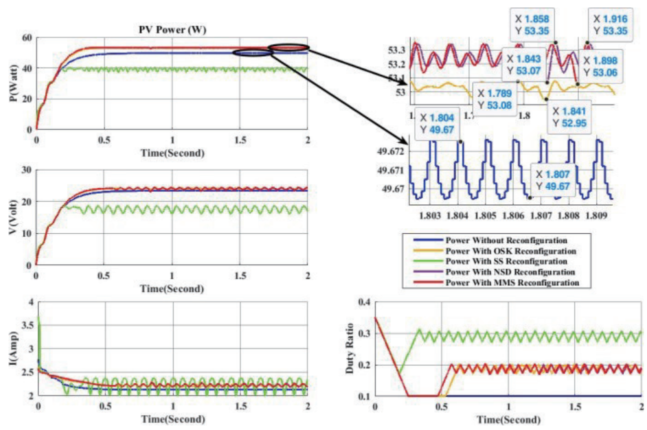

Fig. 17. Simulated PV system power, voltage, and current for conventional TCT and OSK, SS, NSD, and MMS reconfiguration methods with P&O MPPT under Case-IV shading.

tracked power with negligible oscillations. Fig. 15 shows the experimental results with I-V and P-V curves. Fig. 16 and Table IV give the experimental result validation on the 40 W system.

The analysis presented in Fig. 16 demonstrates that when the PV system is combined with MPPT integration, OSK and MMS reconfiguration attain a notable power output of 32.16 W, corresponding to an efficiency of 97.58%. Moreover, the MMS configuration maintains power stability with the most minor power oscillations at 3.99%.

D. PSC-Case-IV

In Fig. 17, simulation results show that under Case-IV, MMS and NSD give the highest power of 53 W and the least steady state power oscillations with the P&O algorithm.

The corresponding experimental result validation is given in Table V, Fig. 18, and Fig. 19. It shows that for MMS reconfiguration P&O, the MPPT algorithm gives the uppermost power tracking efficiency of 97.8%, providing 25.56 W power with the lowest 4.91% steady state power oscillations.

V. CONCLUSION

In this paper, the performance of newly proposed reconfigurations (NSD&MMS), shifting-based reconfiguration (OSK), puzzle-based reconfiguration (SS), and conventional configuration (TCT) have been investigated with the integra-

TABLE IV
MPPT Algorithm Performance for Different PV Array Topologies under Shade Case-III

Array Topology	GMPP at STC	V_{oc}	I_{sc}	V_{mp}	I_{mp}	P_{mp}	V_{mppt}	I_{mppt}	P_{mppt}
TCT	40	29.17	1.09	25.26	1.09	27.58	22.76	1.13	27.50
OSK	40	29.17	1.71	24.12	1.36	32.80	24.30	1.35	32.16
SS	40	29.17	1.72	24.57	1.30	31.99	25.47	1.22	30.16
NSD	40	29.04	1.71	24.24	1.36	32.85	25.56	1.21	31.02
MMS	40	29.17	1.71	24.12	1.36	32.80	24.30	1.35	32.16

TABLE V
MPPT Algorithm Performance for Different PV Array Topologies under Shade Case-IV

Array Topology	GMPP at STC	V_{oc}	I_{sc}	V_{mp}	I_{mp}	P_{mp}	V_{mppt}	I_{mppt}	P_{mppt}
TCT	40	28.63	1.39	24.57	1.04	25.50	24.41	1.04	25.43
OSK	40	28.63	1.30	24.12	1.10	26.58	23.82	1.11	26.40
SS	40	28.63	1.85	17.58	1.15	20.15	19.06	0.89	15.96
NSD	40	28.63	1.29	24.12	1.11	26.70	24.58	1.07	26.36
MMS	40	28.63	1.29	24.12	1.11	26.70	22.15	1.15	25.56

Fig. 18. Experimental result under Case-IV shading condition for TCT connection, OSK, SS, NSD, and MMS reconfiguration.

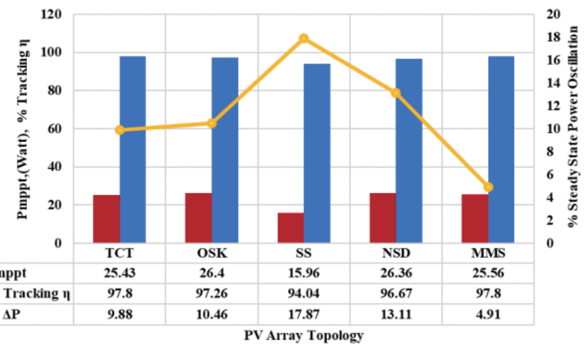

Fig. 19. Performance evaluation under Case-IV shade.

tion of traditional P&O MPPT under PSC on 4×4 PV array structures. The effectiveness of the proposed reconfiguration is evaluated through both simulation studies followed by experimental studies under complex PSCs in terms of tracked GMPP, tracking efficiency, and percent steady state power oscillations around MPP. From the results, it is revealed that the proposed reconfiguration with the conventional P&O MPPT method significantly tracks the GMPP with higher tracking efficiency and also with less steady state oscillation around the GMPP compared to conventional MPPT, which can limit use of filters.

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