A Fast-Converging Radial Basis Function Neural Network-Based MPPT Controller for Static and Dynamic Variations in Solar Irradiation

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***Abstract*—The use of maximum power point tracking techniques, often known as MPPT algorithms, is required to improve the performance of PV systems. In rapidly varying atmospheric conditions, the traditional MPPT approaches do not work as intended. In the paper, a perturb and observe technique based MPPT algorithm is developed together with a radial basis function neural network (RBFNN). To specify and track the maximum power point (MPP), the proposed framework is implemented. Employing the RBFNN as the input-output training information set, the optimal duty cycle is computed while considering varied PV array current and voltage values. Further, an intelligent reconfiguration strategy is developed to enhance the MPP and array characteristics. The proposed hybrid RBFNN and intelligent reconfiguration methodology enhance the performance by 43.05%, 12.22%, 6.81%, 5.6% with the reduced convergence time of 0.06 sec under different shading conditions.**

Keywords— convergence, maximum power point, neural network, partial shading condition, radial basis function

I. Introduction

The effectiveness of solar cells can be affected by a number of factors. The most critical factors are partial or uneven shading, low cell quality, a variety of climatic conditions, and incorrect PV power plant design [1]. Numerous strategies have been laid out thus far from the perspective of design and manufacturing technologies to boost the effectiveness of solar systems. Yet there will always be a need for research and development to boost solar power plant effectiveness. Under certain conditions, the MPPT technique is one of the effective methods to get the highest available power from solar PV production technology [2]. The peak power at which the maximum power may be obtained is known as the maximum power point (MPP). However, the solar PV system's performance experiences issues and has a low efficiency as a result of factors including irradiation and temperature variation, shadowing, series and parallel resistance, etc. It is necessary to employ an efficient maximum power point tracking (MPPT) technique to improve efficacy and tracking performance under varied circumstances in order to address the aforementioned issues. In [3], various MPPT methods for non-uniform and uniform irradiation conditions have been reviewed in detail. Numerous studies have also concentrated on creating sophisticated soft computing methods for MPPT systems operating in both uniform and non-uniform irradiation conditions. Adverse environmental factors and the nonlinear behaviour of MPPT approaches can be addressed using various intelligent methods.

The ability for the SPV system to operate at local maximums is provided by the conventional MPPT control methods such as perturb and observe, hill climbing, incremental conductance etc. While by using the advanced strategies, the operating point of the SPV array can be tracked at the global maximum points under non-uniform irradiation conditions, enhancing the effectiveness of the solar power plants. An enhanced team game optimization technique [4] that uses just one tuning parameter to achieve faster convergence has been offered as a new metaheuristic method. The authors further employed a constant current technique under load variation, which improved the system's response to loading variations by 78.26%. In [5], the authors experimented and proposed a hybrid ANFIS–PSO-based mppt strategy to extract the MPP under fluctuating sun irradiance conditions. By updating the squirrel's position without a predator nearby, a new flying squirrel search optimization (FSSO)-based strategy [6] with a significantly shortened convergence time has been developed. This control strategy produces a steady-state response that is non-oscillatory, smaller transients, and higher tracking efficiency.

A P&O MPPT-based particle swarm optimization (PSO) with enhanced search space, optimized through the Fuzzy Fokker-Planck solution has been proposed in [7]. However, the following shortcomings are inherent with fuzzy logic control-based systems: totally reliant on human knowledge and skill, constant updating of fuzzy rules, procurement of inaccurate input data [8]. To deal with periodic changes and mitigate the steady-state oscillations and errors, a hybrid MPPT method based on the perturb and observe (P&O) algorithm and iterative learning control (ILC) algorithm has been presented in [9]. Nevertheless, the hybrid methods, even though being efficient inherits the complexity and disadvantages of both the methods. All these above-mentioned MPPT controllers track/extract only the MPP. However, the PV array reconfiguration strategies are getting popularity these days which enhances the MPP as well as the array characteristics significantly. The reconfiguration strategies include static and dynamic approaches to configure the panels in a PV array. The static approaches are preferred over the dynamic ones. The static approaches include chaotic-based strategies [10-11], puzzle-based [12], magic square-based [13], encryption-based [14-16], etc. This paper focusses on combining the intelligent reconfiguration strategy with the intelligent radial basis function neural network based MPPT approach for maximizing the MPP and tracking it effectively with

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minimal time. The main contributions of the proposed work are as follows:

- A novel intelligent reconfiguration strategy based on partition numbers-based encryption approach is proposed for enhancing the MPP with enhanced array characteristics.
- A radial basis function neural network based MPPT controller is proposed for tracking the enhanced MPP.
- The proposed hybrid reconfiguration and MPPT approach is tested under dynamic varying solar irradiation conditions and four distinct static partial shading conditions.
- The in-depth analysis of the proposed hybrid approach is presented in detail including the power-voltage characteristics of distinct shading cases.

II. Proposed Methodology

In this paper, a hybrid reconfiguration and MPPT approach is proposed to maximize and track the MPP with improved convergence. The description of the hybrid approach is as follows:

A. *Partition function Encryption-Based Reconfguration*

The set of possible segments of a non-negative integer n is represented by the partition function p(n) in number theory [17]. For example, p(4) = 5 when the integer 4 is divided into 5 equal parts: 1 + 1 + 1 + 1, 1 + 1 + 2, 1 + 3, and 4. The partition function doesn't have a closed-form expression, but it does have asymptotic expansions that closely resemble it and recurring relations that allow for precise calculation. It develops as an exponential function of the argument's square root. The Euler function, which is an alternating sum of the argument's pentagonal number powers according to Euler's pentagonal number theorem, is the multiplicative inverse of the generating function. Starting with p(0) = 1, the partition function's initial few values are as follows: 1, 1, 2, 3, 5, 7, 11, 15, 22, 30, 42, 56, 77…….

Transformation matrices are used in systematic encryption to reposition an image's pixels [18]. The pixels are effectively decorated by the transformation matrices created by the integer sequences. The Partition function series-based transform preserves uniformity, distributing all neighbouring pixels so that they are equally spaced from one another and guaranteeing the most effective encryption. It is important to be noted that a 2×2 matrix created from the first four consecutive integers in the Partition function sequence is a unimodular matrix that effectively repositions the matrix's pixel coordinates and can be used to scramble images using encryption [19]. The mapping $F: T^2 \rightarrow T^2$ is the generalized form of the Partition transform and is defined as follows:

$$\begin{bmatrix} p(i+1) \\ q(i+1) \end{bmatrix} = \begin{bmatrix} P_i & P_{i+1} \\ P_{i+2} & P_{i+3} \end{bmatrix} \begin{bmatrix} p(i) \\ q(i) \end{bmatrix} \bmod Z \qquad (1)$$

where p, q belongs to {0, 1, 2, 3,⋯..N-1}, p(i), q(i) are the old locations and p(i+1), q(i+1) are the new locations of the matrix, P_i is i-th term in a Partition sequence, 'mod' is the mod operation and 'Z' is the matrix size. By using Eq. (1), the numbers in the original matrix are transformed in order to obtain the encrypted matrix shown in Fig.1. The PV panels in the array are configured based on the obtained encrypted pattern shown in Fig.1.

11	12	13	14	15	16	17
21	22	23	24	25	26	27
31	32	33	34	35	36	37
41	42	43	44	45	46	47
51	52	53	54	55	56	57

Original 5×7 matrix

55	41	57	21	34	42	16
33	24	25	26	17	54	12
11	52	32	45	53	36	27
44	35	46	37	15	23	31
22	13	51	14	56	47	43

Encrypted matrix

Fig.1 Original and encrypted matrices

B. *Radial Basis Function-based intelligent MPPT*

For problems involving function approximation, radial basis function neural networks (RBFNN) are a popular variety of artificial neural network [20]. The universal approximation and quicker learning pace of the RBFNNs set them apart from other neural networks. Three layers, the input layer, the hidden layer, and the output layer, make up an RBF network, a form of feed-forward neural network. The duties assigned to each of these tiers vary. Specialized activation functions, including the Gaussian function, multi-quadratics, and inverse multi-quadratics, are used in the RBFNN hidden layer. These activation functions have the benefit of offering localized, confined, and radially symmetric activations, which reduces the distances from function centers in comparison to back propagation neural network (BPNN), which generates global and unbounded activations.

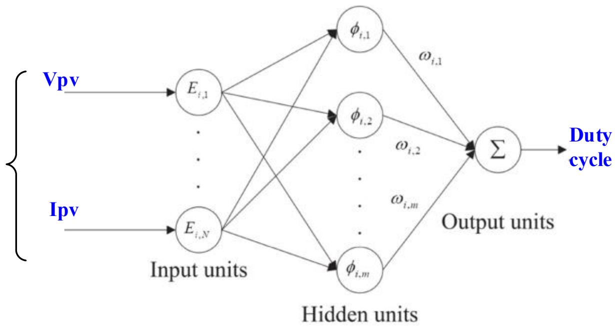

Fig.2 RBF neural network architecture

The Fig. 2 depicts RBFNN. The Gaussian activation function used in the hidden layer is centred on a vector in feature space. From the input layer to the hidden layer, there are no weights [21]. Every j^{th} Gaussian hidden unit receives the input layer directly. The RBF's output for the kth unit is presented as:

$$O_k = B_0 + \sum_{j=1}^{h} W_{jk} * H_j \qquad (2)$$

$$H_j = f\left(\left|I - C_j\right|\right) \qquad (3)$$

where H_j is the j^{th} hidden unit's radial basis output and C $\in R$ corresponds to RBF's centre, which has a radius of r.

$$f(x) = e^{\frac{-\left(\left|I - C_j\right|\right)^2}{r^2}} \qquad (4)$$

where $f(x)$ denotes the Gaussian function equation, $x_i = \left|I - c_{ij}\right|$. Gradient descent learning is the most common method for updating the centre C_j and W_{jk}. The mean square error (MSE) determines how well the neural network performs. The output-layer weights w_{jk} are adjusted to minimise the MSE based on the input 'I' and target vector 'T', and the result is reported as

$$E = \frac{1}{m}\sum_{k=1}^{m}(T_k - O_k)^2$$

where O_k represents network output at k^{th} sample, T_k denotes target network output at k^{th} sample and m denotes total training patterns.

III. Results and Discussion

A standalone 5×7 solar PV (SPV) array with a standard DC-DC boost converter and load resistance, as illustrated schematically in Fig.3, is modelled in the MATLAB/Simulink environment to test the effectiveness and viability of the proposed intelligent controller.

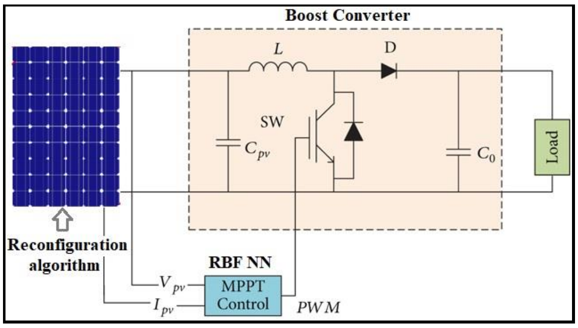

Fig.3 Standalone PV system with proposed hybrid control

The proposed controller enables the PV array to be operated at MPP. The dynamic response of the SPV system in relation to the power output of the SPV array (before and after reconfiguration) corresponding to the MPP of the dc-dc boost converter has been thoroughly studied and is presented as follows:

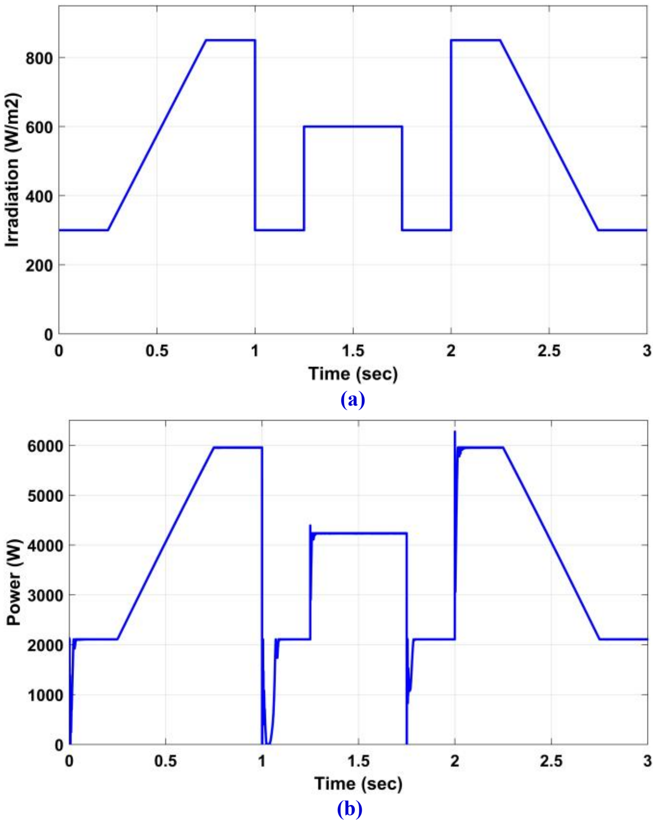

Fig.4 (a) Dynamic ropp irradiation profile (in W/m2) and (b) corresponding power output obtained by the proposed controller

A. *Analysis under Dynamic Variation in Irradiation*

To show the effectiveness of the proposed method, it is validated under both uniform and partially shaded conditions. The proposed method is tested using the Ropp irradiation test profile of uniform shading conditions. In this test, the considered Ropp profile consists of gradual, sudden ascents and descents (Fig.4). From (0 - 0.25) sec, the irradiation of 300W/m^2 is maintained constant. From (0.25 - 0.75) sec, the irradiation is gradually increased from (300 - 850) W/m^2. From (0.75 - 1) sec, the irradiation is kept constant at 850W/m^2. At 1 sec the irradiance is suddenly reduced to 300W/m^2 and maintained the same till 1.25sec and at 1.25 sec the irradiance is again increased to 600W/m^2 and maintained till 1.75sec, at 1.75 sec the irradiance is suddenly reduced to 300W/m^2 and maintained till 2 sec, at 2 sec the irradiance is suddenly increased to 850W/m^2 and maintained till 2.25 sec, at 2.25 sec the irradiance is varied in the form of the reduced slope till 2.75 sec and from here it is maintained at 300W/m^2 constant till 3sec. During these different shading instances (raising slope and falling slope irradiances), the proposed algorithm tracked the MPP at all these varying irradiances within 0.06 seconds.

B. *Analysis under Static Partial Shading Conditions*

The performance of the proposed algorithm under partially shaded conditions is investigated with various-

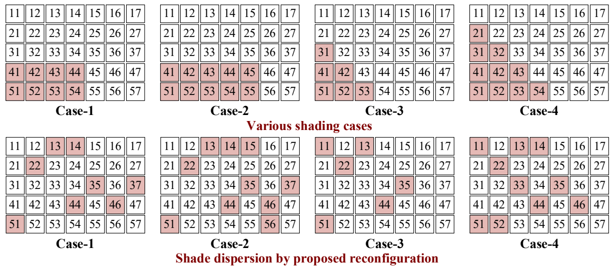

Fig.5 Various static shading cases and respective shadow dispersion by the proposed reconfiguration algorithm

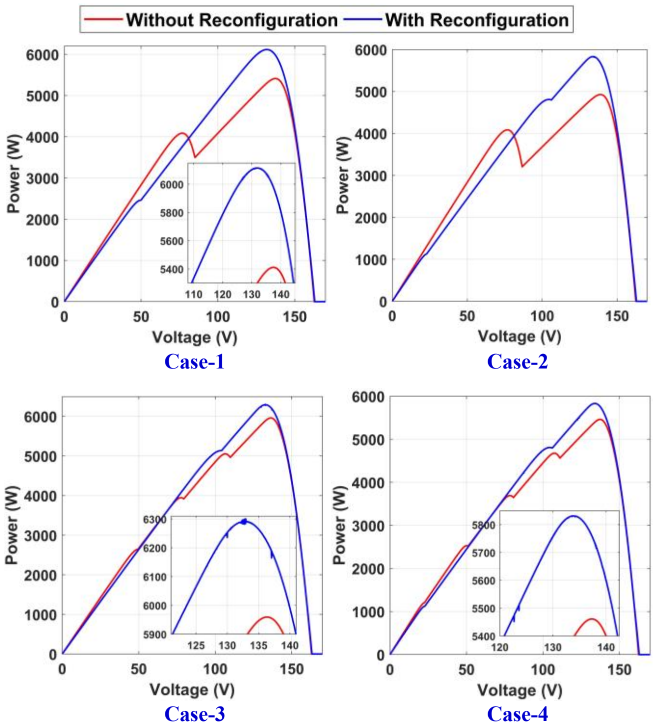

Fig.6 Power-Voltage characteristics under Case-1 to Case-4

-shading patterns such as progressive rectangular and triangular patterns as shown in Fig.5 and the respective Power-Voltage characteristics under Case-1 to Case-4 are shown in Fig.6.

The effectiveness of the proposed hybrid algorithm is demonstrated by performing a comparative analysis of the solar PV system output before and after reconfiguration. In case 1, a rectangular shading pattern is introduced in the PV array where the unshaded panels receive 1000 W/m^2 of the solar irradiance and the shaded panels which are in rectangular shape receive only 500W/m^2 of the solar irradiance which creates the multiple power peaks in the PV characteristics. At this condition the conventional algorithms like P&O, Incremental conductance methods tend to struct at the LMPP, but the proposed method tracked the GMPP. The reconfiguration technique disperses the shading effect uniformly and reduces the multiple peaks in the PV array characteristics. The comparison between before reconfiguration and after reconfiguration is also shown in Fig.7 where the mppt controller tracks the GMPP at 5400W, after reconfiguration the shading pattern is dispersed and the MPPT controller was able to track the GMPP at 6060W thus it is evident that after reconfiguration there is power enhancement in the PV system of 12.22%.

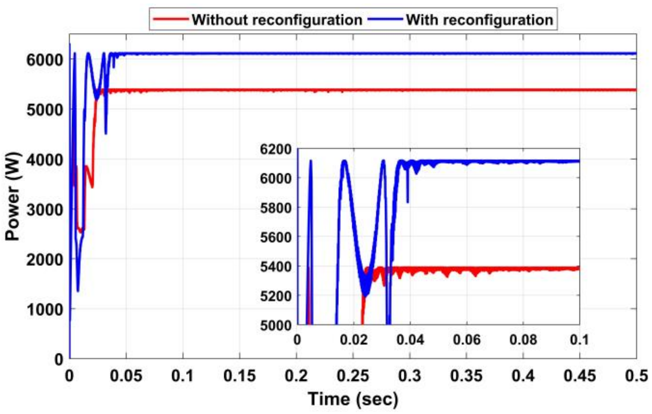

Fig.7 Power output under Case-1 shading condition

In case 2, the rectangular shading pattern that has been considered in case 1 is further progressed over the PV array in order to validate the proposed strategy for progressive shading conditions. Before reconfiguration, the proposed MPPT technique was able to track the GMP at 4074W and after reconfiguration, the GMP was improved to 5828W which shows a significant power increment of 43.05% as shown in Fig.8.

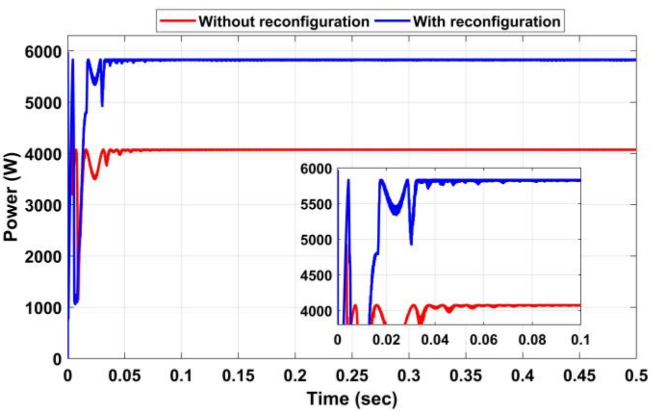

Fig.8 Power output under Case-2 shading condition

In case 3, a triangular shading pattern is introduced as shown in figure.3 where the power output from the PV array is 5955W before reconfiguration and the power output is 6288W which shows a power increment of 5.6% as shown in Fig.9.

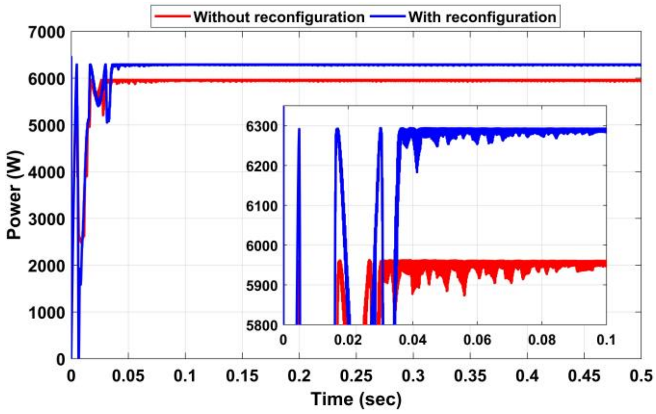

Fig.9 Power output under Case-3 shading condition

In case 4, a triangular shading pattern that has been considered in case 3 is further progressed over the PV array as shown in figure.4 where the power output from the PV array is 5456W before reconfiguration and the power is enhanced to 5828W after reconfiguration which shows a power increment of 6.81% as shown in Fig.10.

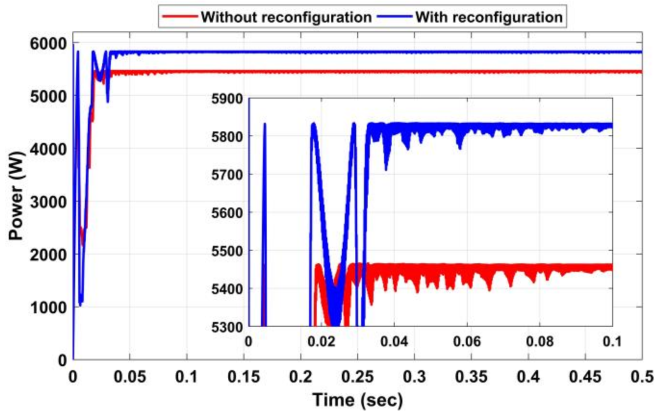

Fig.10 Power output under Case-4 shading condition

TABLE I. COMPARISION OF MPP (IN WATT) BEFORE AND AFTER RECONFIGURTAION UNDER VARIOUS CASES

Shading case	MPP (W)		% gain
	Before Reconfiguration	After Reconfiguration	
Case-1	5400	6060	12.22
Case-2	4074	5828	43.05
Case-3	5955	6288	5.6
Case-4	5456	5828	6.81

It can be inferred from Table.1 that MPP has been enhanced significantly after reconfiguration.

IV. CONCLUSIONS

In this paper, a novel intelligent reconfiguration strategy based on a partition numbers-based encryption approach is proposed for enhancing the MPP with enhanced array characteristics. Further, a radial basis function neural network-based MPPT controller is developed to track the enhanced MPP. The proposed hybrid reconfiguration and MPPT approach is tested under various dynamic varying solar irradiation conditions and four distinct static partial shading conditions. The in-depth analysis of the proposed hybrid approach has been presented in detail including the power-voltage characteristics of distinct shading cases. The proposed hybrid RBFNN and intelligent reconfiguration methodology enhance the performance by 16%, 5%, 16%, and 5% with reduced convergence time and lowered steady-state oscillations under different shading conditions. From the comprehensive analysis, it is noteworthy to mention that the proposed hybrid approach is the need of the moment to mitigate the effects of partial shading conditions.

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