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A cost-effective and optimized maximum powerpoint tracking system for the photovoltaic model

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ABSTRACT

Solar energy is naturally available from sun, and it can be extracted by using a photovoltaic (PV) cell. However, solar energy extraction entirely depends on the climatic conditions and angle of rays falling on PV cells. Hence, maximum powerpoint tracking (MPPT) is considered in most areas under variable climatic conditions, which acts as a controller unit for PV cells. MPPT can enhance the efficiency of PV cells. However, designing an MPPT model is challenging as different uncertainties in the climatic condition may lead to more fluctuations in voltage and current in PV cells. Under the shaded condition, the PV cell may have other MPPT points that lead to the PV cell's low efficiency in analyzing maximum power. Hence, this paper introduces a cost-effective and optimized system for the PV model that can find optimal power and improve PV cells' efficiency. The proposed system achieves better computational performance with ~35% and ~42% than existing MPPT techniques. The improved particle swarm optimization (PSO) is smoother due to the enhanced form of MPP tracking. Hence, improved PSO takes 0.038 sec while the existing PSO technique takes 0.045 sec to obtain the MPP tracking.

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1. INTRODUCTION

The available non-renewable energy-based power system fails to fulfill the current power demand, making all the researchers look into naturally available resources to generate energy. Among these energy resources, solar rays from sun are freely available, generating electricity using photovoltaic (PV) cells [1]. Another significant aspect of solar concerning conventional sources is that pollution is free and costs are too low. However, the climatic variation has more impact on the PV cell-based power generation. Thus, many researchers and academicians suggest using maximum powerpoint tracking (MPPT) and improving the performance of PV cells to extract maximum power under different climatic conditions [2]. Under these conditions, the MPPT controller must be incorporated with PV to extract high power without fluctuations [3], [4]. Many of the works suggested considering external parameters like solar cell temperature to generate the highest power from PV cells and improve their performance [5], [6]. The following features characterize the standard design of the MPPT: i) the fluctuation in the voltage-current characteristics associated with the solar cell where the source of energy is PV; ii) the solar power system will always have a dependency towards solar-charged MPPT controller to obtain the highest range of power obtained from PV module. MPPT also makes a PV module to control the voltage near the highest power point to extract the highest available power; iii) the PV module is used by the MPPT solar charge controller by the user always with the maximized outcome of voltage compared to the operating voltage of the battery; and iv) the complexity associated with the solar charge MPPT controller is reduced, balancing the higher efficiency of the system. More energy sources can also be used in the MPPT controller as the power of PV output is mechanized for directly controlling the converter of direct current-direct current (DC-DC) [7]–[10].

Irrespective of beneficial factors in its usage, there are significant challenges associated with the MPPT control system regarding optimization issues that can be achieved with an evolutionary algorithmic approach. In this sector, particle swarm optimization (PSO) possess the characteristics for achieving maximum probability of exploring solutions towards achieving global optima, better robustness, parallel processing [11]–[13]. In a work of Ibbini and Adawi [14], the accuracy aspects of MPPT are addressed, while in Azary *et al*. [15], an inverter design is carried using MPPT but fails to provide efficiency. An enhanced PV system with a predictive scheme is introduced in Caporal *et al*. [16]. In Ghasemi *et al*. [17], an approximation method is used to extract maximum power faster under partially shaded conditions. Two other authors Jeyaprabha and Selvakumar [18], have introduced maximum power tracking using a flyback converter. A simulation for MPPT is carried in Jiang *et al.* [19], which offers a higher degree of efficiency. Towards enhancing the performance of MPPT in power tracking, various works have been carried [20]. Perturb and observe (P&O) method can offer better power tracking but fails to give optimal tracking under partially shaded conditions [21]. Hence, Parlak and Can [22] have shown a scanning method for accurate tracking of MPPT but exhibit higher computational complexity while tracking. An optimization approach for MPPT is introduced in Zhang and Cao [23] under dynamic climatic conditions, and it lags with a higher convergence time. Ramaprabha *et al.* [24] used a PSO optimization algorithm to get the optimal solution for MPPT and enhance the PV models performance. Thus, from the existing research analysis, it is obtained that there is a need for study on MPPT based researches so that the cost of MPPT approach under shaded conditions is relatively high due to higher computational complexity, and obtaining an optimal solution for MPPT is the challenging task [25]–[27].

This paper describes a cost-effective and optimal approach for MPPT by introducing an improved PSO. The papers organization is as follows: discussion of proposed research methodology is briefed in section 2 while result discussion is addressed in section 3, and the conclusion is discussed in section 4. After reviewing the existing approaches of MPPT, it has been seen that the majority of the existing techniques are characterized by issues of performing tracking at a slower pace. This phenomenon also minimizes the efficiency of utilization. Apart from this, the core problem associated with the power generation of the PV system is overcoming the non-linear characteristics of the array of PV, which is the primary temperature and radiation level. The differences in the panel's voltage can also cause issues associated with the location of universal MPP concerning different positions either under complete or under the partial condition of the atmosphere. Also, solutions offered in the existing system are highly iterative, although they eventually target achieving the best MPPT in PV cells. Hence, irrespective of a better outcome, their applicability cannot be considered accountable. The structure of the existing solution is too complex to be adopted even for smaller or simplified operations. Hence, the problem statement of the proposed system is, "*It is challenging to design a simplified and yet improved optimization approach using PSO to achieve optimal MPPT level in PV cell*." The following section discusses the proposed solution.

The proposed solution targets achieving performance enhancement towards optimizing multiple peak functions. The study considers the higher suitability of PSO [28] towards an MPPT control system associated with a PV system. However, existing approaches using conventional PSO results in overlapping of particles path during searching. Because there is a good possibility of certain particles lying over the path that has been already searched by other particles, too, during the search for a global path and is an unaddressed problem when using PSO with an iterative search towards MPPT in PV cells. Also, it could further adversely affect the convergence speed, which can lower down too. Also, under a particular condition, there is a possibility of swaying certain particles away from the global path. Therefore, the proposed study contributes towards developing a PSO-based optimization of reaching MPPT in PV cells where the particles that perform an iterative search will be transformed into a passive way over a smaller region. This contributes to developing a novel PSO approach that tracks the highest possible power point with higher accuracy. The proposed solution also targets efficient and speedy MPPT with higher improvement as a significant contribution. The proposed solution is to develop a model with a DC-DC converter to achieve MPPT associated with PV cells. The implementation considers both solar radiation and temperature and targets faster computational processing. The following section discusses the proposed research methodology.

2. PROPOSED METHOD

This paper aims to design a cost-effective and optimal PV system to track MPPT points or maximum power. The architectural form of this approach is given in Figure 1. The novelty of the proposed system is that it offers a reliable and simple computational model by incorporating an MPPT algorithm for tracking maximum power in less time. Also, the proposed system does not generate any oscillator circuit causing capacitor discharge. A diode design is used in the proposed system, which performs as a switch; if the applied voltage to the capacitor reaches higher than the threshold voltage or falls below the threshold voltage. Another significance of the proposed PSO is that it allows for a quicker search while still following the maximum power point optimum solution. After particles acquire the MPP, the velocity approaches zero. As a result, there will be no oscillations in the steady-state. The steady-state oscillation is required since it aids MPPT efficiency. Another notable aspect of modified PSO is that it has a three-duty cycle. Hence, it does not lose direction in short-term fluctuations. The proposed PSO is effectively able to track the global peak.

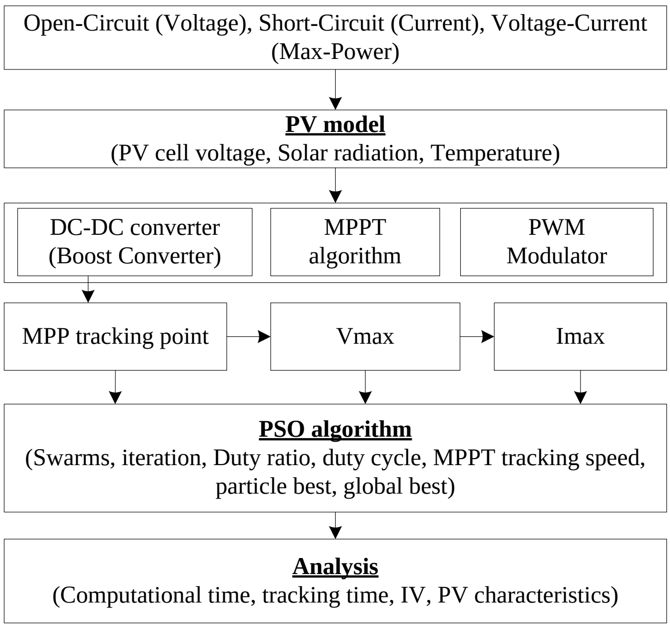

Figure 1. The architecture of the proposed approach

The primary aim of the proposed approach is to design a system with a DC-DC converter to get MPPT in a PV cell. During the design, mathematical modeling is performed to bring a higher degree of feasibility to the design. The design considers four inputs: open-circuit (voltage), short-circuit (current), and maximum power corresponding to voltage and current. The algorithm for MPPT is introduced to make use of the PV model and DC-DC converter for both temperature and solar radiations. In this, the current-voltage (I-V) and power-voltage (P-V) analysis is performed for both solar radiation and temperature aspects. The DC-DC converter helps to identify and rectify the power fluctuations introduced due to variable climatic conditions. To get better tracking speed in MPPT, an improved PSO approach is presented.

The improved PSO algorithm divides the duty cycle (d) into two parts (d_1 & d_2), where the previous duty cycle ratio has a linearization factor (K_1) that can be varied based on the output of the PV array. In search of a better PV curve to get MPPT, the search method moves towards the linearization factor (K_2). The following Figure 2 provides an estimation model for K_1 where it can be observed that the maximum power of array and respective power (P_{MPP}), duty ratio, the relationship among P_b, G_b to DC/DC converter having ΔP_{MMP} with respect to duty ratio. The response optimized λ=1 can be minimized to 0.1, step 0.1. However, there exist two expressions that are considered, which brings the relationship between d_{best} and P_{MPP}. Also, there exists a linear relationship between array power and duty of 9. The new duty cycle is represented in (1) as follows [12]:

$$d_{new} = d_{old} - \frac{1}{K_1}\left(P_{old,MPP} - P_{MPP}\right) \tag{1}$$

where d_{old} is a previous duty ratio for G_b. The slope K_1=(ΔP_{MMP} /Δ_d) for linear relation changes as per change in operating power, and its value is almost equal to the new optimal duty cycle. Hence, the duty ratio initialization must perform the P-V curve searching and quickly track the new MPP.

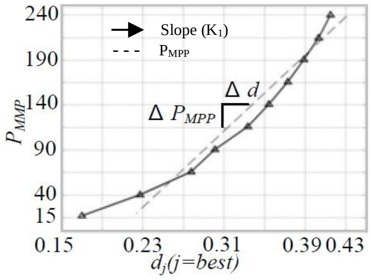

Figure 2. Relation among G_b, duty cycle and P_{MPP}

The above analysis has been found to minimize the solar radiation (from wavelength λ=1 and λ=0.1) like function. This reduction in solar radiation always leads to a load line in PV array I-V gives maximum MPP voltage (V_{MPP}) to the right of the plot curve. The increment in sunshine brings the load line to the right. The following gives the algorithm implementation.

```
Modified PSO Algorithm
Input: Vp, Ip
Output: Gb and Pb
Start
Step-1: initialize & detect Ip and Vp
Step-2: Compute P (t) = Vp x Ip
Step-3: Check if P < 0; P > 0
               Compute (d) at Vi = (1, 2, 3) = 0, Np = 3, K = 0
        Else increment i = i+1;
        Check i > Np
        Increment K = K+1;
                If   K=1;
        Pbest =di
                Else check i = 1;
Step-4:  Compute Pb & Gb
Step-5: Update→ disturbances
End
```

The difference between V_{MPP} and output voltage will become small, leading to a small variation in power. Hence, the exact value of d_{old} and K_1 is not to be deleted. Thus, the PSO algorithm needs to have more iterations to track MPP. To neutralize such types of problems, a simple assumption is made with two different values of K_1 and it is represented in (2) as follows [12]:

$$K_1 = \begin{cases} K_1 \ if \ \Delta P > 0 \\ \frac{K_1}{2} \ if \ \Delta P < 0 \end{cases} \text{ And } \Delta P = P - P_{old} \tag{2}$$

The value of P>0 and P<0 indicates the decrement and increment in sunshine radiation. To get the duty ratio of new perturbation for d1 and d3, respectively. The data ratio updates position and negative direction is represented in (3) as follows [14]:

$$(d_i)_{new} = [(d_1 - K_2), d_2, (d_3 + K_3); \tag{3}$$

The selection mechanism of the $K_2 \geq 0.05$ is considered to get accurate MPPT and it helps to manage low power fluctuation. However, during the partial shade, the use of DC-DC boost converter has reduced the effect of partial shade of solar and increases the working voltage up to 85%; this allows the PSO algorithm to track the global peak more.

The algorithm is initialized by detecting the PV current (I_p) and PV voltage (V_p) (Step-1). Further, the PV cell's initial power is computed using the general formula of power P (t)=$V_p \times I_p$ (Step-2). Later, the condition of P>0 or P<0 is verified (Step-3). If the condition is satisfied, the duty ratio (d) is calculated at duty cycles (1, 2, 3) of voltage V_i (1, 2, 3)=0 number of particles (N_p)=3, constant K=0. If it is not satisfied, then the number of iterations will be incremented by 1. Further, it is checked for '$i>N_p$' and if satisfied, the 'K' value is incremented by 1. If (K=1), the "P_b" value will be duty cycle (d_i) i.e., $P_b=d_i$. Similarly, if the condition is not satisfied, it will be checked for i=1. Then, the value of P_b can be computed after varying the condition P(i)>P(i-1). In case, the condition is satisfied, then "$P_b=d_i$" else "$P_b=d_{(i-1)}$". Similarly, to calculate global best (G_b), the same procedure of incrementing (i=i+1) and checking "i>Np". Based on this condition, G_b is computed and it is represented in (4):

$$G_b = \text{Max}\ (P_b) \tag{4}$$

Finally, the disturbance among P_b, output voltage, and G_b is updated. The duty cycle of disturbance is computed using the previous duty ratio d_i (k) and local P_b. The difference between 'i' and previous d_i (k) and G_b. Hence, the power converter and tracking best P_b, G_b, and i are possible in the proposed algorithm. The significance of the proposed PSO is that it yields a faster search and tracks the MPP optimal solution. After acquiring the MPP by particles, the velocity almost becomes zero. Hence, no oscillations will be observed in the steady-state. The steady-state oscillation is necessary as it helps get the efficiency of MPPT. Another significant feature of modified PSO is that it exhibits 3-duty cycles, and hence, it does not lose direction in short-term fluctuations. The proposed PSO is effectively able to track the global peak.

3. RESULT AND DISCUSSION

The Simulink model of the proposed MPPT model is given in Figure 3. The proposed approachs outcomes are obtained in open-circuit voltage (20 V) and short circuit current (3.50 A) and assumed the maximum power of 60 W and its corresponding voltage and current as 16 V and 3.5 A. The band gap voltage and diode quality factor are accepted at about 1.12 V and 1.2, respectively.

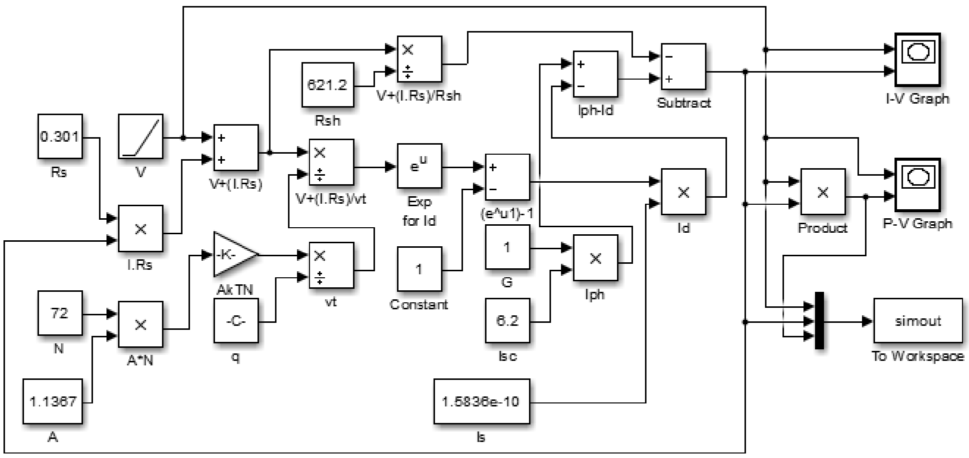

Figure 3. Simulink model of proposed MPPT model

These assumptions are more likely used in many of the research works. To build the simulink model, the PV nodes are considered and computed the current and power. The phase current is computed by using (5) and the phase current at radiance temperature current ($I_{\alpha 1}$) is represented using (6):

$$Ip_h = Ip_1 \times \beta \tag{5}$$

$$Ip_1 = I\alpha_1 + S_e \tag{6}$$

where S_e is solar emission radiation, and constant coefficient $\beta = \left[\frac{\Delta I_s}{I_{s1}} \times \frac{1}{\Delta T}\right] \times \{T_0 - \text{abs}(T_1)\}$, scaling coefficient at temperature (T_1 and T_2) is $\Delta Is = Is_2 - Is_1$, T_0 is initial temperature and ΔT is temperature difference. The resistive current I_r is represented in (7):

$$I_r = \frac{I_s(T_1, T_2)}{B-1} \tag{7}$$

where B is the exponential of open circuit voltage. The system considers temperature and solar radiations as the main aspects of the proposed MPPT analysis. Table 1 provides the PV with voltage, current, and power extracted from different solar radiation ranges from current-voltage (IV) and power-voltage (PV) characteristic at 25 °C. The table shows that current in IV characteristics decreases with voltage increase while power in P-V characteristics increases in voltage until the MPPT point is tracked.

Table 1. PV voltage, current, and power at 25 °C

Solar radiation (μm)	V_{PV} (Volts)	I_{PV} (Amps)	P_{PV} (Watts)
0.2	15.64	0.71A	59.16
0.4	16.20	1.42A	47.18
0.6	16.45	2.13A	35.12
0.8	16.58	2.84A	23.05
1.0	16.64	3.55A	11.11

The IV and PV characteristics at 25 °C for the temperature factor is represented in Figure 4. The IV and PV characteristics are shown in Figures 4(a) and 4(b) respectively. It is observed the same current and power at different temperature cardinalities. At some point of maximum point, the current and power start decreasing with an increase in temperature. The proposed MPPT systems computational performance is compared with other existing techniques considering processing time is tabulated in Table 2.

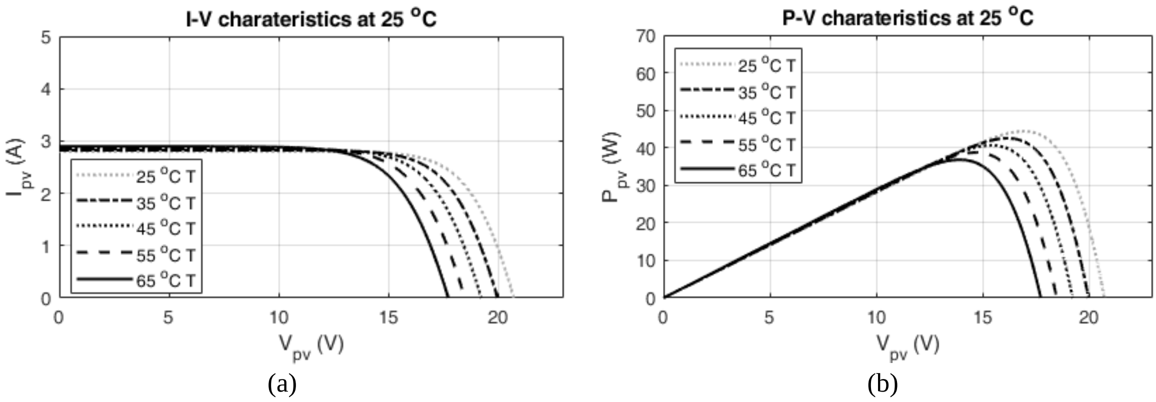

Figure 4. PV model characteristics at 25 °C for temperature factor including (a) IV characteristics and (b) PV characteristics

Table 2. Computational performance of proposed MPPT system

No. of Simulations	Computational Time		
	Ref [29]	Ref [30]	Proposed System
1	0.45	0.51	0.11
2	0.46	0.50	0.12
3	0.46	0.50	0.13
4	0.46	0.50	0.14
5	0.46	0.50	0.15
6	0.47	0.52	0.15
7	0.47	0.56	0.16
8	0.48	0.58	0.17
9	0.48	0.60	0.18
10	0.49	0.62	0.19

From Table 2 it is observed that the proposed system achieves better computational performance with 35% and 42% improvement than MPPT techniques of Kakosimos *et al.* [29] and Nedumgatt *et al*. [30]. With this performance improvement, the proposed system was cost-effective in obtaining MPPT in PV cells. The MPPT tracking time analysis for both the existing PSO technique [31] and improved PSO (proposed) is given in Table 3.

Aiming to the accurate MPP tracking, the existing PSO technique under partially shaded conditions composes large fluctuations due to the general form of PSO. At the same time, the improved PSO is smoother due to the enhanced form of MPP tracking. Hence, it is observed that the existing PSO technique [31] takes 0.045 sec, and improved PSO (proposed) takes 0.038 sec to obtain the MPP tracking. The reduced

MPPT tracking time and the use of DC-DC boost converter has reduced the effect of partial shade of solar and increases the working voltage up to 85%. Thus, it can be said that the proposed system is cost-effective and reliably faster in tracking MPPT points.

Table 3. MPPT tracking time analysis

Methods	MPPT tracking time
Existing PSO approach [31]	0.045 sec
Proposed modified PSO approach	0.038 sec

4. CONCLUSION

The concerns of the MPPT are addressed in this paper and introduced a cost-efficient and optimal MPPT approach for PV cells. The system considers temperature and solar radiations as the main aspects of the proposed MPPT analysis. The current-voltage (IV) and power voltage (PV) characteristics at 25 °C are analyzed in analyzing solar radiation over PV cells. It is observed that current in I-V characteristics decreases with an increase in voltage. In contrast, PV characteristics increase with an increase in voltage until the MPPT point is tracked. Similarly, IV and PV characteristics at 25 °C for temperature factor are analyzed and are observed same current and power at different temperature cardinalities. At some point of maximum point, the current and power start decreasing with an increase in temperature. Also, it is observed that the proposed system achieves better computational performance improvement than existing MPPT techniques. With this performance improvement, the proposed system was cost-effective in obtaining MPPT in PV cells. The proposed system can work better under partial shaded condition and enhance the performance of MPPT with higher degree of improvement in working voltage. The proposed systems futuristic scope can be modified with other heuristic and meta-heuristic methods under climatic variations. Also, the different numbers of PV array sizes can be considered for study and analysis. The proposed system can be incorporated with another renewable resource (wind) based system to build a hybrid model and enhance its performance. The proposed system can be employed for rural electrification where the cable-based power does not reach because the cost of getting MPPT is less.

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