A comparative assessment of popular tracking algorithms used in standalone photovoltaic systems

Barnam Jyoti Saharia[1], Nabin Sarmah[2]
[1]Department of Electrical Engineering, School of Engineering, Tezpur University, Tezpur, India
[2]Department of Energy, School of Engineering, Tezpur University, Tezpur, India

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ABSTRACT

Working performance of a PV module or array is largely reliant on climate (temperature/irradiation) and is also non-linear. Maximum power point tracking (MPPT) must be used to guarantee that the PV array generates the greatest electricity under any conditions. Researchers have proposed many approaches to track peak performance. There are benefits and drawbacks to every approach. Some approaches might be difficult to apply, while others provide erroneous results. MPPT boosts photovoltaic (PV) system efficiency and electricity output. Current research focuses on designing, developing, and using fast-tracking algorithms with strong dynamic performance and tracking capabilities. Without a uniform test bench, defending the optimal algorithm and converter combination is difficult. MPPT uses artificial neural networks, fuzzy logic control, cuckoo search, perturb and observe, and particle swarm optimisation (PSO) approaches. This study suggests evaluating these well-known MPPT algorithms on a 120 Wp standalone PV system with a DC-DC boost converter MPPT power interface. Tracking efficiency, inaccuracy, relative power loss, and gain are best using the PSO algorithm. Tracking efficiency improves by about 1% compared to other methods and roughly 4.5-5% for previously reported values.

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Corresponding Author:

Nabin Sarmah
Department of Energy, School of Engineering, Tezpur University
Napaam, Sonitpur, Assam, 784028, India
Email: nabin@tezu.ernet.in

1. INTRODUCTION

The operating point, irradiation, temperature, and load impedance determine a PV system's performance. PV system current-voltage (I-V) and power voltage (P-V) characteristic curves rely on irradiance and temperature. Temperature and radiation profile impact PV output voltage and current, respectively. The optimal operation of the system demands that the load match with the PV panel resistance at a given operating point subject to every input radiation and temperature. To attempt harnessing the maximum solar energy utility, deployment of maximum power point tracking (MPPT) is inevitable [1]. MPPT uses a control algorithm to maximize power transmission in a manner to configure the DC-DC converter interface between the PV panel and the load such that their respective impedances are equal [2] Figure 1. The MPPT algorithm keeps track of how the operating point of the PV panels changes with solar radiation and temperature to find the operating point of the system that gives the most power [2]–[4].

Researchers have created algorithms for quick tracking and maximum power point (MPP) finding using various methods ranging from perturb and observe (P&O) [5]–[7], fractional-short circuit (FSC) [8], [9], hill climbing [10]–[12], incremental conductance (IC) [13]–[15] fractional open circuit voltage (FOCV) [16], [17], and sliding mode control [18], [19]. Power loss and the necessary hardware for sensing and applying these algorithms prohibit their widespread usage for power tracking. Many scholars have developed alternative soft computing/evolutionary algorithms to address these problems soft computing approaches benefit from the capacity to handle non-linearity, improve search exploration, and locate optimum areas. Genetic algorithms are common algorithms [20]–[22] along with fuzzy logic-based techniques [23], [24], particle swarm optimization [25]–[27], artificial neural networks [28], [29], differential evolution [30], [31], cuckoo search algorithm [32], [33], and ant colony optimization [34], [35]. The fact that these algorithms can enable global MPP tracking at minimal PV power fluctuation with excellent efficiency more than makes up for the requirement for high performance and computing infrastructure, microprocessors.

Most algorithms have focused on establishing algorithms and control techniques to track MPP activity, although converter topology and algorithm performance variables have yet to be investigated. Tracking methods and DC-DC converter interfaces differ in literature. The converter selection affects the MPPT algorithm, tracking capabilities, and operating point efficiency to extract maximum power from solar radiation, temperature, and load profile [6], [36]. Technology-dependent PV panels and converter interfaces require a suitable methodology. The work in [37] discusses MPPT converters used in PV applications, their pros and cons, and the optimal converter architecture for PV power point tracking. Choosing the optimal topology reduces circuit complexity, component count, control flexibility, and system cost. Isolated converters are outperformed under these considerations by their non-isolated counterparts.

From the current research scenario, it is clear and evident that there has been an increasing effort to find fast responsive and accurate tracking algorithms for MPPT. Researchers have focused on the development of the same. However, there is wide variation seen in the reference PV panel for which power is being tracked, the tracking methodology implemented as well as the power converter interface for implementation of the MPPT. To choose the ideal converter and tracking method for a PV system with a connected load, converter topologies, and algorithms must be subjected to a standard test bench system. This research aims to close this gap. The MPPT interface to the PV panel is the non-isolated DC-DC boost converter, and five of the most extensively used algorithms as per reported literature discussed here above are selected to evaluate their ability to track the PV panel's MPP as radiation and temperature change. The overall schematic of the work is presented in Figure 2. The methodology followed in this paper is covered in Section 2 which discusses the PV system modeling, DC-DC boost converter operation, and the MPPT algorithms. The system modeling and simulation carried out along with the findings of comparative analysis is covered in Section 3, the results and discussion. Section 4 presents the conclusion to the work carried out highlighting the major findings.

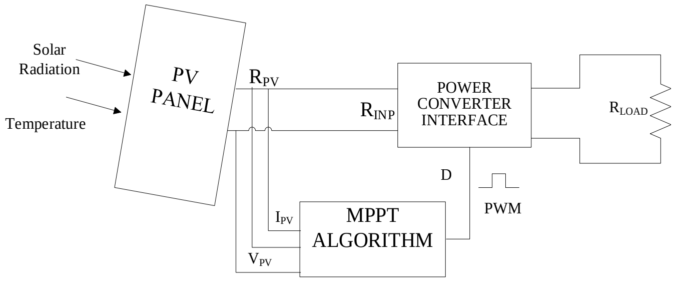

Figure 1. Standalone PV system with MPPT connected to a load

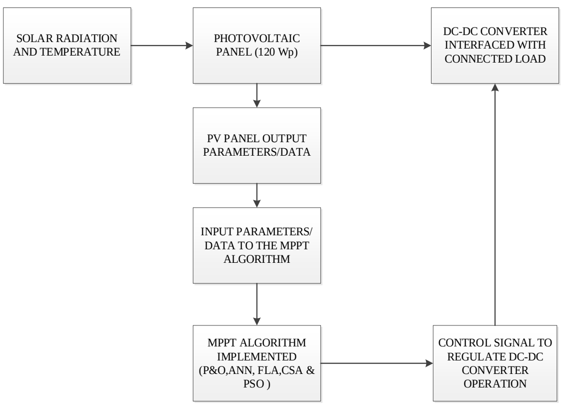

Figure 2. Schematic of PV system integrated with DC-DC Converter and MPPT algorithm

2. METHODOLOGY

The key methodological ideas used throughout the article are presented in the current section. The following subsections discuss in brief, the PV system model developed for reference in the current work, followed by a brief description of the working principle of the boost converter. Discussion on the MPPT algorithms used in this work, and in principle discusses the primary reference algorithm, the particle swarm optimization algorithm in detail concludes this section.

2.1. PV system modelling

Energy from sunlight may be converted into electricity by solar cells thanks to the photovoltaic effect. For an analogous circuit, a solar cell is equivalent to a p-n junction on a semiconductor wafer. When sunlight is exposed to a solar cell, electron-hole pairs with an energy larger than the band-gap of the semiconductor are produced, leading to the creation of photocurrent in a proportionate amount to the incident radiation. Figure 3 depicts the comparable electrical circuit for a photovoltaic cell that produces electricity from radiation that hits it.

The Kyocera KC-120-1 PV module is taken as a reference in this paper and its model in the software platform is developed in MATLAB/Simulink and presented in detail in references [6], [36]. The model developed closely matches the electrical specification provided by the manufacturer's datasheet as seen in Figure 4.

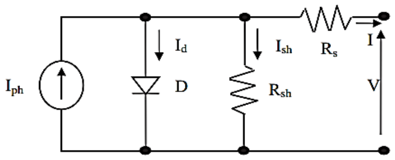

Figure 3. Equivalent circuit diagram for a PV cell

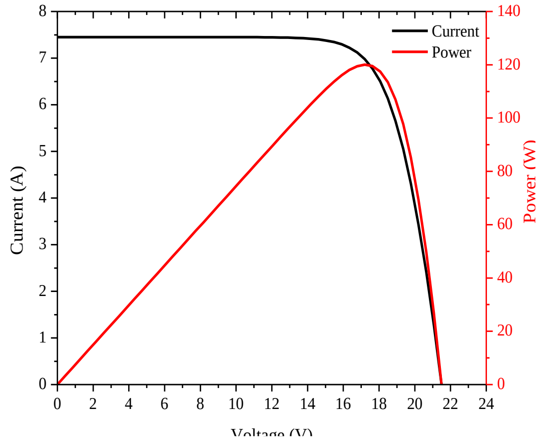

Figure 4. I-V and P-V curve of the PV module at 1 kW/m^2 and 25 ºC

2.2. DC-DC boost converter

Figure 5 shows the schematic diagrams for working of the boost converter. Boost converters are used to make the output voltage higher than the input voltage. Input and output voltages and currents are connected to the duty ratio of the boost converter given by, $\frac{V_{in}}{V_O} = (1 - D) = \frac{I_O}{I_{in}}$.

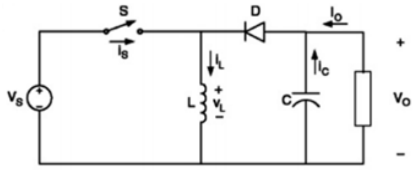

Figure 5. Schematic diagram of the DC-DC boost converter

2.3. MPPT algorithms

The MPPT algorithms automatically monitor the voltage at maximum power (V_{mpp}) and the current at maximum power point (I_{mpp}) at which the PV array connected to a converter must operate to produce the greatest power for a specific level of meteorological insolation and temperature [5]. In partial shading, many local minima might cause the algorithm to track the MPP incorrectly. It was noted from literature review that the algorithms based on perturb & observe, fuzzy logic, artificial neural networks, cuckoo search algorithm based, and particle swarm optimization (PSO) based algorithms find their use in the tracking of the MPP of PV systems. Researchers are suggesting enhancements for the tracking algorithms based on these methods, either as the reference algorithm or as the basic algorithm. The choice of the algorithms in this study is based on two things, as reported in literature, the requirement of minimum sensing parameters for computation purpose, along with the ease of implementation for achieving MPPT keeping the tracking response as fast and accurate as possible**.** The current study implements five popular MPP tracking schemes to make a comparative investigation of their performance to external atmospheric perturbations. To avoid repetition of the well-known algorithms considered for analysis in this study the reader is referred to earlier works which discuss in detail the philosophy of perturb and observe algorithm [6], [5] for fuzzy logic and artificial neural networks and [33], [38] for cuckoo search algorithm.

The particle swarm optimization, one of the most popular optimization methods. Kennedy and Eberhart [39] presented the particle swarm optimization (PSO) to mimic the behavior of swarms of fish or birds. PSO has become a very popular and widely used swarm intelligence-based algorithm over the years due to its simplicity and flexibility. The algorithm operates to alter the particle trajectories as they look for food to find the objective function. The stochastic and deterministic components of the algorithm act as a guide to determine the movement of a particle within the swarm. The particles within the swarm converge towards the global best as well as its own local best position, to allow for random search within the search space, and converge with each iteration as the algorithm searches for the global optimum solution. When a particle locates a place in the search space that is superior to the places already discovered, the position is updated for that particle in the current iteration cycle. The algorithm reaches the termination criterion when the solutions obtained after a certain number of iteration cycles, no longer gets better. Figure 6 shows the movement of particles within the search space, indicating the global best as well as the particle best. The directed movement of the particles in the updated iterative stages is also shown. Mathematically the movement of particles is represented by (1) and (2):

$$x_i^{k+1} = x_i^k + v_i^{k+1} \tag{1}$$

$$v_i^{k+1} = wv_i^k + c_1r_1(P_{besti} - x_i^t) + c_2r_2(G_{besti} - x_i^t) \tag{2}$$

Where, x_i^{k+1} gives the position of the ith particle in the k+1th iteration step, $v_i^{k+1}$is the velocity for the ith particle for the iteration step k+1, best value of the particle for the current iteration is given by P_{besti} while the swarms global best value for the current iteration is given by G_{besti}. The parameter w which acts as an inertial weight factor for the velocity to control the convergence speed, c_1, c_2 act as learning parameters and are selected to be equal to 2 while r_1,r_2 are random vectors having values within the range of (0,1) [40]. Figure 6 shows how the motion of the swarm's particles is represented [41].

2.4. Simulation model/setup

The PV-based MPPT system's system model is created in the current study using MATLAB/Simulink with five algorithms and the DC-DC boost converter as the interface. The reference PV panel selected in the current work is the 120 Wp, Kyocera KC-120-1 module connected to a constant load emulated as a resistance of 10 **Ω**. The "ode45 (Dorman-Prince) solver" with configurable step size is used to run the simulation. Current and voltage ripple of 1 x 10^{-2} A and 0.2 V respectively were considered for selecting the converter inductance and capacitance values. The switching frequency selected was 25 kHz while 21.5 V input voltage was taken, and inductor and capacitor selected were 36 mH and 400 µF respectively. From available literature [42]–[44] it has been noted that the temperature and radiation profiles are chosen for a time range of 0.9 to 3.5 seconds. The temperature and radiation profiles are also taken into consideration in the current inquiry for a duration of 1 sec due to their uniformity and relevance. Accordingly, three scenarios are considered. Two with changing values of radiation at fixed temperature and another at a fixed radiation and temperature constitute the three radiation profiles of the study as shown in Figure 7.

The variation in radiation in the first scenario is gradual from 800 W/m^2 to 600 W/m^2 (0-0.3 sec) followed by a period of steady irradiation of 600 W/m^2. At time = 0.5 sec, the radiation is increased with a constant slope to reach 1000 W/m^2 at 0.7 sec where it is held constant till the end of simulation time, i.e., 1sec. In the second case of the considered profile, the radiation has a steady starting value of 800 W/m^2 and remains so till 0.3 seconds when it gradually decreases to 600 W/m^2 at 0.5 sec simulation time. It maintains the steady value till 0.7 sec when it increases gradually to reach 1000 W/m^2 in 0.8 sec simulation time and holds this value till the end of simulation time of 1 sec. For the third profile, the steady value of 830 W/m^2 is maintained for the entire duration of the simulation time of 1 sec. In all the three cases mentioned above, the value of temperature is kept at 25 °C for uniformity.

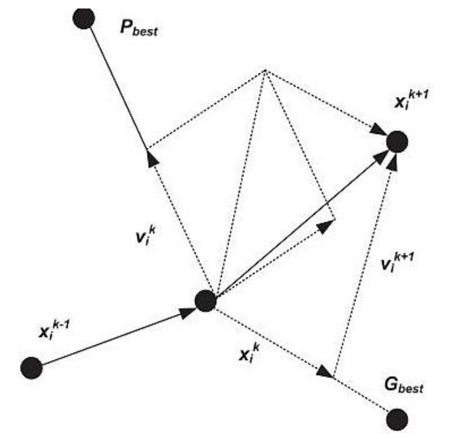

Figure 6. Movement of particles in a swarm in the PSO algorithm [41]

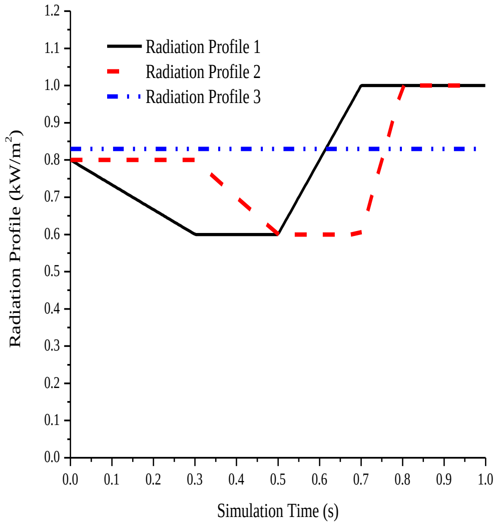

Figure 7. Different set of radiation profiles selected for analysis of MPPT algorithms

Figure 8 depicts simulation model for the MPPT tracking design using a PSO-based method. In this investigation, we set w to 0.4 and C_1 and C_2 to 1.025 for simplicity, in the PSO algorithm. The typical PSO calculates power (P) from PV panel voltage and current. Based on power, the algorithm verifies voltage perturbation. The PSO algorithm uses the PV power and the change in voltage, current, and power to determine the duty ratio D. Figure 8 shows the algorithm implemented as a function with inputs Power and Reset and D as the output. The method climbs the PV curve to the MPP like the hill climb mechanism. The method determines maximum power for each power differential in subsequent stages. The algorithm's new maximum power point determines the velocity particles and duty ratio. This is passed on to the PWM block that generates the signal to the DC-DC converter subsystem for driving the converter to meet the change in the external atmospheric condition and as a result track the MPP. The important parameters required for calculation and analysis are passed on through the output blocks to the workspace and stored for further analysis and graphical display.

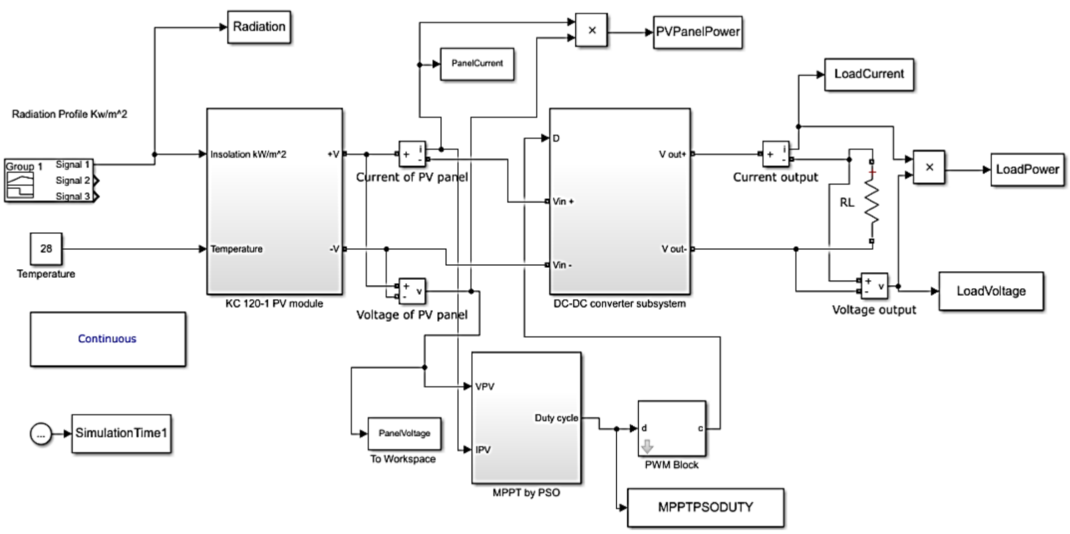

Figure 8. Simulink implementation of PSO MPPT scheme

MPPT tracking utilizing cuckoo search-based technique for a boost converter simulation model schematic is shown in Figure 9. Panel voltage and current are inputs to the Simulink-coded algorithm. Figure 9 shows how the algorithm calculates power (P) from PV panel voltage and current measurements. The algorithm tracks like the PSO, but it uses its own method. The implementation of P&O, FLA and ANN based tracking systems have been implemented from earlier works discussed in [5], [6].

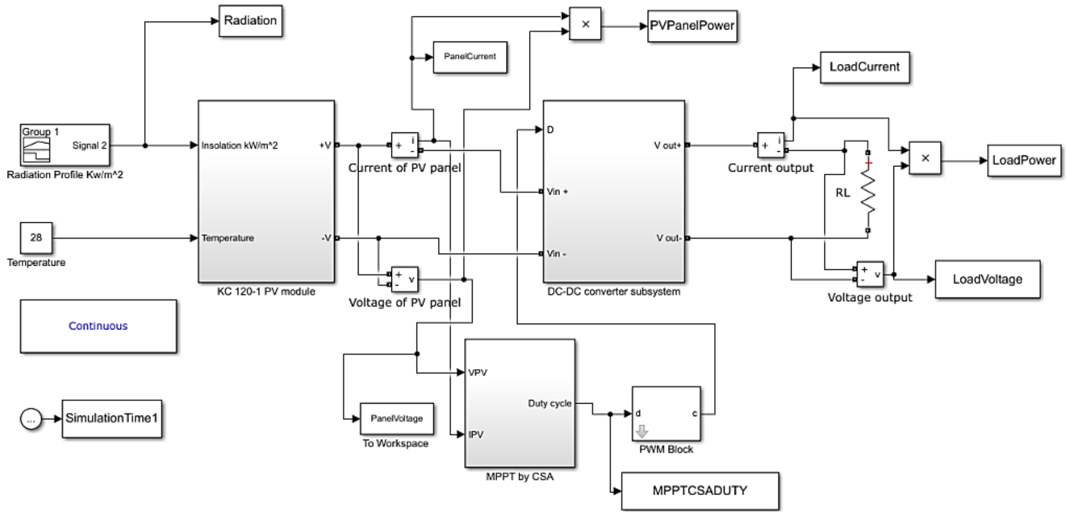

Figure 9. PV system with CS algorithm for boost converter based MPPT scheme

3. RESULT AND DISCUSSION

Tracking efficiency measures an algorithm's ability to match the PV panel's MPP under changing solar radiation and temperature. Which is defined as (3) [3], [6]:

$$\eta = \frac{\int_0^t P_{inst}(t)\, dt}{\int_0^t P_{mpp}(t) dt} \quad (3)$$

where P_{inst} stands for the algorithms, instantaneous power being tracked while P_{mpp} gives the maximum power point at the operating point [36]. The error in the tracking is also another parameter considered for comparative evaluation, defined as (4).

$$\%\, Error = (1 - \eta) \quad (4)$$

In addition to the above two parameters, PV system’s output average power (i.e., the average power tracked by each algorithm for each of the simulation periods), relative power loss (RPL) and relative power gain (RPG) [45] are also considered for performance evaluation of the algorithms. The relative power loss (RPL) and relative power gain (RPG) of the MPPT technique can be calculated by (5) and (6).

$$RPL = P_{TH} - P_{mpp} \quad (5)$$

$$RPG = \frac{P_{mpp,i} - P_{mpp,P\&O}}{P_{mpp,P\&O}} * 100 \quad (6)$$

where, P_{TH} indicates the maximum power theoretically produced by the PV panel at a given condition of Radiation and Temperature, P_{mpp} is algorithm tracked MPP, $P_{mpp,i}$ is the tracked MPP by either PSO, CSA, ANN or FLA, while $P_{mpp,P\&O}$ is the P&O algorithm tracked MPP.

Figures 10 to 12 highlight the changing PV panel power over time, resulting due to the changing radiation and temperature profile it is being subject to, and the corresponding PV power being tracked by the algorithms. Each algorithm—P&O, FLA, ANN, CSA, and PSO—shows its MPPT being tracked. For a simulation time of 1 second, the variation of external atmospheric conditions and the consequent tracking reached by each algorithm clearly shows that the converter's PSO has the best tracking performance, while the combination of P&O and ANN-based algorithm has the worst.

For the boost converter the PSO controlled algorithm, followed by the CSA, the FLA, and finally the ANN algorithm and the P&O algorithm, achieves the greatest tracking. The PSO and CS algorithms are observed to adapt to changes in irradiation levels and monitor the accompanying changes more effectively. The performance of the ANN and P&O algorithms are quite similar however, close analysis shows that there is slow response to track the power change resulting in deviation from the desired operation point. Additionally, the presence of oscillations about the steady state is another important factor to be considered for stable system operation considering the operation of the boost converter. This is accounted for the perturbation of the algorithm to external changes in insolation and temperature values and their subsequent response in the values of the voltage and current inputs to the P&O MPPT controller as the P&O algorithm keeps oscillating and it takes a while to achieve steady state stability. This is evident in the sharp and changing peaks seen in Figures 10, 11 and 12 respectively. Thus, indicating that the algorithm at times is unable to closely monitor and respond to the changes in the external perturbations.

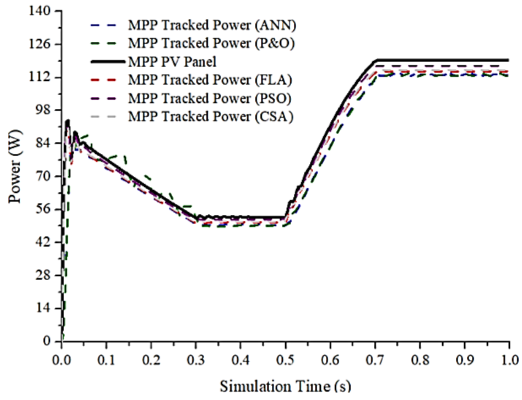

Figure 10. MPPT tracked power for radiation profile 1 for the boost converter using ANN, P&O, FLA, CSA, and PSO based algorithms

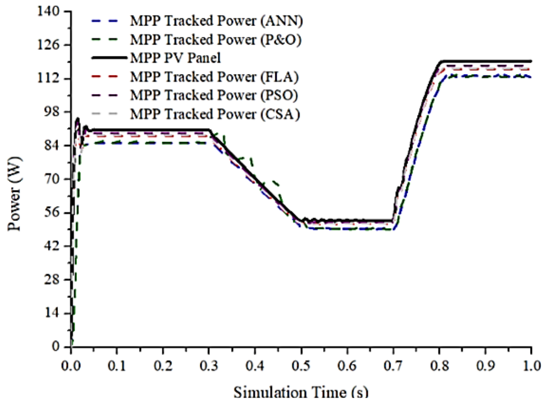

Figure 11. MPPT tracked power for radiation profile 2 for the boost converter using ANN, P&O, FLA, CSA, and PSO based algorithms

For the PSO and CS based algorithm, the duty ratio is altered in reaction to the shifting radiation and temperature contour, providing a more dynamic and quick response while tracking peak power operation. While the changes in the PSO, CSA, FLA and ANN to generate the duty ratios leads to gradual tracking and avoids sudden transitions, the generated duty ratio for P&O algorithm has the most variation. Additionally, there is variation of the duty ratio around the steady state as well as the regions of changes in radiation and temperature. This is evident in the tracked power curves for the algorithm. This specifies that though P&O algorithm is unable to track the changing conditions and closely match the MPP, the oscillations lead to unstable operation and power loss as the switching conditions prevail in the boost converter for frequent changes in the duty ratio values. This is clearly an unwanted scenario and corrective measures are needed to stabilize the system operation. Moreover, the switching transient also plays an important role in the operation of the converters as can be seen from the first peak to reach the maximum steady state indicated in Figures 10 to 12.

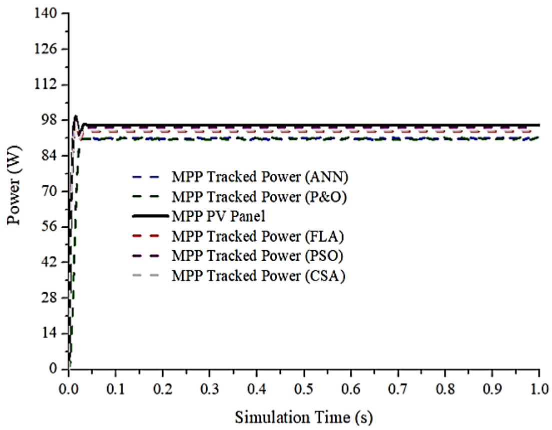

Figure 12. MPPT tracked power for radiation profile 3 for the boost converter using ANN, P&O, FLA, CSA and PSO based algorithms

Table 1 shows the average tracking efficiency, average PV system power output, relative power loss (RPL), and relative power gain (RPG) in tracking for the boost converter and algorithms combination based on simulation results. For the boost converter, PSO has the maximum tracking efficiency (98.99%) and the lowest tracking error (approximately 1%) for the third scenario with constant radiation and temperature profile. CSA tracks efficiently next (efficiency values of 96.5, 97.5 and 97.8). The FLA-based approach, the second-best algorithm, performs similarly (% efficiency = 95.5%, 97.2, and 97.5). ANN-based algorithm with tracking efficiency of 89, 87.56, and 93.8% follows FLA in tracking efficacy. P&O tracking yields 93.29% efficiency. P&O's steady state oscillations reduce boost converter efficiency and switching transients for different duty ratios. The PSO algorithm has the lowest tracking loss in the RPL at 1-3 W, followed by the CSA at 2-4 W and the FLA at 2.3-4.8 W while P&O loses equal 17.3 W. PSO again tops the other three algorithms in RPG with a maximum gain of 19.72%, followed by the CSA and FLA. PSO outperforms ANN, FLA, and CSA in tracking. With the boost converter, the PSO's power differential is within 6-19% of the basis algorithm's reference power, the P&O-based MPPT. Thus, the boost converter with PSO outperforms the other algorithms in tracking efficiency, average power output, RPL, and RPG (indicated in highlighted and bold in Table 1). Furthermore, it is seen that when compared with reported literature as in [15], [29], the tracking efficiency obtained in the current work shows improvement for the radiation profiles by almost 4.5 to 5% respectively for changing radiation profile to constant radiation profile, which shows the effectiveness of the PSO algorithm.

Table 1. Tracking efficiency (%), average power output, RPL, RPG and of the P&O, ANN, FLA, CSA and PSO based algorithms for the boost converter topology

Radiation profile	Algorithm	Tracking efficiency (% η)	Average power output of PV system (P_{avg})(W)	Relative power loss (RPL) (W)	Relative power gain (RPG) (%)
Profile1	P&O	86	91.722	15.048	0
	ANN	89	95.03	11.74	3.6
	FLA	95.5	101.985	4.785	11.12
	CSA	96.5	103.0369	3.737	12.33
	PSO	97.5	104.114	2.66	13.51
Profile 2	P&O	82.27	80.28	17.3	0
	ANN	87.56	85.44	12.135	6.43
	FLA	97.2	94.844	2.731	18.14
	CSA	97.5	95.135	2.44	18.50
	PSO	98.5	96.11	1.465	19.72
Profile 3	P&O	93.29	89.24	6.415	0
	ANN	93.8	89.711	5.944	0.52
	FLA	97.5	93.263	2.392	4.5
	CSA	97.8	93.551	2.105	4.83
	PSO	98.99	94.698	0.957	6.12

4. CONCLUSION

The paper compares the boost converter and five prominent algorithms used in PV-based MPPT tracking systems—P&O, FLA, ANN, CSA, and PSO. The PV system with an MPPT algorithm performs best when the load and dc-dc converter interface are properly selected. The boost converter with PSO with an overall tracking efficiency of 98.33%, and the tracking error being limited to about 1%, gives the best output performance with respect to tracking for the considered combination of converter interface and algorithm for PV based MPPT systems. This is closely followed by the performance of the CSA (%efficiency 97.267%), FLA based algorithm (% efficiency = 96.7%) and that of the ANN algorithm (% efficiency = 90.12%). P&O based algorithm is seen to be the least effective in the tracking of the power for the scenarios considered and the steady state oscillations in P&O make it less efficient in terms of switching transients and operation of the boost converter for varying duty ratios. The lowest loss in tracking considering the RPL is the boost converter with the PSO, while the converter with P&O gives the worst performance. This indicates that with the boost converter, the difference in power tracked by the PSO is within 5% with respect to the reference power gained by the base algorithm, i.e., the P&O based MPPT.

The current work assesses the five most popular tracking algorithms in light of recent research on PV-based MPPT tracking for quick, rapid reaction to external disturbances and steady-state functioning. The limitation of the presented work lies in the hardware implementation and validation, which is still to be assessed. Furthermore, the results are taken at a simulated load of fixed value. The potential of load change exists in real-world applications; thus, it is necessary to implement such conditions to better understand how the system performs under dynamic load-changing circumstances. This brings up the possibility of further research and is worth considering. In any case, the current study should serve as a guide for determining the ideal boost converter architecture and tracking algorithm for PV-based MPPT systems.

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BIOGRAPHIES OF AUTHORS

Barnam Jyoti Saharia received the Bachelor's degree in Electrical Engineering (with Honor's and first class) from Assam Engineering College under Gauhati University of India in 2010. He received the master's degree in Electrical Engineering from National Institute of Technology Agartala (NITA), Tripura, Agartala, India in 2014. Currently He is a faculty in the Department of Electrical Engineering, School of Engineering, Tezpur University, Sonitpur, Tezpur, Assam, India. His research interests include power electronics and renewable energy. He can be contacted at email: bjsece@tezu.ernet.in.

Nabin Sarmah received Bachelor of Science in Physics from Gauhati University, Assam, India, in 2001, Master of Science in Physics from Tezpur University, India, in 2003, Master of Technology in Energy Technology from Tezpur University, India in 2007 and Ph.D. in Mechanical Engineering, Heriot-Watt University, United Kingdom. Currently, he is the faculty in charge of AICTE Cell, Tezpur University, Associate Dean, Student's Welfare as well as Assistant Professor in the Department Energy, School of Engineering, Tezpur University, India. His research interests are solar energy, solar cells, hybrid renewable energy systems. He can be contacted at email: nabin@tezu.ernet.in.