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ADVANCED MAXIMUM POWER POINT TRACKING TECHNIQUE FOR PHOTOVOLTAIC REVERSE OSMOSIS SYSTEMS

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The paper presents a novel control algorithm for a standalone Photovoltaic Reverse-Osmosis (PV-RO) system without a battery. It highlights the importance of tracking the maximum power tracking points in the photovoltaic panels. The development of new methods has become more urgent than before. The PV-RO system combines solar energy and reverse osmosis technology to provide reliable and sustainable access to clean drinking water in remote areas. Traditional PV-RO systems often require energy storage solutions such as batteries to maintain a constant water supply during periods of low solar irradiation. However, the integration of batteries adds complexity, cost, and environmental impact to the system. The paper presents the development of different MPPT techniques, which are better than traditional techniques (more accurate and faster). The paper also provides a comparison with the studied methods (P&O and Incremental Conductance) and the proposed one.

Keywords: *Batteryless system, control algorithm, desalination, MPPT, photovoltaics.*

1. INTRODUCTION

Access to clean drinking water is a fundamental necessity for human well-being and development. However, many regions around the world, particularly in remote and off-grid areas, still face significant challenges in securing a reliable and sustainable water supply. Traditional methods of water desalination and purification often rely on fossil fuels or grid-connected power sources, which may be unavailable, expensive, or environmentally detrimental in these regions [1]. To meet the energy needs of water treatment processes, the implementation of renewable energy sources, such as solar photovoltaic (PV) systems, appears as an appealing option.

In recent years, there has been a notable surge of interest in integrating PV systems with reverse osmosis (RO) technology. Photovoltaic-Reverse Osmosis (PV-RO) systems utilise solar energy to power the desalination or purification process, providing a clean and renewable energy source for water treatment. The intermittent nature of solar energy, however, makes it difficult to maintain a steady supply of water, particularly during times of low solar irradiation, like at night or in periods of cloudy conditions. To overcome this challenge, traditional PV-RO systems often integrate energy storage solutions, typically in the form of batteries, to store excess energy during sunny periods and use it during periods of low solar irradiation.

Although battery integration enables continuous water production, it introduces additional complexities, costs, and environmental concerns. Batteries require maintenance, have a limited lifespan, and contribute to the overall system's weight and footprint. Moreover, the production, use, and disposal of batteries involve environmental and sustainability challenges. Therefore, there is a need for alternative approaches that eliminate the reliance on batteries while maintaining reliable water production in standalone PV-RO systems.

This paper presents a modified control approach for a standalone PV-RO system without a battery. A feed water tank is used as an energy storage, aimed at addressing the challenges. The control algorithm intelligently manages the photovoltaic output power and optimises the operation of the RO unit based on real-time energy availability and water demand. By dynamically adjusting the water production rate and system operating parameters, the approach efficiently mitigates the characteristics of solar energy, and the water consumption demands, thereby obviating the necessity for energy storage solutions.

The goal of the paper is to assess how well the PV-RO system performs with the new control algorithm and compare it to traditional PV-RO systems with batteries. A comprehensive simulation model is developed to analyse the system's energy efficiency, water production reliability, and overall cost-effectiveness. The results of this study make a valuable contribution to the progress of standalone PV-RO systems, offering a practical and sustainable solution for water desalination and purification in remote and off-grid locations.

The paper is structured as follows: An overview of related research in PV-RO systems and control algorithms is provided in Section 2. The technique and simulation model utilised in this investigation are described in Section 3. The results and analysis of the suggested control algorithm are presented in Section 4. The work is concluded in Section 5 by summarising the major contributions and proposing potential directions for further study in this area.

2. LITERATURE REVIEW

The performance and energy efficiency of Photovoltaic-Reverse Osmosis systems are greatly improved by control algorithms. Researchers have focused on developing innovative control strategies to ensure reliable and sustainable water production without the need for energy storage solutions such as batteries [2]. The following provides an overview of key research areas and notable contributions in control algorithms for PV-RO systems.

By tracking the maximum power point (MPP) under fluctuating solar irradiation and temperature conditions, maximum power point tracking (MPPT) algorithms seek to maximise the power output from the photovoltaic array. PV-RO systems have used several MPPT approaches, including Perturb and Observe (P&O), Incremental Conductance, and Fuzzy Logic Control. The performance of the system is enhanced by these algorithms, enabling effective usage of solar energy [3].

Energy Management and Water Demand Control: Based on current energy availability and water demand, researchers have created control algorithms that dynamically regulate the energy distribution between the PV array and the RO unit. These algorithms optimise the water production rate, regulate system operating parameters, and prioritise water supply during periods of high demand or limited energy resources. Advanced control strategies, including model predictive control (MPC) and adaptive control, increase system reliability and efficiency [4].

Power Smoothing and Load Balancing: The solar energy nature can cause fluctuations in power supply to the RO unit [1]. Control algorithms have been developed to smooth out these fluctuations and maintain a stable water production rate. Techniques such as energy buffering, load shedding, and power scheduling algorithms have been employed to balance the energy supply and demand, ensuring continuous water supply while avoiding system instabilities [5].

Fault Detection and Diagnosis: Control algorithms are used to detect and diagnose faults or malfunctions in PV-RO systems. These algorithms analyse system parameters, sensor data, and performance indicators to identify deviations from normal operation. Fault detection algorithms, such as neural networks, fuzzy logic, and machine learning techniques, enable prompt identification of system failures, component degradation, or suboptimal operation, facilitating timely maintenance and improving system reliability [6].

Real-Time Optimisation and Decision-Making: Real-time optimisation algorithms are utilised to continuously adjust system parameters and optimise the operation of PV-RO systems [7]. These algorithms consider factors such as solar irradiance, water demand, energy efficiency, and system constraints to make informed decisions regarding power allocation, water production rates, and operating points. To improve system performance and reduce energy consumption, optimisation approaches such as genetic algorithms, particle swarm optimisation, and model-based optimisation have been used [8].

Control Hardware and Implementation: Research efforts have also focused on developing control hardware platforms, communication protocols, and control system architectures for PV-RO systems. Microcontroller, programmable logic controller, and supervisory control and data acquisition system integration are a few examples of control hardware use. The implementation of control algorithms on hardware platforms enables real-time monitoring, control, and remote operation of PV-RO systems [9].

The research in control algorithms for PV-RO systems aims to optimise energy utilisation, improve water production reliability, and reduce system complexity. These efforts contribute to the development of sustainable water treatment solutions [10], especially in off-grid and remote areas. Future research may focus on advanced control techniques, integration with energy storage technologies, and system-level optimisation to further enhance the efficiency and scalability of PV-RO systems.

3. PV-RO PROPOSED SYSTEM

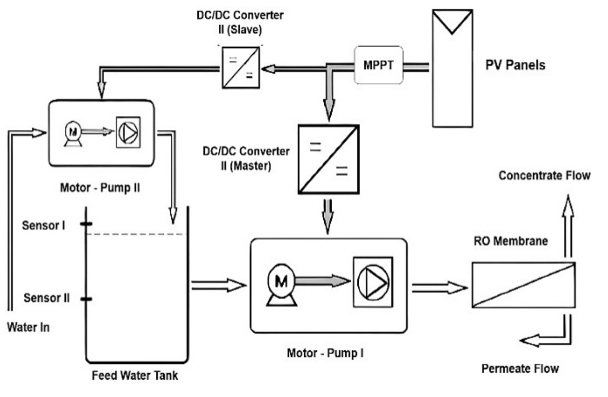

Fig. 1. Principle scheme of PV powered RO desalination.

In this study, we propose a new control algorithm that eliminates the need for a battery in the proposed PV-RO system while ensuring a continuous water supply. The algorithm intelligently manages the power output from the photovoltaic array and optimises the operation of the reverse osmosis unit based on real-time energy availability and water demand. By dynamically adjusting the water production rate and system operating parameters, the proposed control algorithm effectively balances the resulted fluctuations of the solar energy and the requirements of water consumption. This system as shown in Fig. 1 consists of photovoltaic panels, MPPT, DC-DC converters, motors, RO system, and water tank.

A thorough simulation model has been created to assess the performance of the PV-RO system using the new control algorithm. The simulation results show how well the suggested algorithm maintains a consistent water supply while maximising the use of the solar energy that is available. Compared to traditional PV-RO systems with batteries, the standalone system with the new control algorithm exhibits improved energy efficiency, reduced system complexity, and lower overall costs providing a practical and sustainable solution for water desalination and purification in off-grid and remote locations. The proposed control algorithm opens opportunities for widespread adoption of PV-RO systems, promoting and reducing reliance on fossil fuels and traditional energy sources, as well as access to clean drinking water.

4. THE PROPOSED CONTROL ALGORITHM

In contrast to other traditional search approaches, the proposed method operates on a distinct concept. The main goal of this method is to force the circuit current to operate at a value that is comparable to the MPP current value. This method can be used by figuring out predetermined current values that correspond to the highest possible power levels under various irradiation levels. To put it another way, a correlation of the maximum power and what are known as associated currents is found for different irradiation levels.

The average power will be estimated because of the continuous monitoring of the PV's current and voltage. The circuit's required current value will be decided by the computed power and the determined function. This value will be used as a benchmark against which the real value of the circuit's current will be continuously measured [5]. The Pl type control system will be used to regulate the endpoint of the operation's starting point by applying precise switching on the DC/DC converter, which serves as a mediator between the photovoltaic panel as the source of power and the load.

Using current adjustment, the system can track the necessary ideal current value, as shown in Fig. 3. The value of the power at the place where the line representing the load and current-voltage curve intersects can be used to calculate the circuit's normal operating point.

According to the power value, the system will compute a new value of current, Ireference2, and the PI controller's algorithm will push this value of current, which is determined as a function associated with the power, to identify the emphasis of the reference current, and equivalent power of the circuit [11].

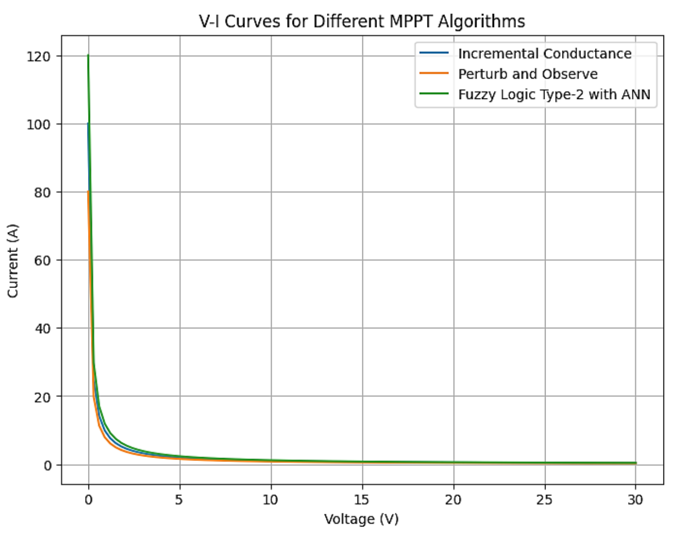

Fig. 3. V-I curve for different MPPT algorithms.

Since it does not rely on any search method, which always takes extra time to achieve the target operating point, the system may quickly follow the MPP in this way within a few milliseconds [4].

5. ALGORITHM SIMULATION

The duty cycle of the DC/DC converter, which serves as a middleman between the PVT module as a power supply and the load, will be adjusted by the Pl type controller before being used to control the location of the operation point.

The temperature will be measured, and the existing values will be updated, as shown within the modified simulation, to account for changes in temperature in three separate ranges (0–20, 21–35, and 36–55 °C). In a nutshell, each temperature variation range will have its own least-square computations for precise MPP determination.

6. CURVE FITTING

Building a curve, or ID mathematical function, that has the best fit to a set of data points while potentially considering constraints, is known as curve fitting. Two methods for fitting curves are interpolation, which requires a perfect fit to the data, or smoothing, which involves building a "smooth" function that roughly fits the data.

The simulation system shown in Fig. 4 has been initially created to track the MPP according to pushing the module values to match values from Table 1.

Table 1. Values of the Module at 25 °C

S(W/m2)	Pmax (W)	Imax (A)
1000	48.786	2.887
950	46.3626	2.8018
900	43.765	2.7441
850	41.4149	2.5827
800	38.9688	2.4341
750	36.6618	2.2357
700	34.2015	2.0905
650	31.6807	1.907
600	29.2523	1.7954
550	26.7682	1.6665
500	24.2757	1.4925
450	21.777	1.3386
400	19.2732	1.20132

The process of using a fitted curve outside the boundaries of the observed data is known as extrapolation. This process involves some uncertainty because the fitted curve may represent the construction process just as much as the observed data.

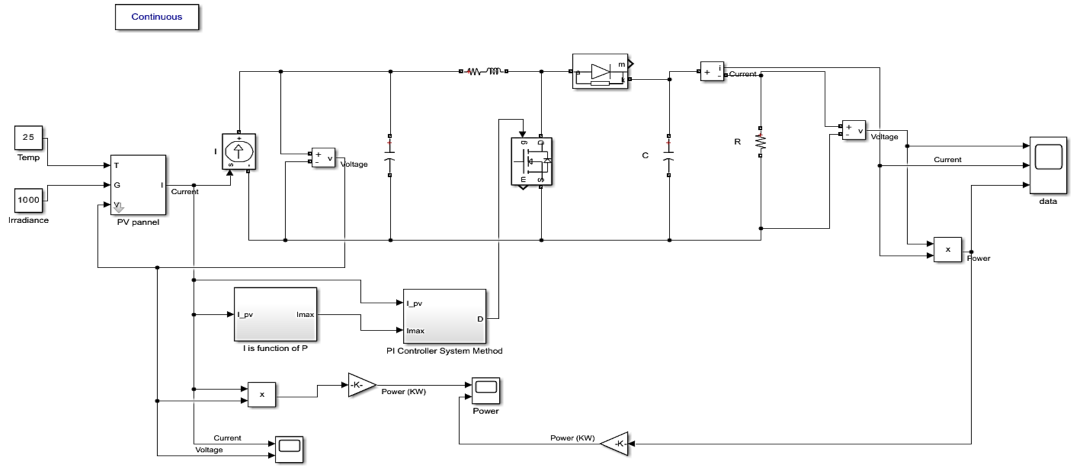

Fig. 4. The proposed method simulation.

The equation for 25 °C is as follows:

$$-7.846*10^{-5} P_{max}^2 + 0.06616 P_{max} + 0.06251. \quad (1)$$

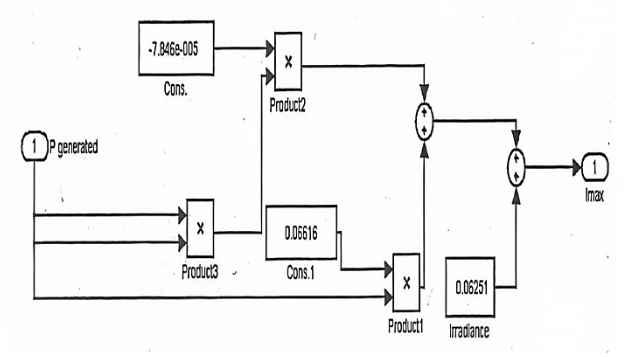

Fig. 5. Curve fitting equation subsystem.

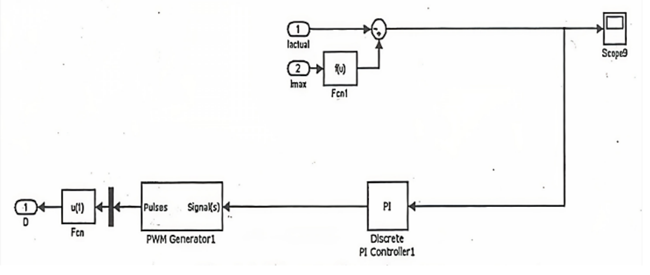

Fig. 6. PI controller subsystem.

The system is very fast in tracking the maximum power with every change of weather and load, and it may have a zero error since the locus of power changes with temperature. The maximum power point will change as well at the same irradiation level, because the PV panel currents are equal to the predetermined values of optimum current values. If the temperature varies from the calculated values at STC (Standard Temperature Coefficient), some errors may occur. An installation of a temperature sensor can solve this issue.

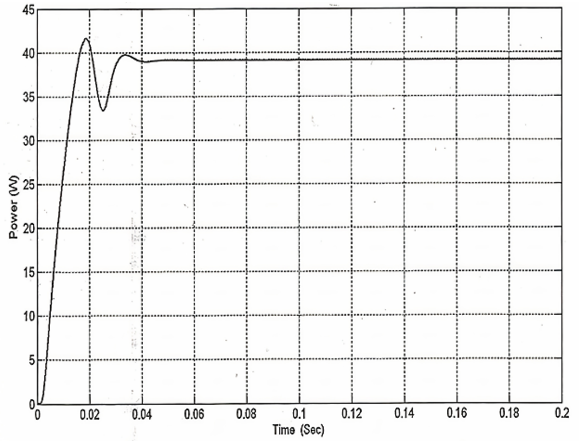

Fig. 7. The proposed method performance at 1000 W/m^2.

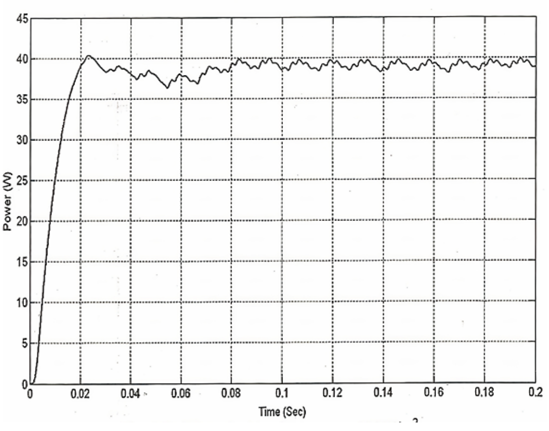

Fig. 8. IC method performance at 1000 W/m^2.

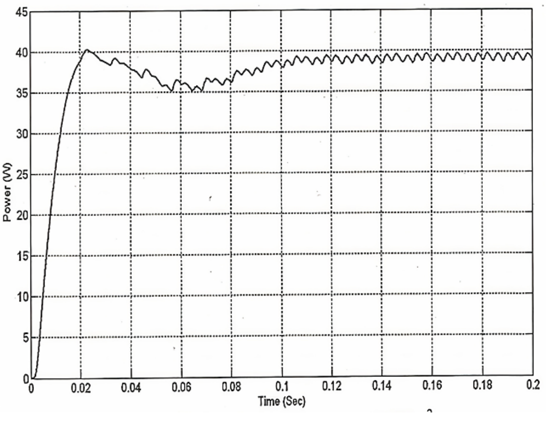

Fig. 9. PO method performance at 1000 W/m^2.

Table 2. Curve Fitting Equations

T(C)	Second degree curve	SS_E	RMSE
$0 \leq T < 20$	$4.65*10^{-5} P_{max}^2 + 0.0563 P_{max} + 0.0937$	0.005	0.023
$0 \leq T < 35$	$-7.846*10^{-5} P_{max}^2 + 0.06616 P_{max} + 0.06251$	0.012	0.035
$T \geq 35$	$-7.896*10^{-5} P_{max}^2 + 0.06616 P_{max} + 0.034$	0.004	0.022

The simulation results are given in detail and discussed with a suitable comparison with the Perturb and Observe and Incremental Conductance methods to validate the proposed method. Advantages and disadvantages of the proposed algorithm are also compared with the two traditional search methods (Table 4).

7. BEHAVIOUR OF MPPT ALGORITHM

It is difficult to evaluate MPPT behaviour, when there are two devices, and their interaction is involved in the measurement (PV module and MPPn). The actual readings of the current and voltage are measured by the PVG, but it is not easy to determine their maximum values, which vary with irradiance, temperature and other conditions.

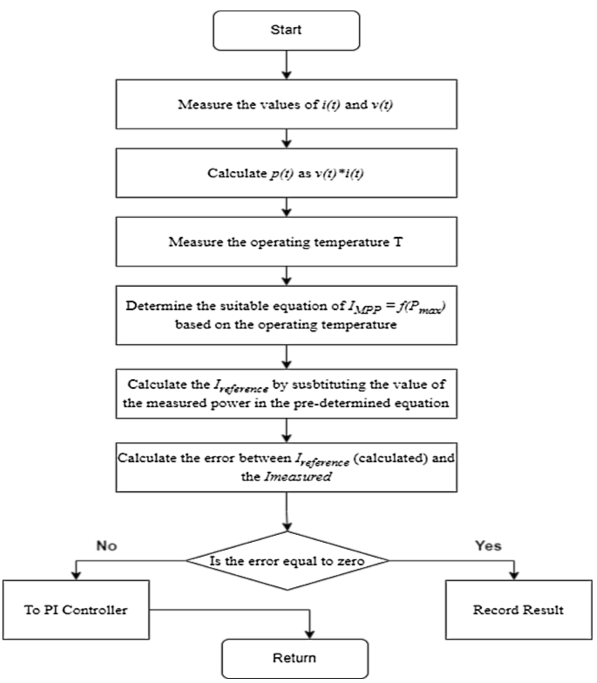

Fig. 10. Flow chart for the proposed algorithm.

The indices defining the behaviour of the MPPT algorithms shown in this section under static and dynamic modifications are provided as follows [12], [11]:

One of the straightforward and typical metrics used to show how closely the MPPT resembles the MPP is the a_{MPPT} during I_{MPP} [3]:

$$a_{mppt.p} = \frac{P}{p_{max}} * 100; \quad (1)$$

$$\text{or } \frac{v}{v_{max}} * 10 ; \quad (2)$$

$$\text{or } \frac{i}{i_{max}} * 100. \quad (3)$$

(η) The static efficiency index serves as a measure of how effectively actual PV power or energy compares to the available amount, and it is defined as follows (an example of accuracy in a specific scenario):

$$\eta_{mppt.p} = \frac{P}{p_{max}} * 100. \quad (4)$$

Let us consider that voltage or power can be used to define Eq. (1). Additionally, Eq. (6) provides the following definition for the relative tracking error (ε):

$$\varepsilon_{mppt} = P - P_{max} \text{ (Absolute)}; \quad (5)$$

$$\varepsilon_{mpp} = (\frac{P}{p_{max}} - 1) * 100 \text{ (Relative)}. \quad (6)$$

Additionally, to explain the MPPT's proximity to the maximum power point during a time period from 0 to tm, the energetic error of the MPPT ($\varepsilon_{mppt.E}$) and the energetic efficiency ($\eta_{mpp.E}$) are given as follows:

$$\eta_{mppt.E} = \frac{\int_0^{tm} P(t)d(t)}{\int_0^{tm} P_{max}(t)d(t)} * 100; \quad (7)$$

$$\varepsilon_{mppt.E} = (\frac{\int_0^{tm} P(t)d(t)}{\int_0^{tm} P_{max}(t)d(t)} - 1) * 100. \quad (8)$$

8. RESULTS

Table 3 shows the percentages of these indices for all the MPPT algorithms under study. It is notable that the proposed algorithm guarantees better values compared to the corresponding values of the conventional P&O and IC based MPPT algorithms.

Table 3. The Assessment of Algorithm Characteristics

Characteristics	Perturb and observe	Incremental conductance	Proposed
$a_{mppt.p}$	97.95	97.24	98.2
$\eta_{mppt.p}$	97.95	97.24	98.2
$\varepsilon_{mppt.p}$	2.45	2.96	1.95
$\eta_{mppt.E}$	86.0	88.0	91.0
$\varepsilon_{mppt.E}$	16.0	14.0	11.0

Table 4. Comparison of Advantages and Disadvantages

MPPT	Advantages	Disadvantages
P&O	1) Simple 2) Cheap 3) A few numbers of sensors needed 4) More common in usage	1) Not suitable in fast changes in weather 2) Slow response speed
IC	1) Simple 2) Faster than P&O method 3) Common in usage	1) More complex 2) More expensive
PI	1) Very fast response 2) Suitable for fast changes in irradiation and loads 3) Zero error is reached if the current generated equal Imax 4) High efficiency in dynamic weather changes	1) More complex 2) If the calculations of curve fitting have some errors, the efficiency of the system will decrease 3) Temperature dependency

According to the comparison between the proposed MPPT technique and the two previous methods (Table 4), it is concluded that the proposed technique is the best in tracking the MPP and can be used as a supplementary method.

9. CONCLUSION

An algorithm for tracking maximum power points under various operating conditions has been provided in this paper, and it is based on an investigation of the mathematical correlation between the maximum power points and the related currents. The performance, efficacy, benefits, and drawbacks of the proposed method in comparison to the traditional Perturb and Observe and Incremental Conductance methods have been highlighted by simulation results. The choice of the proper fitting relation between the maximum power and its associated current value is one of the primary contributions of this study. However, compared to other conventional MPPT approaches, the proposed method, nonetheless, has the drawbacks of being expensive and dependent on the photovoltaic.

It should be noted that the equations are greatly affected by two factors, i.e., how the system is able to achieve the MPP and how fast the system is able to achieve it. All the equations have been calculated over time from t=0 to t=tm. Energetic efficiency enhances, if the module can work very closely to the required MPP and is too fast.

Notably, the proposed approach promises the improved results compared to the values of the traditional P&O and IC-based MPPT techniques and can be utilised as an additional approach.

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