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Maximizing off-grid solar photovoltaic system efficiency through cutting-edge performance optimization technique for incremental conductance algorithm

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ABSTRACT

The maximum power point tracking (MPPT) algorithms are required to deliver the optimal energy from solar photovoltaic cells/array (PV) under numerous weather conditions. Therefore, MPPT circuits driven by defined rules called algorithms are designed. These algorithms range from simple to complex in design and implementation and are selected based on the scenarios of the surroundings. However, the incremental conductance (InC) MPPT algorithm is one of the market's most simple, easy to implement, and demanding algorithms. The drawback associated with the InC algorithm is its tracking speed. To overcome this weakness various researchers have made multiple improvements. Although the performance became better but was not satisfied. Further, the improvements introduce steady-state oscillations of the operating point around the MPP. So, the user needs to pick and choose based on demand. Keeping the target in focus, we have introduced a couple of modifications in the structure of INC. that remain fruitful. The proposed structure named the augmented InC algorithm has shown marvelous improvement in tracking speed and steady-state oscillations. The results have been compared with the conventional InC algorithm, where the proposed augmented InC algorithm has outperformed the conventional InC algorithm in tracking speed and steady-state oscillations. We have used the MATLAB script to code the conventional InC algorithm and proposed augmented InC algorithms based on their designed flowchart. Both algorithms have been applied to the standalone solar photovoltaic system composed of a solar photovoltaic array, DC/DC boost converter, illumination and temperature inputs, MPPT algorithm, and a DC load. The model is designed in Simulink/MATLAB.

1. Introduction

In the modern world, scientists are struggling to get rid of conventional energy technologies that affect humanity in terms of economy, health, reliability, and life threats in the future. The continuous jumps taken by energy prices, greenhouse gas emissions, depletion of fossil fuels, and unreliability are the issues that force the world to look for renewable, sustainable, and cheap energy alternate technology. Therefore, the world has invested billions in finding an efficient alternate technology that comes up with solar, wind, and multiple other renewable energy technologies. Currently solar and wind are the leading technologies in renewables.

Moreover, in traditional grids, large energy generation plants, be they fossil fuel-based or renewable, are often remotely located from load centers. Under such circumstances, unpredictable weather-related disruptions to concentrated renewable energy sources can destabilize the entire system. To prevent system instability, fossil fuel-based spinning reserves must be maintained, incurring significant costs and environmental concerns. Consequently, it becomes evident that the full potential of renewable energy to alleviate network overloads, GHG emissions, soaring energy demands, escalating costs, and system vulnerabilities is constrained within the boundaries of conventional grids [1-4]. In contrast, smart grids seamlessly integrate energy generation plants in both centralized and distributed configurations [5].

Standalone renewable energy generation systems find ideal applications in remote rural areas and situations [6-8] where alternative power sources are impractical or unavailable for meeting lighting, appliance, and other energy needs [6]. Renewable energy sources encompass various forms such as hydro, solar, wind, biomass, biofuels, tidal waves, and geothermal [9-14]. Among these, solar energy stands out as the most abundant natural resource on Earth [15]. Furthermore, solar photovoltaic (PV) technology boasts minimal energy conversion losses due to its direct conversion of sunlight into electrical energy [16, 17]. It is renowned for its reliability, environmental friendliness, pollution-free operation, low maintenance requirements, and ease of installation in residential, commercial, park, and vehicle parking settings [18-20]. A PV cell typically has a lifespan of 25-30 years and a payback period of around three years [21].

Consequently, opting for standalone PV systems in remote areas is more cost-effective than extending power lines and cables from local electricity providers [22]. MPPT is regarded as the simplest, most cost-effective, and highly effective means of enhancing PV system efficiency. It requires minimal investment and can:

- Reduce overall PV system costs
- Increase electricity generation
- Reduce the physical footprint of PV systems
- Shorten the payback period

MPPT algorithms can be categorized into two groups: 1) Conventional algorithms, which employ incremental scanning methods to identify the MPP based on the power-voltage (P-V) curve of an array without exploring the entire curve. These algorithms are less suitable for global MPPT (GMPPT) under partial shading conditions (PSCs) [23-25], and 2) Soft-computing algorithms, which utilize randomization concepts to address nonlinear problems like GMPPT under PSCs [26].

The performance evaluation of MPPT algorithms is based on well-defined benchmarks sourced from the existing literature [27, 28], including:

- Tracking speed
- Structural complexity
- Computational complexity
- Efficiency
- Steady-state oscillations
- Array dependence

Tracking speed measures how quickly an algorithm reaches the MPP to save time, while structural complexity gauges the implementation challenges, and computational complexity relates to tracking speed and implementation difficulties. Steady-state oscillations indicate the stability of power output, while array dependence impacts tracking speed [29].

The solar photovoltaic (PV) cell, a remarkable feat of scientific innovation, showcases a power-voltage (P-V) characteristics curve that embodies a distinct non-linear nature. Central to this curve is a crucial concept known as the Maximum Power Point (MPP), a pivotal juncture at which the PV cell optimally delivers its highest power output. This concept can be intuitively grasped through the insightful visual representation found in Fig. 1 [30-32], where the red curve illustrates the P-V characteristic, and the blue curve portrays the voltage-current (V-I) characteristic. The point of operation where maximum power delivered by solar PV cell is marked as MPP.

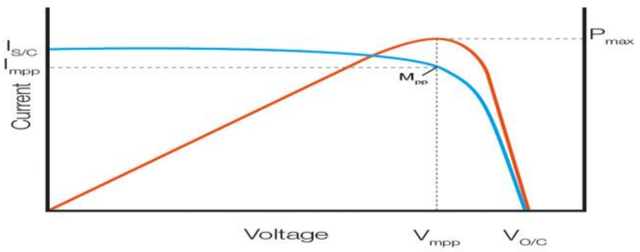


Fig. 1. Characteristic Curves of Solar PV Cell under Uniform Weather Conditions [32, 33]

1.1 Literature Review: Conventional MPPT Algorithms

The conventional MPPT algorithms include:

- Perturb and observe [3, 34-42]
- Hill Climbing [35, 43-49]
- Incremental Conductance [50-53]
- Fractional Short Circuit Current [54-56]
- Fractional Open Circuit Voltage [57-59]

1.1.1 Perturb and observe (P&O)

The P&O is one of the simplest and most used MPPT algorithms in the market. It perturbs the voltage or current in one direction and notices the effect at power. Based on the information received after comparison it selects the direction of perturbation. Its simplicity, easy implementation, and cost-effectiveness are its main strengths, whereas, the dependency on the size of the PV array, steady state oscillations, and tracking speed are the associated drawbacks.

Additionally, it faces challenges in accurately tracking the Global Maximum PowerPoint (GMPP) under Partial Shading Conditions (PSC).

An enhancement of the P&O algorithm, which employs variable step sizes, is outlined in references [34, 60-63]. Initially, it operates with a larger step size, progressively reducing the step size as it approaches the MPP. This modification accelerates the tracking process but does not eliminate the oscillation issue.

The Delta P&O algorithm, introduced in reference [59], departs from the conventional perturbation step size by using a fixed step size, resulting in improved performance. Here, the perturbation step size is optimally set to enhance tracking.

In a significant advancement, reference [61] introduced a hybrid approach, combining the P&O algorithm with Fuzzy Logic Control (FLC) algorithms. Oscillations are mitigated by incorporating changes in error (D) into the algorithm, calculated using a fuzzy rule table.

Research findings in reference [60] revealed an inverse relationship between perturbation and the efficiency of the photovoltaic (PV) module. An innovative method introduced a constant duty ratio perturbation rate, effectively reducing steady-state oscillations.

Additionally, a novel approach detailed in reference [64] introduced boundary conditions for temperature and power variables. The MPPT controller generated duty cycles based on data, leading to effective oscillation reduction. Furthermore, the issue of oscillations was successfully addressed in reference [64] through the introduction of a clever condition within the P&O algorithm, termed "decrease and fix." When oscillations occur, the step size progressively decreases with each perturbation until it reaches zero. Additionally, it monitors changes in voltage and current to detect weather variations.

It is imperative to note that while the P&O algorithm and its refined iterations have demonstrated remarkable success in Uniform Weather Conditions (UWC), they encounter limitations when dealing with Partial Shading Conditions (PSCs).

1.1.2 Hill climbing (HC)

The Hill Climbing (HC) algorithm, akin to the Perturb and Observe (P&O) algorithm, shares a similar approach with the primary distinction residing in the variable subject to perturbation. In the HC algorithm, the duty cycle (D) serves as the perturbed variable.

The HC algorithm systematically modulates the duty cycle (D) while observing changes in the power output of the photovoltaic (PV) array. When a positive change in power is detected, the algorithm continues the perturbation in the same direction. Conversely, when a negative change occurs, the perturbation direction is reversed. Oscillations can arise when the Maximum Power Point (MPP) is reached, as explained in references [50, 51, 40].

An effort to enhance the tracking precision of the HC algorithm was undertaken in reference [51], employing an interleaved boost converter. Notable success was achieved under scenarios characterized by a consistent change in illumination.

In a subsequent advancement, a novel approach was introduced in reference [50], utilizing a Digital Signal Processor (DSP) controller to create a hardware model. This model underwent testing across various illumination conditions, resulting in a remarkable 17.5% improvement in convergence speed.

A similar approach was applied in reference [51] to assess the applicability of the HC algorithm for grid-connected systems, making a comparative analysis with the P&O algorithm. It is imperative to underscore that while the HC algorithm offers its advantages, it remains susceptible to oscillations around the Maximum Power Point (MPP) and encounters challenges in accurately tracking the Global Maximum Power Point (GMPP) under Partial Shading Conditions (PSC).

1.1.3 Incremental conductance

The Incremental Conductance (InC) algorithm shares its fundamental concept with the Perturb and Observe (P&O) algorithm but differs in its criteria for perturbation. InC initiates changes in a variable, typically voltage, after recording the values of "P" (power), "V" (voltage), and current. It calculates the ratio of the change in power (ΔP) to the change in voltage (ΔD). If this ratio is positive, the algorithm continues to adjust the voltage in the same direction; conversely, it reverses the perturbation direction if the ratio is negative. This process persists until the ratio of ΔP to ΔD reaches zero, signaling the attainment of the Maximum Power Point (MPP).[62]

An enhancement introduced in reference [41] involved incorporating a variable step change in voltage to expedite the tracking speed. Furthermore, an alternative approach exploring the utilization of a Fly-back converter was detailed in reference [45]. A new fuzzy logical novel design of PV System based on an INC algorithm for tracking Maximum Power Point

Tracking (MPPT) has been discussed in this article. The proposed system uses the step size voltage variation method to obtain MPP. In this method, the efficiency of tracking MPP is improved. In the paper, the authors compared two methods (I) the conventional INC algorithm and (II) the fuzzy logic-based INC algorithm, and tell the fuzzy logic basic INC is better than the conventional INC algorithm. [42]

It is vital to note that the Incremental Conductance (InC) algorithm is compatible with low-power applications and demonstrates remarkable efficacy when confronted with slow changes in illumination, as highlighted in references [35]. However, as mentioned, the problem of steady-state oscillation remains unresolved [48,65-68].

The experimental study of adaptive incremental conductance (AIC) and Adaptive Perturb & Observe (APO) algorithm for tracking MPPT in PV systems is presented in [69]. The authors performed the simulation of the AIC and APO algorithms and compared the performance with INC and P&O in different static and dynamic conditions. Results show that efficiency above 98% is achieved when both algorithms are used under dynamic conditions.

The study of the photovoltaic systems under dynamic test EN50530 for MPPT is presented in [70]. The authors have performed three different dynamics tests under daily work by using three MPPT techniques (i) P&O (ii) INC and (iii) hybrid step size beta method. The authors used three dynamic tests (i) the stepped dynamic test procedure (ii) the day-by-day dynamic test and (iii) the EN-50530 procedure to evaluate the performance of the PV System in different weather conditions. The hybrid beta step size algorithm has outperformed the other two algorithms.

1.1.4 Fractional short circuit algorithm

The Fractional Short Circuit (FSC) algorithm [54-56], measures the value of the short circuit current and operates the system at this 90% value. The reason behind this is the observation made by researchers that says the MPP of the solar PV cell lies at 90% of its short circuit current under uniform weather conditions [71].

This algorithm is specifically designed for high voltages and low current applications. However, the algorithm has not gotten much attention from the research community or the market [72].

An optimized FSC algorithm was presented by researchers in [72], using upper and lower limits to assist in finding the change in the value of the short circuit current. Moreover, the performance of the FSC algorithm was improved by adding a lookup table in [73], by comparing the calculated values to calculate the error, which would further be removed or reduced using a PI controller. The weakness of this research article is not to conduct a comparative analysis.

1.1.5 Fractional open circuit voltage

The Fractional Open Circuit (FOC) algorithm follows the same approach as the FSC algorithm but it proceeds with an 80% value of open circuit voltage instead of a 90% value of short circuit current [74, 75].

To get more accurate results a variable is introduced in the conventional structure of the FOC algorithm to maintain the output below the upper limit to get a reliable reference point for the PI controller [76]. A switched semi-pilot cell has also been implemented in [58] with minor improvement.

Limited research has been conducted on the FOC algorithm for the same reasons mentioned above for the FSC algorithm. However, to ensure effective implementation the open circuit voltage should be measured precisely [63].

1.1.6 Performance Analysis of Conventional MPPT Algorithms

Conventional MPPT algorithms are simple in structure and therefore easy to implement, and cost-effective. However, the steady-state oscillations, slow tracking speed, and dependency on the size of the PV system are their weaknesses. A summary is presented in Table 2.

The paper is organized as follows, Section 2 explains the incremental conductance algorithm, section 3 presents the proposed algorithm along with its results and comparison, section 4 shares the future work, section 5 concludes the research, and section 6 presents the list of references.

Table 1

Performance valuation of conventional MPPT algorithms

Evaluation Parameter	P&O	HC	INC	FSCC	FOCV
Maximum Power Point	Average	Average	Reduce	Zero	Zero
Tracking velocity	Variable	Variable	Variable	Moderate	Moderate
Global MPP Capability	Absent	Absent	Un Available	Missing	Missing
Structural Complexity	Minimal	Minimal	Limited	Minimal	Minimal
Execute Time	High	High	High	High	High

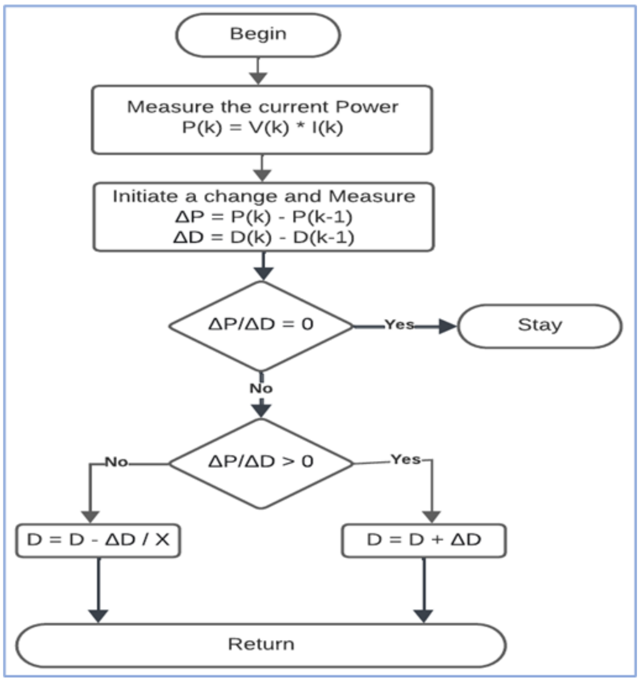
2. Incremental Conductance Algorithm

The incremental conductance algorithms record the initial values of voltage, current, and power. Then, it introduces a change in voltage and measures the change in power for the initiated change in voltage using the derivative of power concerning voltage. A positive change in power indicates that the operating power point occurs at the left side of the MPP and a negative change in power indicates that the position of the operating power point is at the right side of the MPP. Considering this information the incremental conductance algorithm determines its direction of tracking the MPP. However, the zero or no change in power indicated that the operating power point occurs at the MPP and the algorithm tries to stay there.

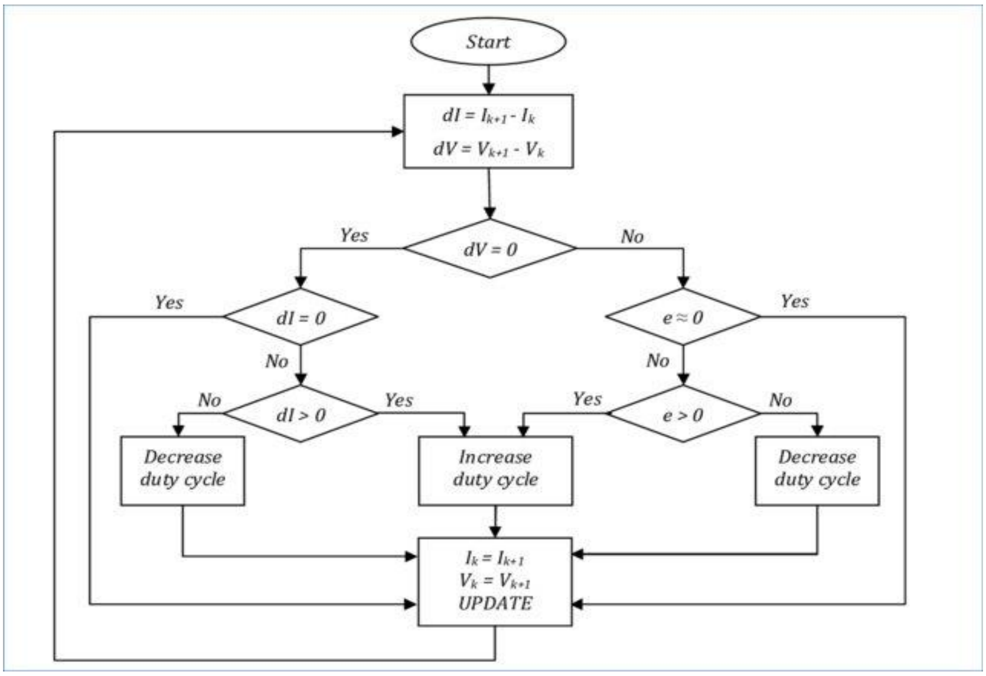
3. Proposed Augmented InC MPPT Algorithm

To overcome the weaknesses of the conventional InC algorithm, we have made some structural modifications to its structure and created a new tracking strategy. Instead of dealing with voltage and then generating a new duty cycle to check and compare the new value of power against the new position of voltage, we make it simple and throw out the voltage check step. In the proposed structure the augmented InC computes the power and alters the duty cycle to check the change in power. If the change is zero it stops the tracking process. Otherwise, it decides the tracking direction based on the result of the derivative computed for the power concerning the duty cycle.

The initial change in the duty cycle is set to increase the tracking speed and reduce the size when getting closer to the MPP. However, to overcome the steady-state oscillations that are created due to the changing size of the duty cycle, we have introduced a factor "X" that reduces the size of the duty cycle until it gets closer to the MPP and turns it to zero when operating power point reaches the MPP. This strategy increases the MPP tracking speed and eliminates the problem of steady-state oscillations. The flow chart of the conventional and the proposed augmented InC algorithm is presented in Fig. 2.



(a)



(b)

Fig. 2 Flowchart of the (a) Proposed Augmented Incremental Conductance Algorithm (b) Conventional

3.1. Testing Scenarios for MPPT Algorithms

A standalone solar PV system is designed and depicted in Fig. 3. It consists of a Solar PV module, DC/DC converter, MPP tracker, and a DC load. The MPP tracking process is independent of the load [76]. The conventional and the proposed augmented InC algorithms have been tested in this standalone system under constant and changing weather conditions using different loads at the output.

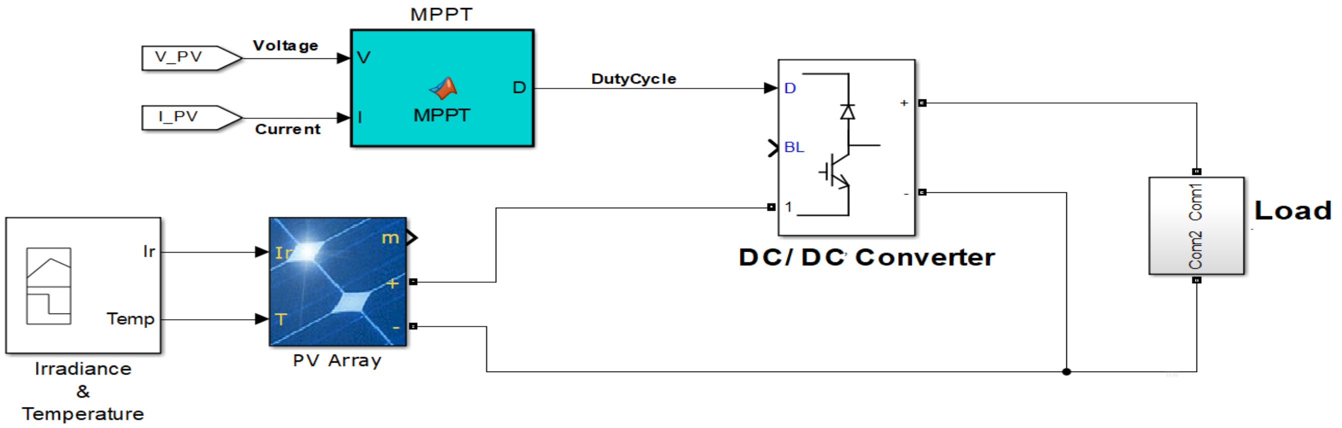


Fig. 3. Standalone Solar Photovoltaic System

3.2 Result and Discussions

A PV system of 60watts is designed for the simulation, testing, and results comparison of the conventional InC and the proposed AInC MPPT algorithms. The power-voltage (P-V) characteristic curve for the 60-watt PV system is presented in Fig. 4.

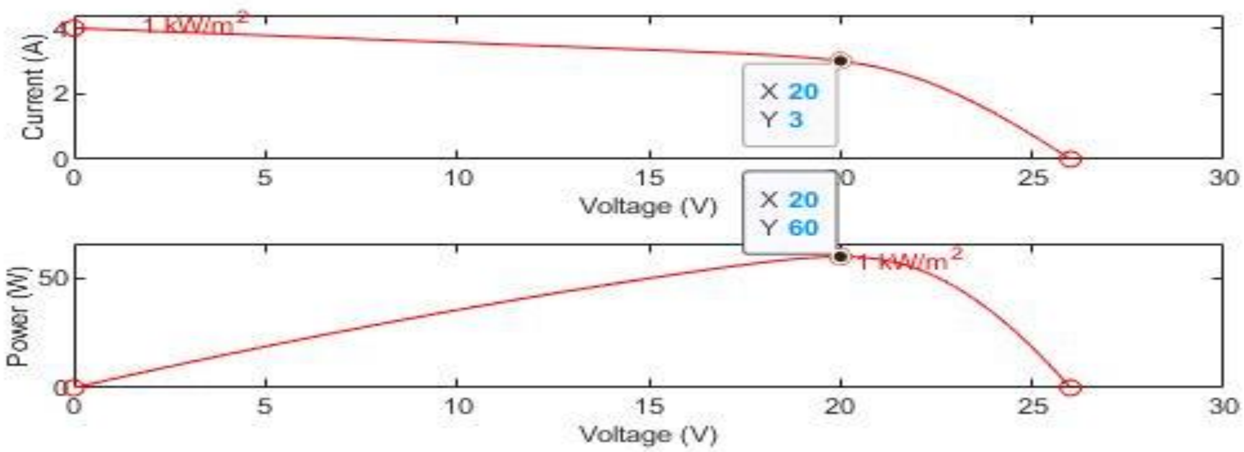
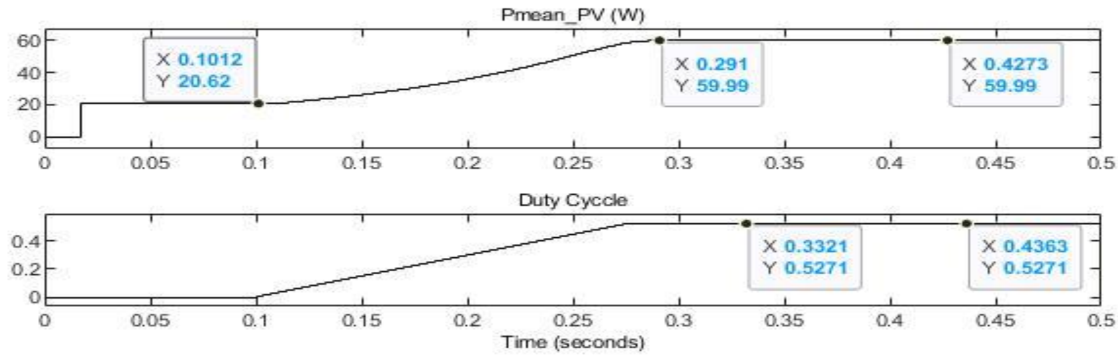


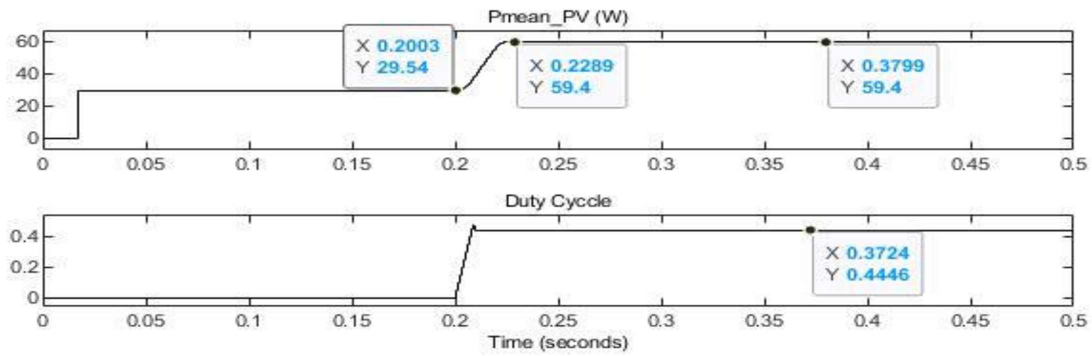
Fig. 4. Power-Voltage Characteristic Curve of 60-Watt PV System

The P-V characteristic curve in Fig. 4 depicts that under non-shading and at standard test conditions (1000W/m2, and 25oC) the PV system produces 60-watt, at 20-volts and 3-amperes at its MPP. Considering this standard value, the extracted output of both the conventional InC and the proposed augmented InC will be evaluated. However, the MPPT tracking speed comparison will be relative to each other. Initially, we applied the InC algorithm to the designed 60-watt solar PV system that tracked the MPP and extracted 59.99-watt output in 0.19-sec with an efficiency of 99.9%.

At the application of the proposed AInC MPPT algorithm, we have found remarkable findings at large step sizes (the reason and logic are explained in the section-3.2). The proposed AInC algorithm attained 59.4-watt power output with 99% efficiency in just 0.024-sec. These achievements of the proposed AInC MPPT algorithm against the conventional InC algorithm are visually explained in Fig. 5 and are summarized in Table 2.



(a) Conventional InC Algorithm with Small Step Size



(b) Augmented InC Algorithm with Large Step Size

Fig. 5. Simulation Results of the InC and AInC Algorithms at Standard Test Conditions

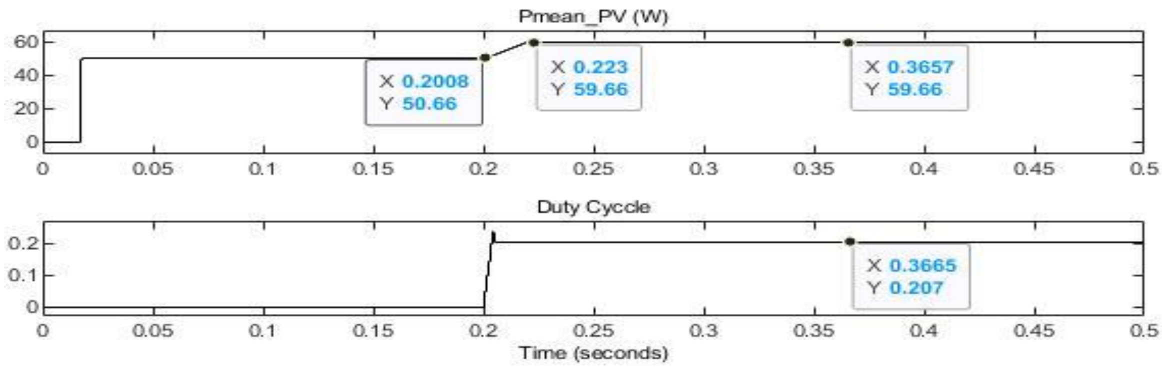
Table 2

Performance summary of InC and AInC algorithms at standard test conditions

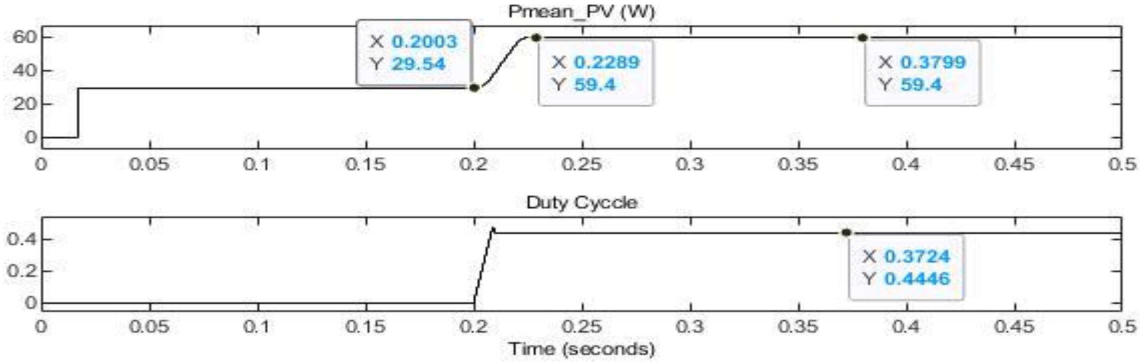
Case	Algorithms	Rated Power	Extracted Power (W)	Efficiency(%)	Tracking Speed (Sec)	Improvement in Tracking Speed
1	Conventional INC	60	59.99	99.99	0.19	85%
2	Augmented INC	60	59.4	99.00	0.028	

As claimed in the description, the proposed AInC MPPT algorithm has attained its target and outperformed the conventional InC MPPT algorithm in MPPT tracking speed.

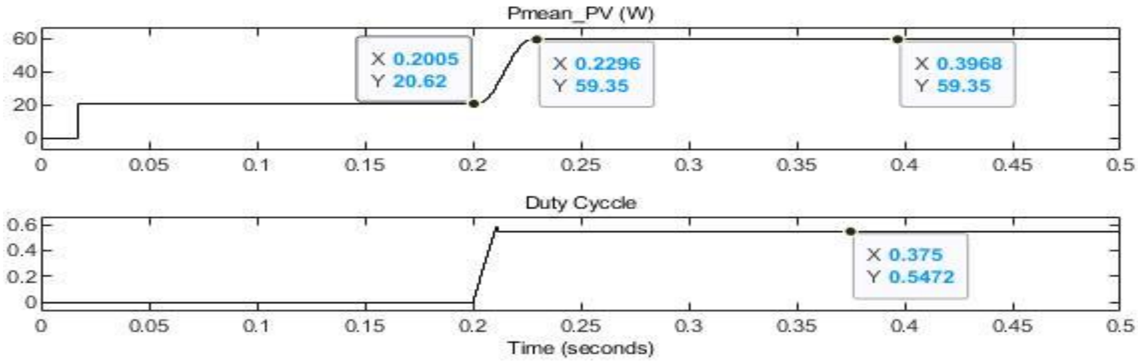
However, to further evaluate the performance of the proposed AInC MPPT algorithm, the designed PV system is operated with different loads. Efficient and fast output at a variety of loads for the same PV system verifies the tracking capabilities of the proposed AInC MPPT algorithm. The results of the proposed AInC MPPT algorithm for the three different loads of 10-ohm, 20-ohm, and 30-ohm are presented in Fig. 6. The proposed AInC MPPT algorithm has successfully retained its performance and extracted the maximum possible output power from the solar PV system with various loads connected to the output, by continuously operating the solar PV system at its MPP.



(a) Performance of the Proposed AInC Algorithm at 10-ohm Load



(b) Performance of the Proposed AInC Algorithm at 20-ohm Load



(c) Performance of the Proposed AInC Algorithm at 30-ohm Load

Fig. 6. Performance Evaluation of the Proposed AInC Algorithm at Various Loads

The summary of the MPPT ability of the proposed AInC MPPT algorithm with various loads is summarized in Table 3. Moreover, the ability of the proposed AInC MPPT algorithm to detect the change in weather conditions to stop or resume its operation is tested. For this purpose, the change in solar illumination/irradiation is introduced twice in a row to check if the proposed AInC MPPT algorithm can detect and restart the tracking process or not. The results demonstrated that the proposed AInC MPPT algorithm has successfully stopped tracking after attaining the goal (MPP) and restarted the tracking process, each time it detects the change in solar illumination/irradiation. The results of this illumination-changing activity are presented in Fig. 8. Before that, a P-V characteristic curve of the solar PV system for the changed position of the solar illumination/irradiation is generated as shown in Fig. 7 and compared for the results.

Table 3

Performance Summary of the Proposed AInC Algorithms at Various Loads

Load	Algorithms	Power(Rated)	Extracted Power	Efficiency	Tracking Speed
10	A-INC	60	59.66	99.43	0.022
20	A-INC	60	59.4	99.00	0.028
30	A-INC	60	59.35	98.92	0.029

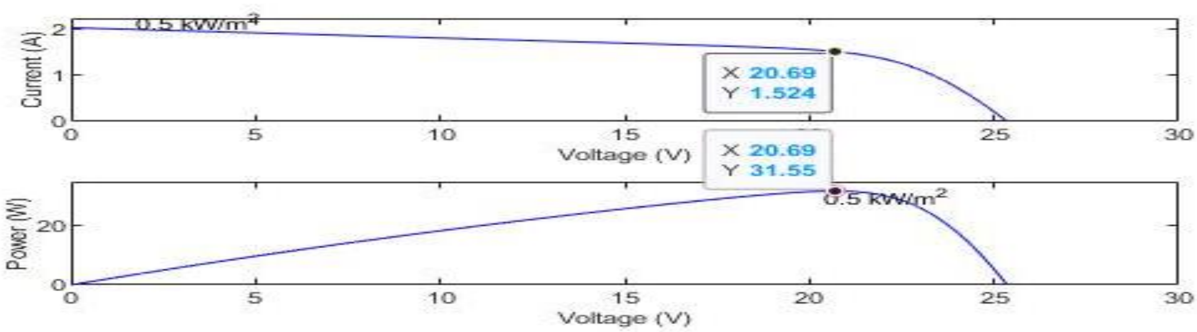


Fig. 7. Power-voltage Characteristic Curve of a 60-Watt PV system for 500W/m2 Illumination

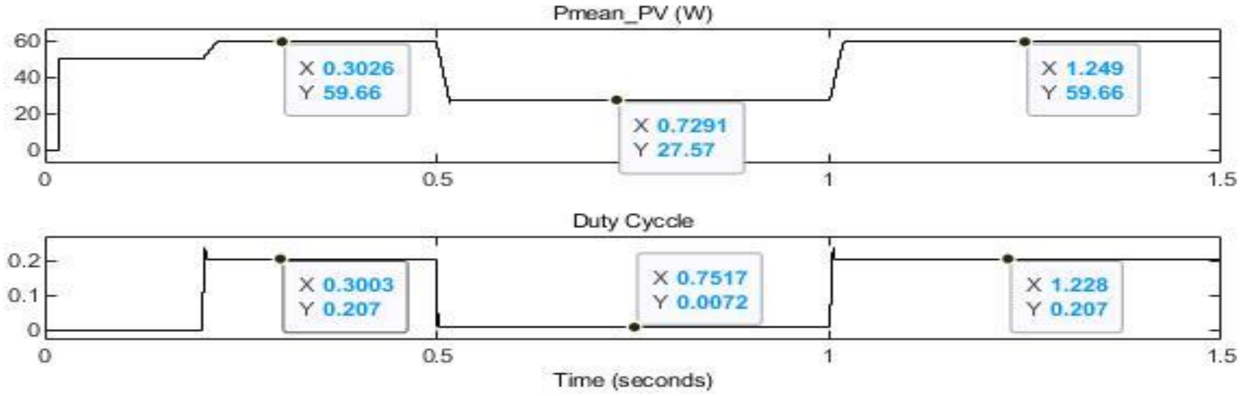


Fig. 8. Performance Evaluation of the Proposed AInC Algorithm for Changing Weather Condition

The performance evaluation of the proposed AInC MPPT algorithm for the changing weather conditions is presented in Fig. 8. The proposed AInC MPPT algorithm has retained its performance and not only successfully detects the changing weather but reinitiates the tracking process to move the system to the new MPP, to get the maximum possible power

4. Conclusion

The ultimate goal of this research is the optimal power extraction from the solar PV system under numerous weather conditions. For this purpose, we have studied the existing tracking strategies of MPP and found these categorized as conventional and nature-inspired. The nature-inspired are fruitful in shading but have complex structures, costly implementation, and are unsuitable for simple or average-size systems. On the other hand, conventional algorithms are simple, cheap, easy to implement, and are favored by all the researchers for low and average power systems. For the defined reasons, one of the most demanding, simple, easy to implement, and cost-effective conventional MPPT algorithms called the incremental conductance algorithm has been selected based on its strengths and weaknesses. The incremental conductance algorithm is the only one in conventional algorithms that has negligible steady-state oscillations. To overcome the weaknesses that are due to its basic structure and some created during its previous optimizations, we have introduced a strategy that was found very fruitful when tested at the standalone solar PV system under constant and changing weather conditions using different loads. The proposed augmented incremental conductance algorithm has outperformed the conventional incremental conductance algorithm in terms of tracking speed and efficiency. Furthermore, the issue of steady SteadyState oscillations has also been resolved. The proposed algorithm has attained a 0.99% increase in efficiency and an 85% increase in tracking with zero steady-state oscillations which is remarkable. Although the increase in efficiency is good the dramatic achievement in tracking speed explains the worth of effective use of concepts.

5. Future Work

Future research in the field of Maximum Power Point Tracking (MPPT) for photovoltaic (PV) systems holds great potential. First, practical hardware implementations of the Augmented Incremental Conductance (AInC) algorithm should be developed and tested in real-world PV systems. Second, adaptive control strategies employing machine learning and artificial intelligence could enhance MPPT algorithms' ability to self-optimize under varying environmental conditions.

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