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Comparative analysis of incremental conductance MPPT for enhanced algorithm performance

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ABSTRACT

The incremental conductance (INC) approach is limited in terms of its response speed, accuracy during steady state, and ability to handle oscillations. As a result, this algorithm is ineffective in situations with variations in solar radiation and temperature, particularly abrupt fluctuations. An enhanced variable step size INC approach is suggested to improve system efficiency and performance. The proposed algorithm is subjected to rigorous testing and analysis with other INC methods for better results. The research findings indicate that the proposed algorithm's tracking efficiency can be enhanced to 99.83% under varying radiation conditions and constant temperature. Additionally, the method utilizing the second model achieves a 99.83% tracking efficiency, while the method employing the first model achieves a tracking efficiency of 89.99%. In comparison, the conventional method achieves a tracking efficiency of 96.36%. Regarding radiation and temperature circumstances, the tracking efficiency value varies for different methods. Specifically, the tracking efficiency is 95.21% for the approach using the proposed algorithm's, 92.94% for the method using the second model, 83,39% for the method using the first model, and 91.19% for the conventional way. Therefore, it can be inferred that the suggested Maximum power point tracking (MPPT) algorithm performs better than other algorithms under both test situations.

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1. INTRODUCTION

Solar energy is an abundant and environmentally friendly energy source without pollution [1], [2]. It is a sustainable energy source that can be transformed into electrical energy. It has recently become a substitute for addressing the limited supply of fossil energy sources and their adverse consequences [3]–[6]. Nevertheless, the primary obstacle lies in optimizing solar energy extraction to transform it into electrical energy efficiently. Various aspects that have an impact include the efficacy of the solar panels utilized and environmental conditions such as fluctuations in solar radiation levels and temperature [7], [8]. The primary factors that exert the most significant influence on the production of electrical energy are variations in solar radiation and temperature.

Professionals employ diverse techniques to optimize the generation of electrical energy. Maximum power point tracking (MPPT) is a frequently used approach utilized by professionals to optimize the conversion of solar energy into electrical energy [9]–[11]. The incremental conductance (INC) methodology is a widely adopted and popular MPPT method because of its simplicity, low complexity, and cost-effectiveness [12]–[14]. The INC technique has also enhanced its effectiveness in tracking the maximum power point (MPP) by effectively adapting to changes in solar radiation levels and temperature, particularly rapid variations in radiation [15], [16]. Research on the MPPT method is important be conducted to identify an MPPT algorithm that can effectively enhance system efficiency in the face of changing environmental conditions, such as variations in radiation leading to system instability and oscillations causing power losses and reduced efficiency. Among the factors, the MPPT algorithm’s ability to track MPP if there is a change in radiation value has become the main determinant. Then, the speed of convergence refers to the duration needed for the system to achieve stability. Furthermore, the problem of oscillation that can be caused by changes in radiation value. The algorithm's responsiveness to changes in radiation value is crucial for accurately tracking the position of the MPP. Similarly, the algorithm's capacity to regulate the system in a manner that maximizes the convergence time. Reduced oscillation value leads to enhanced stability and improved efficiency of the system. It is imperative to do this research to guarantee the proper attainment of the specified criteria, namely high tracking speed, rapid convergence time, and low oscillation.

The operational procedure of the INC approach for MPP tracking involves modifying the duty cycle converter based on the P-V characteristic curve or detecting the highest point on the P-V curve. The position of the operating point of a solar panel can be determined using the INC technique, which involves comparing the ratio of changes in current (dI) and voltage (dV) in the form of dI/dV, as well as the output conductance (I/V). The (1) to (3) provided below can be utilized to ascertain the precise position of the working point of the solar panel [17], [18]. Figure 1 displays how in (1) to (3) explain the P-V characteristics in INC algorithm.

$$\frac{dI}{dV} = -\frac{I}{V} \tag{1}$$

$$\frac{dI}{dV} > -\frac{I}{V} \tag{2}$$

$$\frac{dI}{dV} < -\frac{I}{V} \tag{3}$$

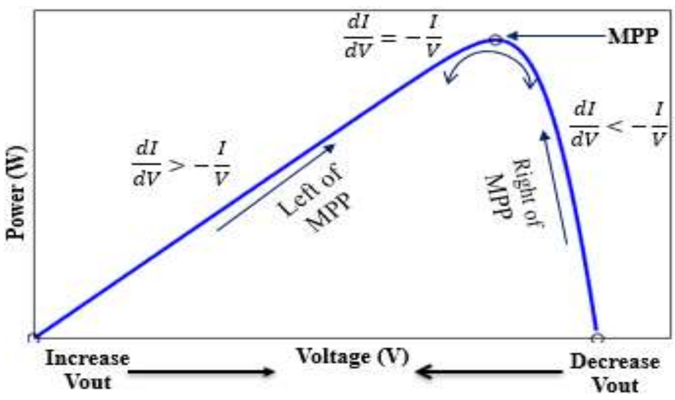


Figure 1. P-V curve for INC algorithm

If (1) satisfies, the solar panel operates at the MPP. If (2) is satisfied, the operating point is to the left of the MPP. If (3) is satisfied, the operating point of the solar panel is to the right of the MPP. Maximum electrical energy will be generated when the solar panel functions at the MPP. Under these circumstances, the power alteration resulting from voltage variations is null. Nevertheless, the INC method's drawback lies in its inability to effectively monitor the MPP in the presence of fluctuations in solar radiation and temperature. In order to prevent the occurrence of oscillations in steady-state conditions, it is necessary to ensure that changes in power caused by variations in voltage are not negligible.

This paper discusses and analyzes the performance of various INC methods in photovoltaic systems. The aim is to determine which type of INC method is more suitable if environmental conditions change. The changes in conditions are changes in solar radiation and temperature, including changes in radiation that occur quickly. The type of INC method that is more suitable can be seen from tracking speed, convergence time, oscillation, and tracking efficiency.

2. CHARACTERISTICS OF PHOTOVOLTAIC

In order to create a mathematical representation of a solar panel, it is necessary to have a fundamental equation that describes an equivalent circuit, as depicted in Figure 2. To calculate the electric current generated by a solar panel, you can utilize (4) through (6) [19], [20].

$$I = I_{ph} - I_s \left(exp \frac{q(V+R_s I)}{\alpha K T N_s} - 1 \right) - \frac{(V+IR_s)}{R_{sh}} \quad (4)$$

where;

$$I_{ph} = \left(I_{sc} + K_i (T - 298.15) \right) \frac{G}{1000} \quad (5)$$

$$I_s = \frac{I_{sc} + K_i\,(T - 298.15)}{exp\left(\frac{q(V_{OC} + K_V (T-298.15))}{\alpha K T N_s} \right) - 1} \quad (6)$$

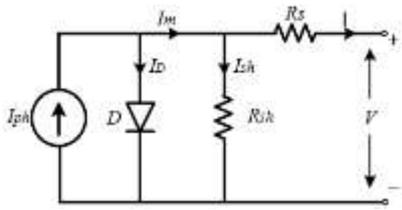


Figure 2. Equivalent circuit

This research used monocrystalline solar panels with the Solana SOL-M12100W series brand. The parameter values of the solar panels used can be seen in Table 1. The electrical output generated by a solar panel is significantly affected by environmental factors, including variations in sun radiation and temperature fluctuations. Figure 3 depicts the variation in electrical energy generated by the SOL-M12100W solar panel in response to changes in solar radiation levels. Meanwhile, Figure 4 illustrates the electrical energy generated in response to a variation in temperature. This research will examine this situation by employing diverse MPPT methods to optimize solar energy conversion into electrical energy.

Table 1. Characteristics of the SOL-M12100W

No	Parameters	Value
1	P_{max}	100 Wp
2	V_m	18.1 V
3	I_m	5.52 A
4	V_{oc}	22.1 V
5	I_{sc}	5.86 A
6	Temperature coefficient of I_{sc}	+0.006 %/^{0}C
7	Temperature coefficient of V_{oc}	-0.35 %/^{0}C
8	Number of cells	36

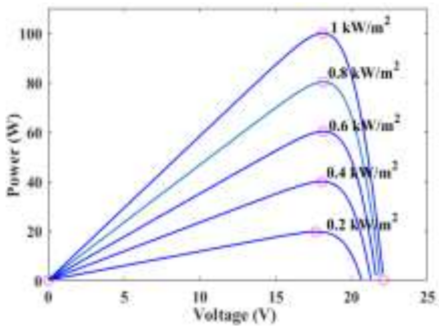


Figure 3. P-V characteristics of the SOL-M12100W with changes in solar radiation

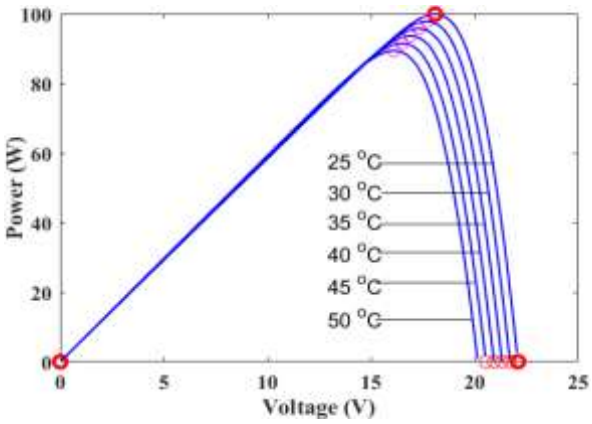


Figure 4. P-V characteristics of the SOL-M12100W with temperature changes

3. INCREMENTAL CONDUCTANCE MPPT ALGORITHMS

3.1. Incremental conductance methods with fixed steps

The INC algorithm, or the traditional INC algorithm, utilizes in (1) to (3) to calculate the duty cycle. However, a variant of the INC algorithm has been enhanced to achieve superior MPP tracking performance. In (1) to (3) are derived from the maximum point on the P-V curve when the rate of change of the curve is zero. This condition can be mathematically expressed using (7).

$$\frac{dP}{dV} = 0 \tag{7}$$

Moreover, in (7) can be reformulated as (8) and subsequently extended to (10) [21]. The algorithm for the INC technique is depicted in Figure 5.

$$\frac{dI}{dV} = V\frac{dI}{dV} + I\frac{dV}{dV} \tag{8}$$

$$\frac{dP}{dV} = V\frac{dI}{dV} + I \tag{9}$$

$$V\frac{dI}{dV} + I = 0 \tag{10}$$

The algorithm depicted in Figure 5 utilizes (1) through (3) to calculate the duty cycle for managing the PV system to track the MPP, which is also referred to as fixed step size. A method with this notion has the drawback of necessitating greater steps to achieve a higher tracking speed. However, it becomes challenging for the system to identify the correct MPP, and oscillations will manifest in a steady state. Obtaining precise step sizes can be difficult, mainly when there is a sudden fluctuation in radiation levels, which might impact the precision and efficiency of tracking. In order to address this issue, one can employ variable step sizes.

3.2. Incremental conductance with varying steps

An effective approach to address issues encountered with the fixed step size method is to employ variable steps. The variable step size approach is based on the idea that when the solar panel operating point is significantly distant from the MPP, the step size is enlarged to facilitate a faster tracking procedure. When the operating point is near the MPP, lowering the step size significantly minimizes steady-state oscillations and improves efficiency. The issue with the fixed step size notion can be addressed by using a step size determined by (11) [22], [23].

$$Step = N\left|\frac{dP}{dV}\right| \tag{11}$$

The variable N is used as a scaling factor to modify the step size. In order to increase the convergence time, this variable must fulfil in (12).

$$N = \left|\frac{dP}{dV}\right| < \Delta D_{max} \tag{12}$$

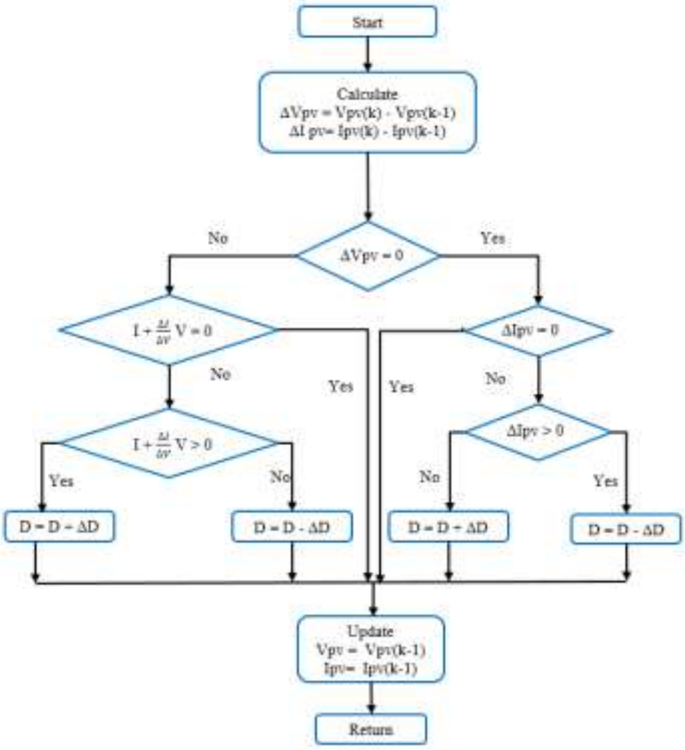


Figure 5. Incremental conductance algorithm

The most significant step size utilized in the fixed step size approach is denoted as ΔD_{max}, and the scale factor can be determined using (13).

$$N < \Delta D_{max}/\left|\frac{dP}{dV}\right| \tag{13}$$

Suppose in (13) is not satisfied. In that case, it is also feasible to augment the previous value employed by the maximum value of the fixed step to enhance the convergence speed and mitigate steady-state oscillations. When a change in radiation occurs, there will be a significant change in power (dP), but the change in voltage will be relatively small (dV). Due to the step size depending on the dP/dV value, an increase in the duty cycle ratio might result in a significant change, leading to a deviation of the operating point from the MPP. A significant decrease in power value will require a longer time to reach the new MPP again. As a result, power losses due to transients will increase, and tracking efficiency will decrease. To overcome this problem the author proposes that the value of the step size variable is only influenced by changes in the power value (dP) as in (14) [24], [25].

$$Step = N * |dP| \tag{14}$$

Eliminating the variable (dV) further simplifies the algorithm and eliminates step size variations that may arise when there are slight changes in voltage. Step size that may occur when there are slight changes in voltage. While it may initially slow the tracking process, it can reduce oscillations around the MPP, enhancing tracking precision and efficiency. In addition, it can also minimize the deviation of the operating point from the MPP in the event of a sudden change in radiation. Consequently, the response will be enhanced, and the lost power will be reduced.

3.3. Proposed incremental conductance algorithm

The modification occurs when there is a positive curve slope condition (dP/dV). This condition indicates that the MPP has not been reached and the operating point is on the left side of the curve. and the operating point is situated on the left side of the curve. To achieve MPP, it is necessary to increase the duty cycle value and accurately determine the direction of the change in the duty cycle. Specific steps are also required to avoid the wrong direction. In the algorithm of Figure 6, several modifications have been implemented, one of which involves the condition $\Delta V>0\&\&\Delta I>0$. This condition indicates that the current and voltage values increase with the position of the working point being on the left side of the MPP. If this condition is achieved, the duty cycle value must be increased. Conversely, if the condition $\Delta V<0\&\&\Delta I<0$ is achieved, the operating point is on the right side of the MPP and the duty cycle value must be decreased. The difference with the algorithm in Figure 5 is the existence of an optimized step in detecting changes in voltage and current values. This step is used to identify the appropriate duty cycle value that should be increased or decreased in order to achieve an operating point close to the MPP. Hence, the duty cycle coefficient can be modified despite the fluctuating output voltage and current values of the solar panel, ensuring that the working point remains consistently around the MPP. Nevertheless, traditional methods, as shown in Figure 5, lack these phases and also maintain a constant duty cycle value. In order to enhance the efficiency and convergence speed, the suggested method is integrated with the notion of variable step size, as in (14). Detailed information about the suggested algorithm is available in Figure 6. This research utilizes a DC-DC boost converter, and its equivalent circuit is illustrated in Figure 7.

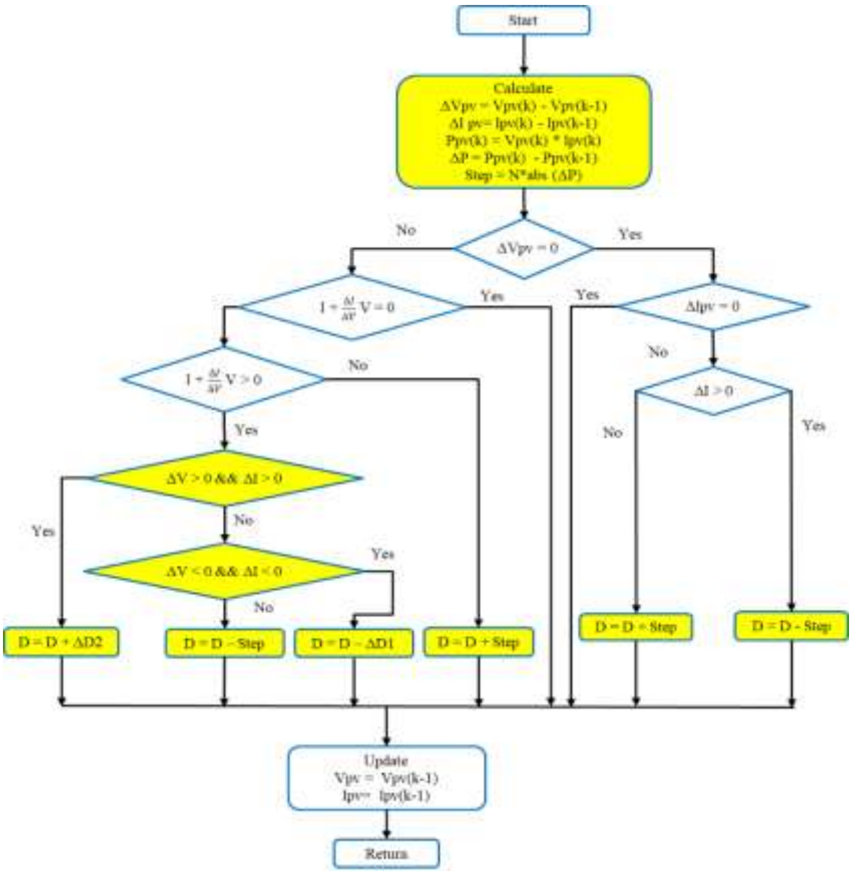


Figure 6. The proposed MPPT algorithm

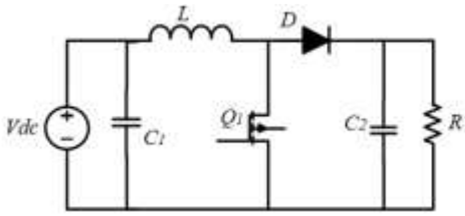


Figure 7. The boost converter equivalent circuit used in the system

In determining the component values of the boost converter, a set of (15) to (18) is applied modeling of photovoltaic [26], [27]:

$$\frac{V_O}{V_{PV}} = \frac{1}{1-D} \tag{15}$$

$$C_1 \geq \frac{D}{8\,x\,f^2\,x\,L\,x\,0.01} \tag{16}$$

$$C_2 \geq \frac{D}{f\,x\,0.02\,x\,R} \tag{17}$$

$$L = \frac{D\,x\,(1-D)^2\,x\,R}{r\,x\,f} \tag{18}$$

V_o is the converter output voltage value, Vpv is the converter input voltage from the solar panel, and D is the duty cycle. Meanwhile, C_1 and C_2 are, respectively, the input and output capacitor values of the converter, f is the switching frequency, R is the resistor load value, and *r* is the signal current ripple ratio value, which is usually used between 0.3 and 0.5. Using this equation, the parameter values for the boost converter used in this research are L = 2.2 mH, switching frequency 31.5 kHz, D = 0.7, and R = 135.

4. METHOD

The aim of this work is to enhance the efficiency of the MPPT system, particularly, in the presence of variations in solar radiation and temperature. The selected MPPT algorithm is the incremental conductance algorithm, which is then enhanced to optimize his performance. The incremental conductance algorithm is selected due to its simplicity when implemented. This algorithm is also compared with other similar algorithms to observe its performance. The presented study utilizes two comparison algorithms: the conventional incremental conductance algorithm and the incremental conductance algorithm incorporating the variable step size concept, denoted as (11) in the first model and (14) in the second model. The algorithm's performance is evaluated using a simulation approach based on the block diagram shown in Figure 8. Experimental testing is conducted in two scenarios: one when the solar radiation value varies while the temperature value remains constant, and the other when both the temperature value and radiation value vary. This system utilizes a boost converter with a fixed resistor load value. Furthermore, the detail solar panel specifications is presented in Table 1. The performance of the system is analyzed based on the convergence time, oscillation value, and tracking efficiency of the MPPT algorithm used.

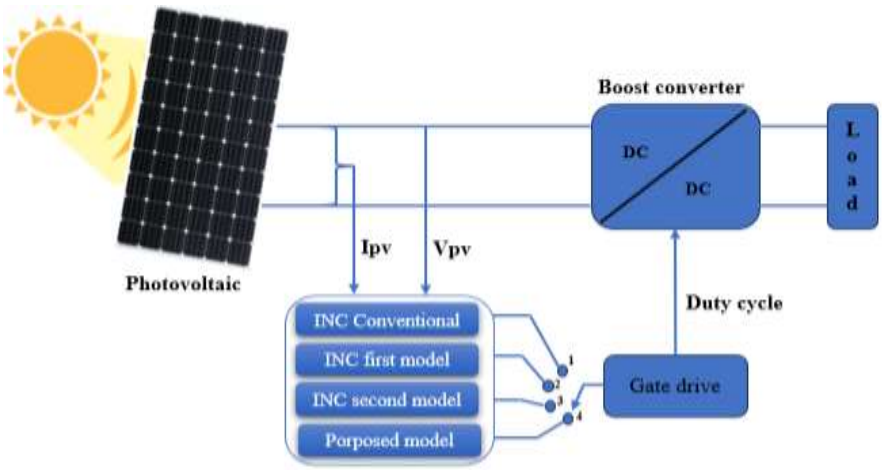
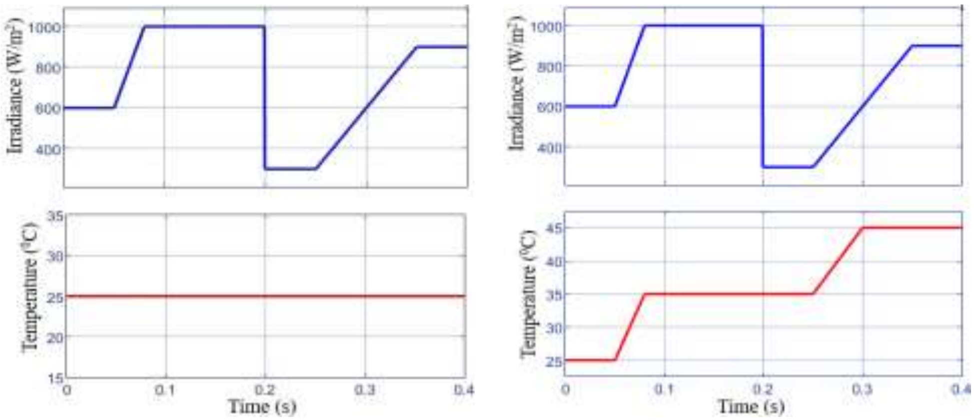


Figure 8. The system block diagram proposed in the research

5. RESULTS AND DISCUSSION

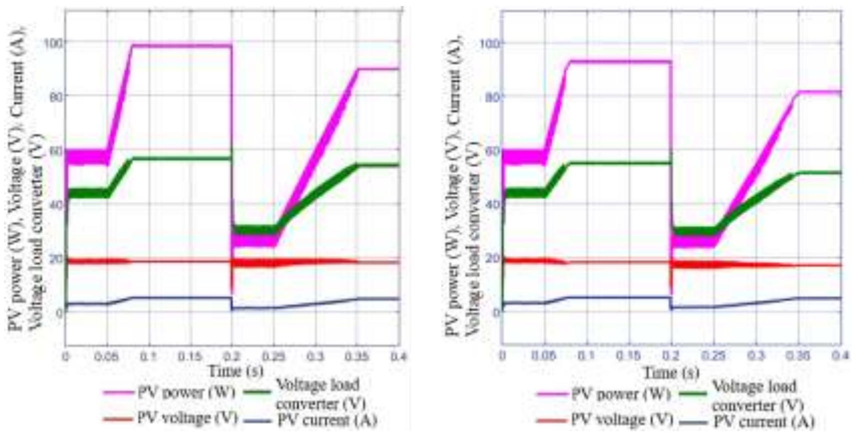
Figure 9 is the pattern of solar radiation and temperature used in this research as described in the research method. Figure 9(a) depicts the pattern of solar radiation variations under constant temperature conditions of 25 °C, which is commonly referred to as standard test conditions (STC). Figure 9(b) represents the second scenario in which changes in both radiation and temperature values are observed.



(a) (b)

Figure 9. Radiation and temperature curves (a) the changes in radiation while the temperature is constant and (b) the changes in radiation and temperature

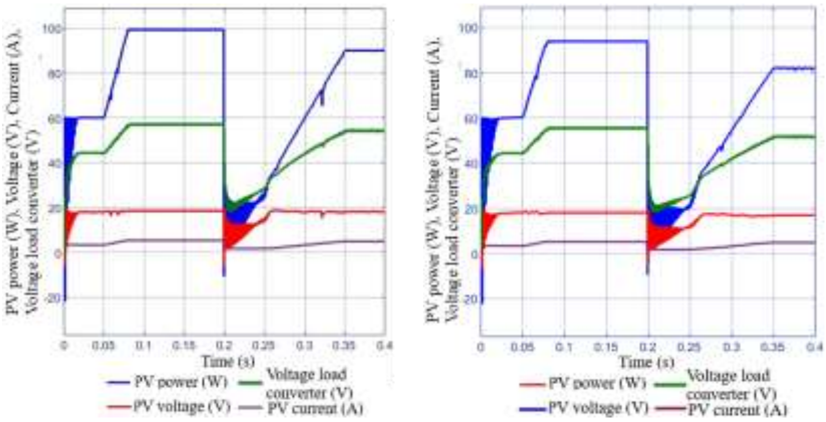
Figure 10 displays the MPPT performance method under varying radiation conditions, employing the conventional INC algorithm. Figure 10(a) shows the performance of the algorithm when the radiation changes while the temperature remains constant. Figure 10(b) shows the performance of the algorithm when both radiation and temperature change. The simulation results revealed significant challenges in achieving a satisfactory convergence value for the system. Additionally, oscillations were observed for each variation in radiation value. In both test settings, overshoot was observed when the radiation value saw a substantial and rapid decrease from 1000 W/m^2 to 300 W/m^2. The electrical power generated by solar panels using the conventional incremental conductance algorithm decreased for every change in radiation value and the decrease in the power value generated would be even greater if there was an increase in temperature value. even greater if there was an increase in temperature value. In changing radiation conditions with a fixed temperature value, the power output was 98.5%. While for the same radiation and temperature conditions, there was a decrease to 92.08%.



(a) (b)

Figure 10. The performance of the conventional INC algorithm (a) the changes in radiation while the temperature is constant and (b) the changes in radiation and temperature

A strategy to address the limitations of the previous approaches is by implementating the variable step size in the algorithm. How this variable works in the second model is similar to that in the first model. When the operating point is far from the MPP, the algorithm will increase the step size which allows the system to quickly find the MPP. The weakness is if the step size is too large, it will cause the system to be unstable. If the operating point is close to the MPP, the algorithm will reduce the step size. By the reduction of oscillation value in the steady state, it is possible to enhance the efficiency value. Figure 11 illustrates the performance of the system achieved by the first variable step size model concept using (11). Figure 11(a) shows the algorithm's performance when the radiation value changes while the temperature value remains constant, whereas Figure 11(b) shows the performance when both radiation and temperature value change. From Figure 11, it can be seen that applying the variable step size concept can reduce the oscillation value and increase the convergence time even though the stability is not yet optimal. However, oscillation still occurs at the beginning of the test and when the radiation value drops significantly from 1000 W/m2 to 300 W/m2. Furthermore, apart from oscillation, there is also an increase in the overshoot value when there is a significant decrease in the radiation value. Under conditions of varying radiation while maintaining a constant temperature, the electrical power produced at maximum radiation is 99.3% and in condition where both radiation and temperature varied, the electrical power produced at maximum radiation is 93.85%.



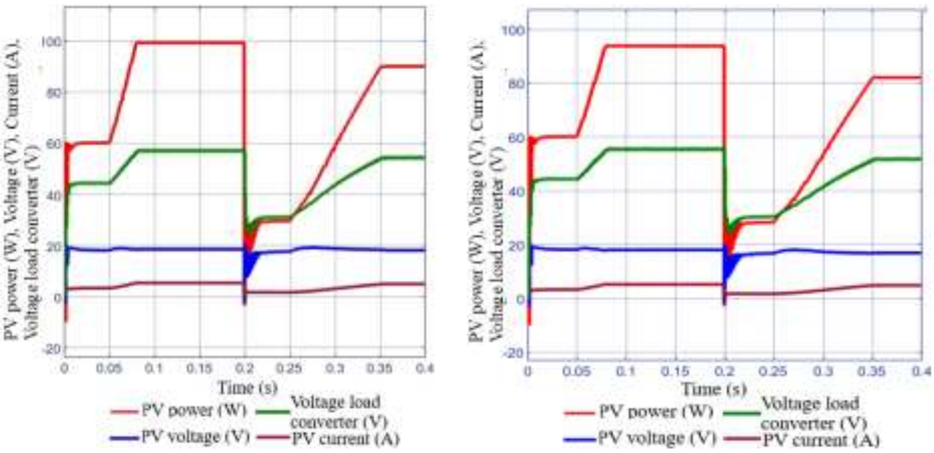
(a) (b)

Figure 11. Performance of the INC algorithm using (11) (a) the changes in radiation while the temperature is constant and (b) the changes in radiation and temperature

In order to address the limitations shown in Figure 11, the second model of a variable step size is implemented. This concept is simpler and easier to implement because it is only based on the value of the power change. According to the second variable step size model, the absolute value of the power change will always be positive, regardless of whether it increases or decreases. It is because the absolute value of the power change only considers the size of the shift, not its direction. This circumstance enables the algorithm to respond faster, more effectively, and with greater stability, particularly if the system operates around the MPP. Figure 12 shows the performance of the second variable step size model concept using (14). The performance under the condition of changing radiation with constant temperature is shown in Figure 12(a), while the performance under changing radiation and temperature is shown in Figure 12(b).

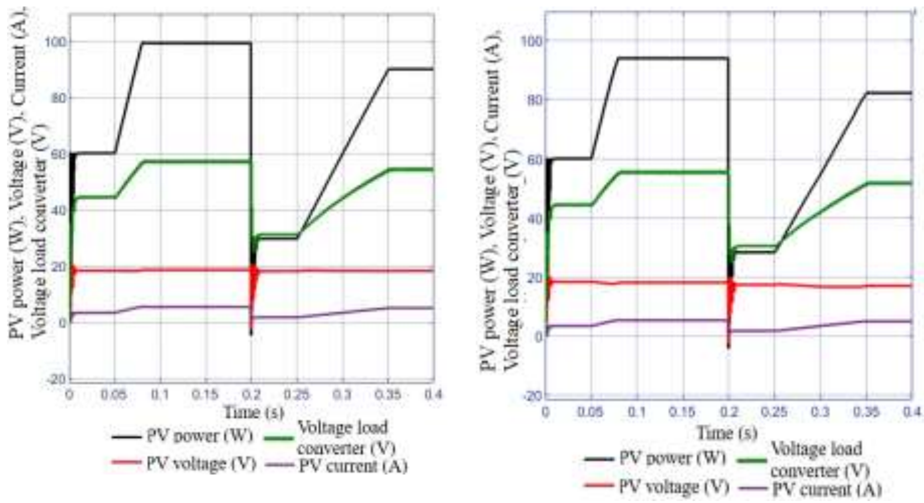
Implementing the variable step size concept in the second model can enhance operational efficiency by minimizing oscillation, improving convergence, and ensuring stability. In comparison to the performance shown in Figure 11, the performance of the algorithm with the variable step size concept using the second model equation can reduce the overshoot value that occurs when the radiation value drops significantly from 1000 W/m2 to 300 W/m2. In conditions of changing radiation and constant temperature, the electrical power generated at maximum radiation conditions is 99.3%. While in conditions of radiation and temperature both changing, the electrical power generated is around 93.85%.

Figure 13 depicts the performance results of the MPPT algorithm proposed by the researcher to improve the incremental conductance technique displayed in Figure 6. The performance under changing radiation conditions with constant temperature is shown in Figure 13(a) and for both changing conditions can be seen in Figure 13(b). In (14) serves as the foundation for the revised algorithm, which employs the variable step size notion. The algorithm improvement was made when the curve slope condition (dP/dV) was positive. This signifies that the MPP point has not been achieved, and the operating point remains to the left of the MPP, necessitating an increase in duty cycle value. When compared to the existing approach, the new MPPT algorithm performs better. Figure 13 also shows that the convergence time, oscillation value, and system stability are all much better than the others. The problem discovered is that there is still overshoot when the radiation value is greatly reduced. At the maximum radiation value, the electrical power generated under changing radiation conditions while maintaining a constant temperature is 99.3%. It generates 93.9% of electrical power under changing radiation and temperature conditions.



(a) (b)

Figure 12. Performance of the INC algorithm using (14) (a) the changes in radiation while the temperature is constant and (b) the changes in radiation and temperature



(a) (b)

Figure 13. Performance of the INC algorithm of the proposed method (a) the changes in radiation while the temperature is constant and (b) the changes in radiation and temperature

In Figure 13, it can be seen that the convergence value can be significantly increased, along with the oscillations that particularly arise in steady state condition. The slow convergence speed can be surmounted, but there is still an overshoot when the radiation value decreases significantly. Figure 14 displays a performance comparison of each algorithm in generating electrical energy. Figure 14(a) depicts a scenario where the radiation value varies while the temperature remains constant at 25 °C. The magnified section of the image reveals the superior performance of one method over the other, particularly in terms of convergence time and tracking error. Tracking errors occur as the radiation value gradually increases from 300 W/m^2 to 900 W/m^2 in this investigation. These problems are particularly noticeable when using the variable step size approach with (11) and (14), while the conventional method shows far more significant oscillations. When the radiation value is set to its maximum, the suggested variable step size and method yield a higher electrical power output than the conventional method. Figure 14(b) depicts the correlation between changes in radiation value and temperature and their impact on the production of electrical energy. The performance pattern remains mostly unchanged under constant temperature settings, albeit with a drop in electrical energy production. Tables 2 and 3 provide a comprehensive analysis of the performance of each MPPT algorithm in terms of convergence time, oscillation at steady state, and tracking efficiency.

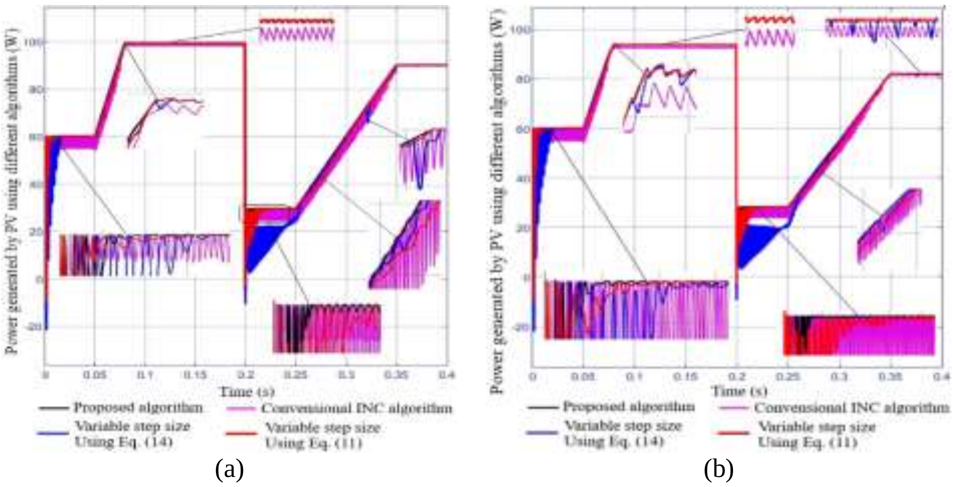


Figure 14. Comparison of performance in producing electrical energy for each algorithm (a) the changes in radiation while the temperature is constant and (b) the changes in radiation and temperature

Table 2. System performance in producing electrical energy with various MPPT algorithms under changing radiation with constant temperature

MPPT algorithm	Convergence time (seconds)				Oscillations at steady state (watts)				Average tracking efficiency (%)
	600 W/m^2	1000 W/m^2	300 W/m^2	900 W/m^2	600 W/m^2	1000 W/m^2	300 W/m^2	900 W/m^2	
INC Conventional	NA	NA	NA	NA	6	0.764	5.813	0.359	96.36
INC using the first model [22], [23]	0.018	NA	NA	NA	NA	NA	NA	0.071	89.99
INC using the second model [25]	0.015	NA	0.228	NA	NA	NA	NA	NA	99.83
Proposed	0.009	NA	0.209	NA	NA	NA	NA	NA	99.83

Table 3. System performance in producing electrical energy with various MPPT algorithms under changing radiation and temperature conditions

MPPT algorithm	Convergence time (seconds)				Oscillations at steady state (Watts)				Average tracking efficiency (%)
	600 W/m^2	1000 W/m^2	300 W/m^2	900 W/m^2	600 W/m^2	1000 W/m^2	300 W/m^2	900 W/m^2	
INC conventional	NA	NA	NA	NA	5.984	0.9	4.893	0.55	91.19
INC using the first model [22], [23]	0.039	0.006	NA	NA	NA	0.012	NA	0.36	83.39
INC using the second model [25]	0.015	NA	0.021	NA	NA	NA	NA	NA	92.94
Proposed	0.009	NA	0.008	NA	NA	NA	NA	NA	95.21

The term NA in the Tables 2 and 3 states that convergence conditions are not achieved yet. The resultant signal undergoes oscillations until there is a change in the radiation value. Furthermore, a drawback of the method employed in this work is the tendency for overshooting upon a substantial decrease in the radiation value. This study focused on the scenario when the radiation value decreased from 1000 W/m^2 to 300 W/m^2.

Based on the conducted research, the proposed method demonstrates superiors performance compared to existing models, including the conventional INC method, the first INC model, and the second INC model. It exhibits faster convergence times, reduced oscillation during the changes in radiation values and temperature, and improved tracking efficiency, particularly under conditions of varying radiation and constant temperature. Even when both radiation and temperature fluctuate, the proposed method consistently outperforms its predecessors. Therefore, it can be confidently asserted that the proposed method is a significant advancement in the field.

6. CONCLUSION

To maximize electrical power generation, photovoltaic working systems primarily depend on the MPPT system to ensure that it can operate at MPP. Therefore overall efficiency of the system can be enhanced. In this study, the performance of the developed MPPT system is observed under different circumstances including changes in both radiation and temperature. To provide accurate analysis, some parameters are used as a comparison to other methods such as convergence time, oscillation, overshot, and tracking speed. The study findings revealed that the proposed algorithm, known as the improved incremental conductance algorithm, had better convergence time, oscillation, and tracking speed compared to previous algorithms. In the simulation, the test was conducted under two conditions : i) radiation changes with constant temperature and ii) both radiation and temperature change. The simulation results indicate that the suggested approach is applicable to real conditions in the field and has a low level of complexity. This research can be further enhanced using several existing MPPT methods to achieve improved outcomes, particularly in situations characterized by unpredictable variations in radiation and temperature.

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