Performance Analysis of an Incremental Conductance MPPT Algorithm for Photovoltaic Systems Under Rapid Irradiance Changes

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***Abstract* – The control algorithm for tracking the maximum power point (MPPT) is a crucial factor that influences the system's capacity to harness the maximum energy from the sun using photovoltaic. Incremental conductance stands out as one of the most commonly employed MPPT techniques due to its simplicity and low implementation complexity. However, it has various shortcomings, rendering it less effective in adapting to changing solar radiation conditions. Therefore, this study proposed a modification to enhance the algorithm's performance. The proposed modified algorithm is validated through experiments, revealing that the fastest tracking time for the adjusted incremental conductance algorithm was 72 ms, whereas the unmodified algorithm took 84 ms. Additionally, oscillations observed during changes in radiation values were 2 W and 1.66 W for the unmodified algorithm, occurring during decreases and increases in radiation values, respectively.**

In contrast, the proposed modified incremental conductance algorithm resulted in a consistent oscillation of 1.33 W for each change in radiation value.Furthermore, it can be concluded that the modified incremental conductance algorithm can increase the tracking time as well as reduce oscillations that occur under various conditions of changes in radiation values.

***Keywords* – Incremental conductance, MPPT, tracking performance, solar radiation, boost converter.**

1. Introduction

Solar energy is one of the prominent renewable energy sources that can address several issues, such as the electrical energy crisis, escalating fossil fuel costs and CO2 emissions, and climate change [1], [2], [3], [4]. Many energy experts anticipate that by 2050, renewables will meet a portion of the world's electrical energy needs, with solar energy accounting for 10% [5], [6]. However, extracting energy to the maximum with ever-changing solar radiation conditions throughout the day is a challenge that must be solved. This challenge arises from factors such as shadows obstructing sunlight on the PV surface or the changing position of the sun from morning to evening. Apart from solar radiation, other factors that affect the process of absorbing solar energy are temperature, the tilt position of the panel, and most importantly the method used in tracking the maximum power known as MPPT. It is crucial to optimize the performance of PV, ensuring they operate at their maximum efficiency.

The results showed various MPPT methods, as shown in [7]. MPPT techniques are divided into three main categories based on control theory and implementation: traditional, intelligent, and in partial shading conditions.

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The traditional approaches involve utilizing selection control parameters, for instance, short-circuit current tracking (SCT), open-circuit voltage tracking (OVT), constant voltage tracking (CVT), as well as direct control techniques like incremental conductance (InC), perturb and observer (P&O), ripple correlation control (RCC), and other methods.

The maximum power point (MPP) can be effectively tracked under uniform irradiation conditions using conventional methods, but not for irradiation conditions that are always changing, especially sudden changes. The MPPT intelligent method is divided into artificial intelligence (AI) and nonlinear methods. The MPPT method uses more advanced intelligent algorithms to overcome the weaknesses of traditional methods such as sliding mode control (SMC), neural network controller (NN), and fuzzy logic controller (FLC). However, this method has a high complexity of implementation, system performance depends on experience in determining rules and membership functions and high switching frequency in the SMC method causes chattering problems [8], [9], [10]. In contrast, the MPPT method in partial shading conditions (PSCs) consists of AI, modified direct control, array reconfiguration, and other methods.

The MPPT InC method is the most extensively used due to its efficiency and rapid tracking speed, as well as its relative simplicity of implementation in comparison to other conventional methods [11], [12], [13]. The InC method is also widely used for PSC conditions by improving algorithm performance to work in PSC conditions. In addition to modifying the InC algorithm, efforts to improve its performance are also carried out by combining several algorithms known as the hybrid method [14], [15], [16], [17]. The InC algorithm is less complicated and easier to implement. It compelled us to employ the InC technique in this research. In this study, this algorithm was modified to increase the MPP speed under varying solar radiation conditions. In addition, the improvement of the InC algorithm is also intended to reduce oscillations around the maximum point in steady-state conditions so as to reduce power losses. Several forms of algorithm modifications are tested and compared using stand-alone photovoltaic (PV) systems to obtain better performance to meet the goals to be achieved

2. System Description

Figure 1 shows the system used in the study to perform tests of the InC algorithm. As can be seen in Figure 1, it combines PV modules, a boost converter, a load, and a processor as the control unit of the MPPT algorithm. The controller that we used in this study is an Arduino Uno.

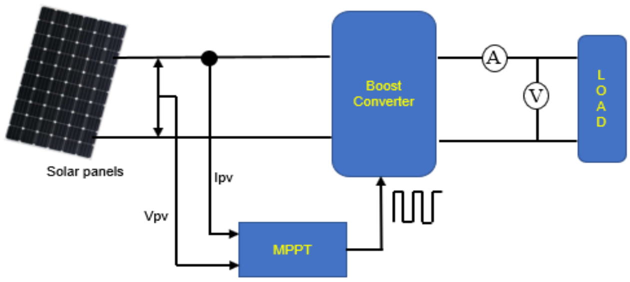

Figure 1. The diagram block of the designed PV

2.1. Photovoltaic Modules

PV modules are a combination of solar cells in series or in parallel, while PV arrays are a combination of series relationships and parallel relationships of PV modules [18]. The PV design and the equivalent circuit are presented in Figures 1 and 2, respectively.

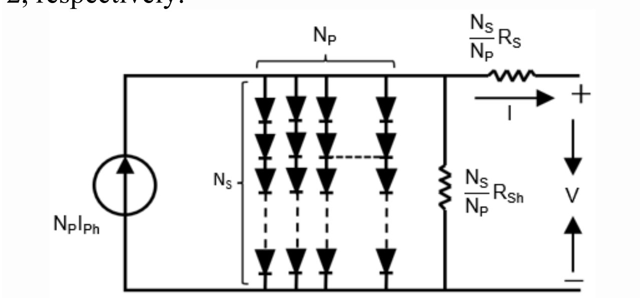

Figure 2. Equivalent circuit of a PV module

Determining the current of the PV module can be done using equation (1) [19].

$$I=(I_{ph}xN_p)\text{-}(I_0xN_p)\left[exp\left(\frac{\frac{V}{N_s}+I\,x\,\frac{R_s}{N_p}}{nV_t}\right)\text{-}1\right]\text{-}I_{sh} \qquad (1)$$

I and V represent the output current and voltage of a PV system, I_{ph} is the current of the photocell (A), the number of cells connected in parallel is Np and series is Ns, V_t is the thermal voltage of the diode (V), and I_{sh} is the current at parallel resistance (A). The specifications of the PV in this study can be seen in Table 1.

Table 1. Specifications of PV Greentek MSP-100W

No	Parameters	Values
1	Pmax	100 W
2	Vmp	18.1 V
3	Imp	5.54 A
4	Voc	22.2 V
5	Isc	6.00 A
6	Temperature coefficient (Voc)	-(0.40 ± 0,05) % / ^{0} C
7	Temperature coefficient (Isc)	(0.065 ± 0,01) % / ^{0} C
8	Ns	72 (4 x 18)

Theoretically, the impact of fluctuations in solar radiation on the generated energy is represented by the P-V and I-V characteristics, as illustrated in Figure 3 and Figure 4, respectively.

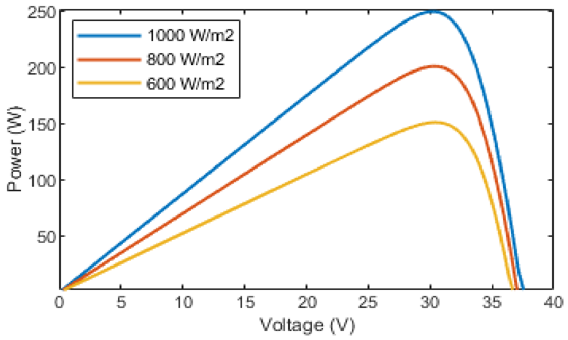

Figure 3. Characteristics of the P-V

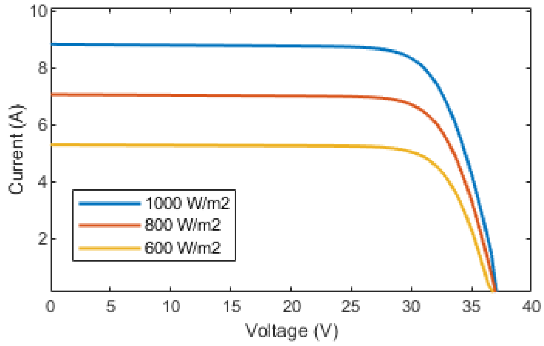

Figure 4. Characteristics of the I-V

As shown in Figures 3 and 4, variations in solar radiation having a notable effect on the generated current and power. However, this condition does not have much effect on the voltage value and indirectly also causes a shift in position from MPP. Therefore, to track MPP on all changes in radiation causing the duty cycle value to also vary.

2.2. Boost Converter

In accordance with Figure 1, the circuit of the boost converter is shown in Figure 5.

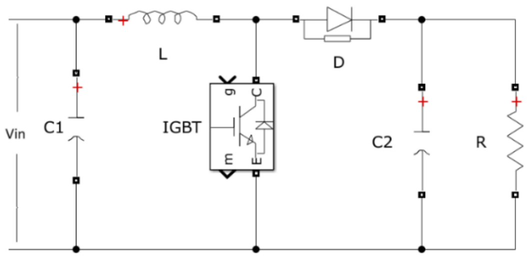

Figure 5. Equivalent boost converter circuit

The function of changing the duty cycle value is to maintain PV operation at the MPP point with the appropriate voltage (Vmp) and current (Imp) values. While the parameters for designing a boost converter are determined by the input voltage value, output voltage value, and load power.

Equations (2) to (5) can be used to calculate output voltage, inductor values, and input and output capacitors [20], [21].

$$V_0 = \frac{V_{in}}{1 - D} \tag{2}$$

$$L \geq \frac{D \ x \ (1 - D)^2 \ x \ R}{r \ x \ F} \tag{3}$$

$$C_1 \geq \frac{D}{8 \ x \ F^2 \ x \ L \ x \ 0.01} \tag{4}$$

$$C_2 \geq \frac{D}{F \ x \ 0.02 \ x \ R} \tag{5}$$

V_{in}, V_o, and D refer to the boost converter input, output, and duty cycle. L, C, and R are the component values of the inductor, capacitor, and resistor. The parameters value of the boost converter are presented in Table 2.

Table 2. Parameters value of the boost converter

No	Parameters	Values
1	C in	100 uF
2	C out	47 uF
3	L	2.2 mH
4	R	135 Ohm
5	F	7812.5 Hz

3. Incremental Conductance MPPT Algorithm

The working process of the InC algorithm is guided by the incremental conduction (ΔI/ΔV) of the characteristics of PV, which serve to detect the slope of the P-V characteristic curve (ΔP/ΔV) [22]. At the MPP point, this slope value will be zero, large from zero if on the left side of the MPP, and small from zero if on the right side. If the slope encountered is negative, then the operating point is shifted to the left by the controller by reducing the PV array voltage value, and vice versa. This happens until the slope becomes zero, and the adjustment of the voltage value will stop, indicating that the MPP has been reached [23]. Mathematically, it can be seen in equations (6) to equations (8) [23], [24].

$$\frac{\Delta P}{\Delta V} = 0 \text{ at the MPP} \tag{6}$$

$$\frac{\Delta P}{\Delta V} > 0 \text{ at the left position of the MPP} \tag{7}$$

$$\frac{\Delta P}{\Delta V} > 0 \text{ at the right position of the MPP} \tag{8}$$

From equation (6) it can be redeveloped into equation (9) to (12)

$$\frac{\Delta P}{\Delta V} = \frac{\Delta (V \ x \ I)}{\Delta V} = I + V\left(\frac{\Delta I}{\Delta V}\right) = 0 \tag{9}$$

$$\text{Then } \frac{\Delta I}{\Delta V} = - \frac{I}{V} \text{ at the MPP} \tag{10}$$

$$\frac{\Delta I}{\Delta V} > - \frac{I}{V} \text{ at the left position of the MPP} \tag{11}$$

$$\frac{\Delta I}{\Delta V} < - \frac{I}{V} \text{ at the right position of the MPP} \tag{12}$$

The InC algorithm, as shown in Figure 6, is a conventional algorithm widely used nowadays because of its simple characteristics and cheaper financing and application [25], [26].

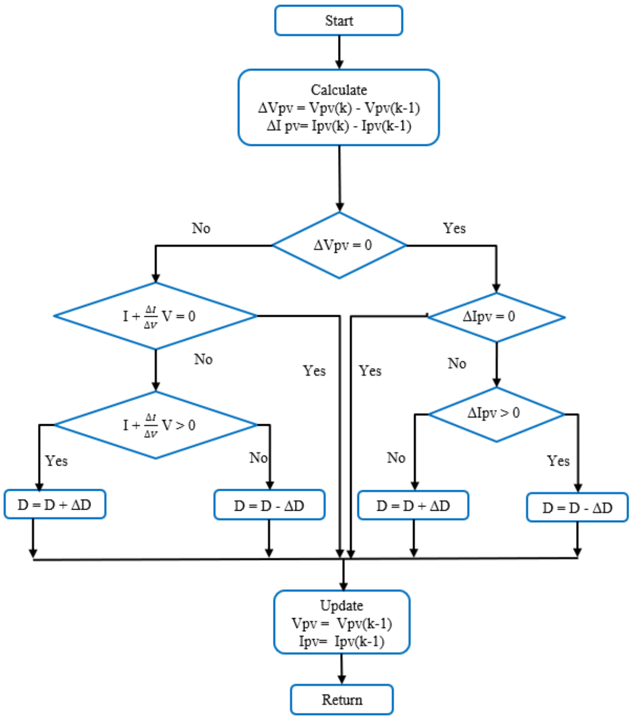

Figure 6. MPPT Algorithm using the InC method

This InC algorithm is effective for tracking MPP under uniform radiation conditions. However, it cannot work well when there is a rapid change in radiation and causes oscillations around MPP at steady state. The algorithm responds inaccurately to the change of the first step in the task cycle of the converter during increased solar irradiation and the time to find MPP is also longer. Based on these problems, it is proposed to modify the InC algorithm. This algorithm aims to quickly track the location of the MPP or optimal operating point on changes in solar irradiation values, especially for irradiation changes that occur suddenly. It tracks MPP points based on voltage variations guided by equation (14). Figure 7 shows the modified InC algorithm.

The proposed algorithm as in Figure 7 tracks MPP by checking changes in voltage and current values. Usually, the radiation value and temperature will remain if the state is stable where the characteristics of the current and voltage indicate that the change in voltage is followed by a change in the current value with different signs. However, if the voltage disturbance causes a current disturbance with different signs, PV is under varying environmental conditions [27]. The modified InC algorithm as in Figure 7 is able to distinguish between these two conditions so that differences that occur such as variations in environmental conditions that will change the direction of interference can be avoided.

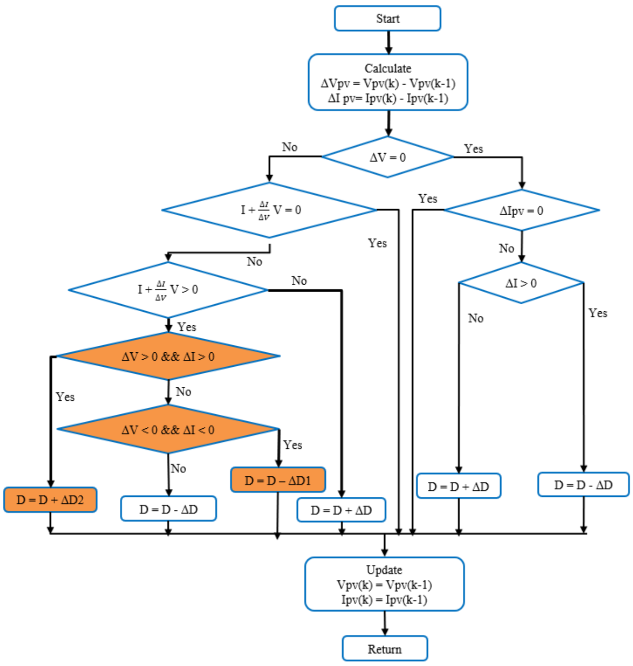

Figure 7. MPPT Algorithm using the modification InC method

A modification of the conventional algorithm is the colored part in Figure 7 consisting of changes in current and voltage with equal signs in response to rapid changes in solar radiation

4. Experimental Results and Analysis

Figure 8 shows the system construction to observe how the MPPT algorithm works. The PV used is 200 Wp with a stand-alone system using parameters according to Table 1. The lighting source for PV is based on halogen lamps with a capacity of 150 watts, with as many as 12 pieces arranged in parallel. Meanwhile, to vary the lighting value, a dimmer circuit is used. Both tested algorithms were implemented using Arduino Uno, and for current and voltage sensors, using ACS712 and F031-06.

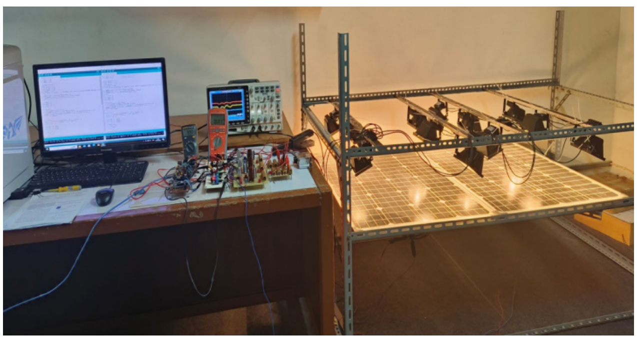

Figure 8. System experiments

In the initial stage of testing, experiments were carried out with two different radiation values. The irradiation values are set at 500 W/m^2 and 300 W/m^2 with variations in duty cycle values from 5% to 95%.

This testing process is carried out to obtain power-voltage (P-V) characteristics and power-duty cycle (P-D) characteristics. The test result for each characteristic is shown in Figure 9 and Figure 10. From the tests obtained for radiation of 500 W/m^2 and 300 W/m^2, the maximum power for each is 16.52 W and 9.63W. Both the incremental conduction algorithm and the modified incremental conduction algorithm were tested for changes in radiation with fixed duty perturbation (ΔD) with variations from 1% to 5%.

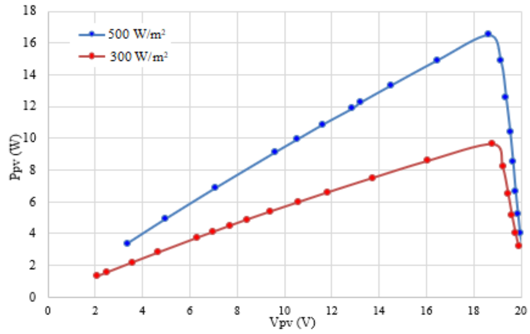

Figure 9. The test result characteristics: P-V characteristics

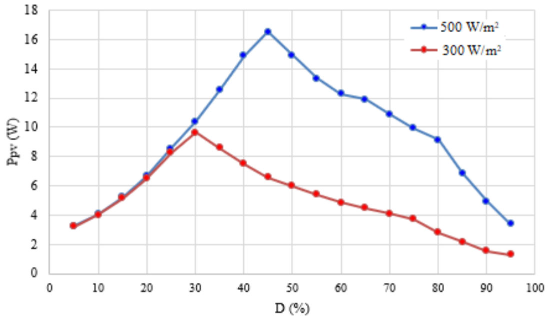

Figure 10. The test result characteristics: P-D characteristics

Figure 11 is the test result when the radiation value drops from 500 to 300 (W/m^2) using the InC algorithm. In the testing process, MPP trace time varies based on the value of ΔD. The greater the value ΔD, the faster the tracking time. Figure 12 is the test result, with the radiation value rising from 300 to 500 (W/m^2). In conditions of increased radiation, the higher the value ΔD, the longer the MPP tracking time. Figure 13 and Figure 14 are test results using a modified InC algorithm. Figure 13 shows the radiation value dropping from 500 to 300 (W/m^2). The test results show that the MPP tracking time is getting faster if the ΔD value is getting bigger. Likewise, Figure 14 is a test condition with the radiation value rising from 300 to 500 (W/m^2). At the time of testing, it was found that the greater the value of ΔD, the longer the tracking time to find MPP.

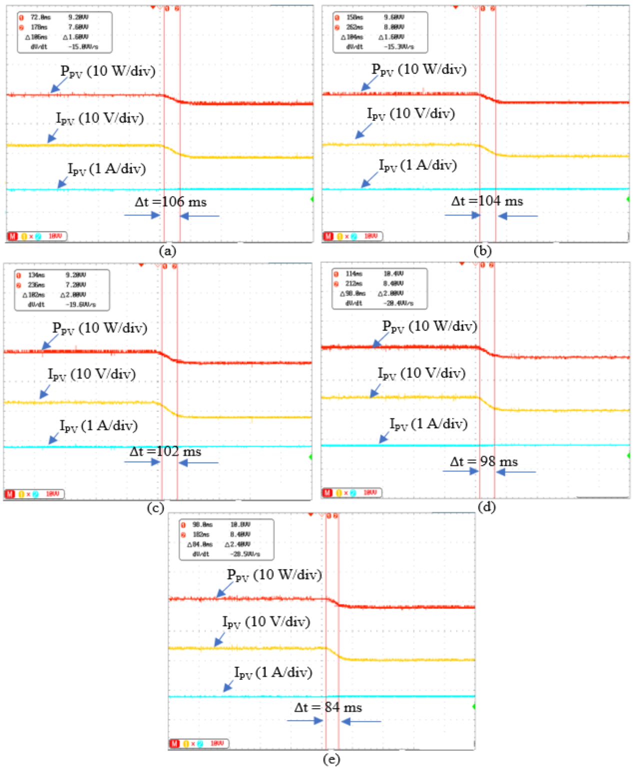

Figure 11. Testing using the MPPT InC algorithm when there is a decrease in the radiation value with a perturbation (ΔD) values of 1% to 5% sequentially from (a) to (e)

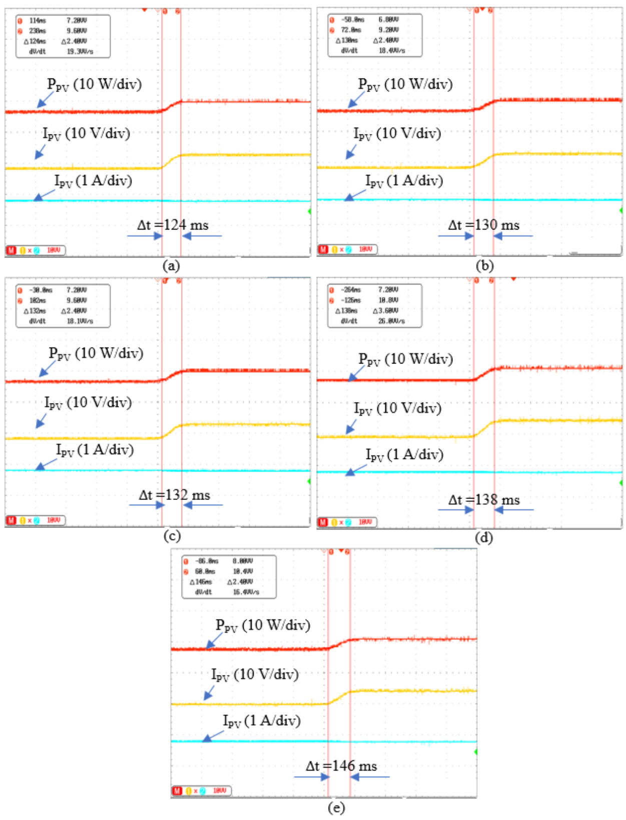

Figure 12. Testing using the MPPT InC algorithm when there is an increase in the radiation value with a perturbation (ΔD) values of 1% to 5% sequentially from (a) to (e)

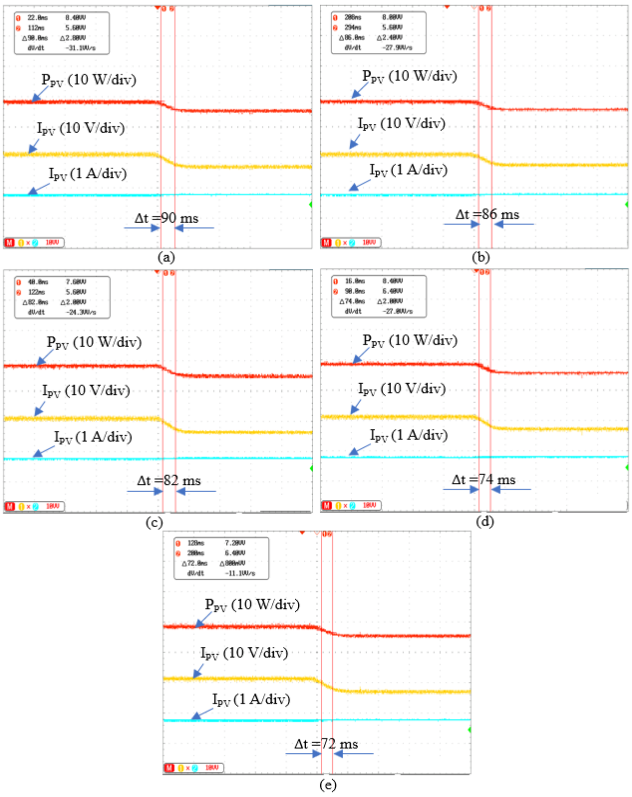

Figure 13. Testing using the modified InC algorithm when there is decrease in the radiation value with a perturbation (ΔD) values of 1% to 5% sequentially from (a) to (e)

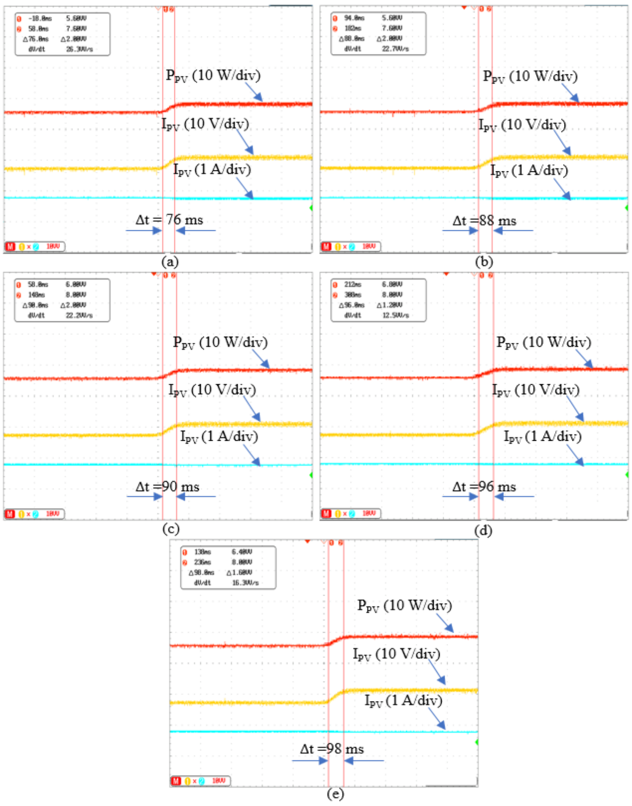

Figure 14. Testing using the modified InC algorithm when there is an increase in the radiation value with a perturbation (ΔD) values of 1% to 5% sequentially from (a) to (e)

5. Discussion

Table 3 presents the time taken by each MPPT algorithm under different conditions to track MPP. MPP tracking is carried out with differences in perturbation (ΔD) and changes in radiation values from 500 W/m^2 to 300 W/m^2 or vice versa. Based on the test results in table 3, the modified InC algorithm has a faster time to track MPP both under down and vice versa radiation conditions and with different perturbations.

Table 3. Tracking results from conventional and modified InC techiques for MPP tracking under different conditions

		The time required by the InC algorithm to track MPP.		The time required by the modified InC Algorithm to track MPP.	
No	Perturbation (ΔD)	Radiation changes from 500 to 300 (W/m^2)	Radiation changes from 300 to 500 (W/m^2)	Radiation changes from 500 to 300 (W/m^2)	Radiation changes from 300 to 500 (W/m^2)
1	1 %	106 ms	124 ms	90 ms	76 ms
2	2 %	104 ms	130 ms	86 ms	88 ms
3	3 %	102 ms	132 ms	82 ms	90 ms
4	4 %	98 ms	138 ms	74 ms	96 ms
5	5 %	84 ms	146 ms	72 ms	98 ms

According to the test findings in Table 3, the fastest MPP tracking time is 72 ms with 5% ΔD when the radiation is changed from 500 to 300 (W/m^2) using the modified InC algorithm. At the same radiation value settings, the fastest tracking time for the unmodified InC algorithm was 84 ms with 5% ΔD. During the test, oscillations that occur with each change in radiation value were also observed. The oscillations that occur in unmodified InC algorithm testing with changes in radiation values from 500 to 300 (W/m^2) are 2 W, the same for each change in ΔD values. While the change in radiation value from 300 to 500 (W/m^2) is 1.66 W and is also the same for every change in the value of ΔD. In tests using a modified InC algorithm for radiation changes from 500 to 300 (W/m^2) or vice versa is 1.33 W and the value is the same for each change in ΔD value. Consequently, it can be explained that the adjustment made to the InC algorithm is effective in decreasing the time required for MPP tracking and minimizing the oscillation associated with alterations in radiation levels.

6. Conclusion

Modifying the MPPT algorithm aims to improve performance, especially the speed of MPP tracking when there is a change in solar radiation.

This study made modifications to the InC algorithm to achieve the intended goal. The test results found that the modified algorithm's performance was indeed better overall than the unmodified InC algorithm. The fastest time for MPP tracking using a modified algorithm is 72 ms, while the unmodified algorithm has a time of 84 ms. While the oscillations that occur for each change in radiation value are 2 W and 1.66 W, each of which is when the change in radiation value decreases and increases using the InC algorithm, while testing the modified InC algorithm, it caused an oscillation of 1.33 W, and the value was the same for each change in radiation value. Based on the test results, it can be concluded that the modified InC algorithm can increase the tracking time as well as reduce oscillations that occur under various conditions of changes in radiation values.

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References:

[1]. Çelik Ö., Tan A., Inci M., & Teke A. (2020). Improvement of energy harvesting capability in grid-connected photovoltaic micro-inverters. *Energy Sources, Part A: Recovery, Utilization and Environmental Effects*, 1–25. Doi: 10.1080/15567036.2020.1755389

[2]. D. Al-Majidi S., F Abbod M., & S. Al-Raweshidy H. (2019). Design of an efficient maximum power point tracker based on ANFIS using an experimental photovoltaic system data. *Electronics*, *8*(858), 1–20. Doi: 10.3390/electronics8080858

[3]. Trujillo C. L., Santamaría F., & Gaona E. E. (2016). Modeling and testing of two-stage grid-connected photovoltaic micro-inverters. *Renewable Energy*, *99*, 533–542. Doi: 10.1016/j.renene.2016.07.011

[4]. Ranjan Jha R., Chandra Srivastava S., & Kumar M. (2017). Development of control schemes for a cluster of PV-integrated houses in islanded mode. *IET Renewable Power Generation*, *11*(7), 903–911. Doi: 10.1049/iet-rpg.2016.0048

[5]. Owusu Sarfo K., Mbora Amuna W., Nkabe Pouliwe B., & Boafo Effah F. (2020). An improved P&O MPPT algorithm under partial shading conditions. *PES/IAS PowerAfrica*, 1–5.

[6]. Alik R., Jusoh A., & Sutikno T. (2017). A study of shading effect on photovoltaic modules with proposed P & O checking algorithm. *International Journal of Electrical and Computer Engineering*, *7*(1), 29–40. Doi: 10.11591/ijece.v7i1.pp29-40

[7]. Mao, M., Cui, L., Zhang, Q., Guo, K., Zhou, L., & Huang, H. (2020). Classification and summarization of solar photovoltaic MPPT techniques: A review based on traditional and intelligent control strategies. *Energy Reports*, 6, 1312–1327. Elsevier Ltd. Doi: 10.1016/j.egyr.2020.05.013

[8]. Villegas-Mier, C. G., Rodriguez-Resendiz, J., Álvarez-Alvarado, J. M., Rodriguez-Resendiz, H., Herrera-Navarro, A. M., & Rodríguez-Abreo, O. (2021). Artificial neural networks in mppt algorithms for optimization of photovoltaic power systems: A review. *Micromachines*, *12*(10). MDPI. Doi: 10.3390/mi12101260

[9]. Katche, M. L., Makokha, A. B., Zachary, S. O., & Adaramola, M. S. (2023). A Comprehensive Review of Maximum Power Point Tracking (MPPT) Techniques Used in Solar PV Systems. *Energies 16*(5). MDPI. Doi: 10.3390/en16052206

[10]. Jamshidi, F., Salehizadeh, M. R., Yazdani, R., Azzopardi, B., & Jately, V. (2023). An Improved Sliding Mode Controller for MPP Tracking of Photovoltaics. *Energies*, *16*(5). Doi: 10.3390/en16052473

[11]. Mishra J., Das S., Kumar D., & Pattnaik M. (2019). Performance comparison of P&O and INC MPPT algorithm for a stand-alone PV system. *Innovations in Power and Advanced Computing Technologies (i-PACT)*, 1–5.

[12]. Ji R., & Wang Z. (2023). Improved variable-step incremental conductance MPPT algorithm applied to photovoltaic storage systems. *International Conference on Smart Grid and Energy Internet (SGEI)*, *2427*(1), 1–7. Doi: 10.1088/1742-6596/2427/1/012045

[13]. Ajesam Asoh D., Damien Noumsi B., & Nyuysever Mbinkar E. (2022). Maximum power point tracking using the incremental conductance algorithm for PV systems operating in rapidly cChanging environmental conditions. *Smart Grid and Renewable Energy*, *13*(5), 89–108. Doi: 10.4236/sgre.2022.135006

[14]. Al-Dhaifallah M., M. Nassef A., Rezk H., & Sooppy Nisar K. (2018). Optimal parameter design of fractional order control based INC-MPPT for PV system. *Solar Energy*, *159*, 650–664. Doi: 10.1016/j.solener.2017.11.040

[15]. Harrison A., Henry Alombah N., & de Dieu Nguimfack Ndongmo J. (2023). A new hybrid MPPT based on incremental conductance-integral backstepping controller applied to a PV system under fast-changing operating conditions. *International Journal of Photoenergy*, *2023*, 1–17. Doi: 10.1155/2023/9931481

[16]. Sun C., Ling J., & Wang J. (2022). Research on a novel and improved incremental conductance method. *Scientific Reports*, *12*(1), 1–14. Doi: 10.1038/s41598-022-20133-7

[17]. Shang, L., Guo, H., & Zhu, W. (2020). An improved MPPT control strategy based on incremental conductance algorithm. *Protection and Control of Modern Power Systems*, *5*(1). Doi: 10.1186/s41601-020-00161-z

[18]. Asnil A., Krismadinata K., Husnaini I., & Astrid E. (2022). Design and performance of dual axis solar tracker based on light sensors to maximize the photovoltaic energy output. *Journal of Theoretical and Applied Information Technology*, *100*(22), 6554–6564.

[19]. Hieu Nguyen X., & Phuong Nguyen M. (2015). Mathematical modeling of photovoltaic cell/module/arrays with tags in Matlab/Simulink. *Environmental Systems Research*, *4*(1), 1–13. Doi: 0.1186/s40068-015-0047-9

[20]. Motahhir S., El Ghzizal A., Sebti S., & Derouich A. (2018). Modeling of photovoltaic system with modified Incremental Conductance Algorithm for fast changes of irradiance. *International Journal of Photoenergy*, *2018*, 1–14. Doi: 10.1155/2018/3286479

[21]. Motahhir S., El Ghzizal A., Sebti S., & Derouich A. (2017). MIL and SIL and PIL tests for MPPT algorithm. *Cogent Engineering*, *4*(1), 1–18. Doi: 10.1080/23311916.2017.1378475

[22]. Motahhir S., Chalh A., El Ghzizal A., & Derouich A. (2018). Development of a low-cost PV system using an improved INC algorithm and a PV panel proteus model. *Journal of Cleaner Production*, *204*, 355–365. Doi: 10.1016/j.jclepro.2018.08.246

[23]. Ismail M. Ali A., Muhammed Alaas Z., A. Sayed M, Almalaq A., Farah A., & A. Mohamed M. (2022). An efficient MPPT technique-based single-stage incremental conductance for integrated PV systems considering flyback central-type PV inverter. *Sustainability (Switzerland)*, *14*, 1–15. Doi: 10.3390/su141912105

[24]. Jalali Zand S., Hsien Hasia K., Eskandarian N., & Mobayen S. (2021). Improvement of self-predictive incremental conductance algorithm with the ability to detect dynamic conditions. *Energies*, *14*(5), 1–14. Doi: 10.3390/en14051234

[25]. Amin S., Khan S., & Qayoom A. (2018). Comparative analysis about the study of maximum power point tracking algorithm: A review. *International Conference on Computing, Mathematics and Engineering Technologies (ICoMET).*, 1–8.

[26]. Shixun M., Qintao Y., Kunping J., Xiaofeng M., & Gengyu S. (2022). An improved MPPT method for photovoltaic systems based on mayfly optimization algorithm. *Energy Reports*, *8*, 141–150. Doi: 10.1016/j.egyr.2022.02.160

[27]. Belkaid, A., Colak, I., & Isik, O. (2016). Photovoltaic maximum power point tracking under fast varying of solar radiation. *Applied Energy*, *179*, 523–530. Doi: 10.1016/j.apenergy.2016.07.034.