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Authors	SUNARDI*, Abdul Fadlil, Arsyad Cahya Subrata
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Bukti Korespondensi

Tahap 1
Submission, 09 May 2022

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09-May-2022

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Tahap 2
Respon Editor: successfully submitted, 11 May 2022

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11-May-2022

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Tahap 3
Respon Editor: Revision, 04 July 2022

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Editor, ETRI Journal

Editor Comments to Author:

Section Editor: 1
Comments to the Author:
(There are no comments.)

Editor: 2
Comments to the Author:
Please improve the manuscript along the suggested lines indicated by the reviewers. State clearly what is new in this paper with respect to already published work. A single paragraph is not sufficient, one has to make the novelty case long enough in order to convince the readers.

Reviewer(s)' Comments to Author:

Reviewer: 1

Comments to the Author
1] Already fuzzy logic technique has been suceessfully applied for MPPT in Solar PV system. What is the novelty in this work?
2] Hardware implementation of the proposed algorithm has to be carried out.
3] The language used in the paper needs to be improved.

Reviewer: 2

Comments to the Author
The proposed technique is well explained and worth publishing in this journal.

To improve the quality of the paper, a few suggestions are as follows.
1. The literature review presented here is highly insufficient and generalized. Please improve it using recent papers.
2. Eqn. 2 is not clear. Please elaborate.
3. Few variables are not defined. Please correct it.
4. The picture quality of waveforms should improve.
5. Few short forms have been used without giving full forms. Please cross-check throughout the paper properly.
6. To improve the introduction and reference sections, you should follow quality papers. A few suggestions are as follows. doi: 10.1109/TSTE.2019.2891558, doi: 10.1109/TIE.2018.2890497, doi: 10.1109/TCSI.2020.2996775, doi: 10.1109/TPEL.2019.2898319, doi: 10.1109/TIE.2018.2889617.

7. Please go through those papers, and include and improve your literature review portion of the paper.
8. Elaborate discussions of results. Try to point out each waveform using proper justification.
9. Rewrite the conclusion section in the summarized form.

Reviewer: 3

Comments to the Author
This paper present MPPT techniques for PV system. P&O, Variable Step Size P&O and Fuzzy MPPT discussed in this paper have already been analyzed comprehensively in many articles. No novelty or contribution is found in the article.

Tahap 4
Revised paper successfully submitted, 21 July 2022

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21-Jul-2022

Dear Mr. Subrata:

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Original Article Title: “Optimum Solar Energy Harvesting System using Artificial Intelligence”

To: ETRI Journal Editor

Re: Response to reviewers

Dear Editor,

Thank you for allowing a resubmission of our manuscript, with an opportunity to address the reviewers’ comments. Thank for comments and suggestions for improving our paper.

We are uploading (a) our point-by-point response to the comments (below) (response to reviewers), (b) an updated manuscript with yellow highlighting indicating changes, and (c) a clean updated manuscript without highlights (PDF main document).

Best regards,

<Sunardi> et al.

Reviewer#1, Concern # 1:

Author response: Already fuzzy logic technique has been suceessfully applied for MPPT in Solar PV system. What is the novelty in this work?

Author action: Thank for Reviewer#1's comments. This paper discusses artificial intelligence algorithms, precisely the Fuzzy Logic Control (FLC) algorithm, to control new high-gain voltage DC/DC converters. As far as we can see, the converter topology has not been tested for harvesting solar energy with PV by optimizing harvesting using the MPPT technique.

Reviewer#1, Concern # 2:

Author response: Hardware implementation of the proposed algorithm has to be carried out.

Author action: Thank for your suggestions. We conducted a preliminary study of controlling the converter using the FLC algorithm for harvesting solar energy with PV. We are currently implementing hardware and will report it in the following article.

Reviewer#1, Concern # 3:

Author response: The language used in the paper needs to be improved.

Author action: We have improved the grammar in the paper.

Reviewer#2, Concern # 1:

Author response: The literature review presented here is highly insufficient and generalized. Please improve it using recent papers.

Author action: We have improved the literature review using recent papers.

Reviewer#2, Concern # 2:

Author response: Eqn. 2 is not clear. Please elaborate.

Author action: The parameters of the PV cell model are highly dependent on environmental conditions. The dependence of photocurrent on environmental conditions was characterized by (2).

Reviewer#2, Concern # 3:

Author response: Few variables are not defined. Please correct it.

Author action: We have fixed and added definitions of some variables that were not previously defined.

Reviewer#2, Concern # 4:

Author response: The picture quality of waveforms should improve.

Author action: We have improved the quality of the waveforms in Figure 10.

Reviewer#2, Concern # 5:

Author response: Few short forms have been used without giving full forms. Please cross-check throughout the paper properly.

Author action: The short forms you mean may refer to Figures 9 (a) and (b). Figures 9 (a) and (b) are detailed forms used to refer to the explanations of the letters "a" and "b" in Figure 8.

Reviewer#2, Concern # 6:

Author response: To improve the introduction and reference sections, you should follow quality papers. A few suggestions are as follows. doi: 10.1109/TSTE.2019.2891558, doi: 10.1109/TIE.2018.2890497, doi: 10.1109/TCSI.2020.2996775, doi: 10.1109/TPEL.2019.2898319, doi: 10.1109/TIE.2018.2889617.

Author action: Thank for your suggestion. We have added these references to the Introduction section to strengthen the literature review.

Reviewer#2, Concern # 7:

Author response: Please go through those papers, and include and improve your literature review portion of the paper.

Author action: We have added a literature review according to the references you suggest.

Reviewer#2, Concern # 8:

Author response: Elaborate discussions of results. Try to point out each waveform using proper justification.

Author action: We have added some improvements in section 6. Result and Discussion

"Seen in Figure 10a, the P&O algorithm reacts to an extreme when there is a change in irradiation. The P&O algorithm causes an instantaneous drift when the irradiation changes and takes longer to return to a stable state. Different results are shown in the FL algorithm and the step-size P&O variable, where there is no extreme reaction when irradiation changes. Both tend to produce a smoother slope. Also, when viewed in more detail, as shown in Figure 9a, the step-size P&O algorithm tends to have oscillations even though they only look small."

Reviewer#2, Concern # 9:

Author response: Rewrite the conclusion section in the summarized form.

Author action: We have added in section 7. Conclusion

"The P&O algorithm reacts to extremes when there is a change in irradiation which causes a momentary deviation when the irradiation changes and takes longer to return to a stable state. On the other hand, the FL algorithm shows no extreme reaction when the irradiation changes."

Reviewer#3, Concern # 1:

Author response: This paper present MPPT techniques for PV system. P&O, Variable Step Size P&O and Fuzzy MPPT discussed in this paper have already been analyzed comprehensively in many articles. No novelty or contribution is found in the article.

Author action: Thank for Reviewer#3's comment. This paper discusses artificial intelligence algorithms, precisely the Fuzzy Logic Control (FLC) algorithm, to control new high-gain voltage DC/DC converters. As far as we can see, the converter topology has not been tested for harvesting solar energy with PV by optimizing harvesting using the MPPT technique.

Received: Date Month Year | Received: Date Month Year | Accepted: Date Month Year

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WILEY ETRI Journal

ARTICLE TYPE

Optimum Solar Energy Harvesting System using Artificial Intelligence

| |

1

Correspondence

Renewable energy is promoted massively to overcome problems that fossil fuel power plants generate. One popular renewable energy type that offers easy installation is a photovoltaic (PV) system. However, the energy harvested through a PV system is not optimal because influenced by exposure to solar irradiance in the PV module, which is constantly changing due to weather. The maximum power point tracking (MPPT) technique was developed to maximize the energy potential harvested from the PV system. This paper presents the MPPT technique, which is operated on a new high-gain voltage DC/DC converter that has never been tested before for the MPPT technique in PV systems. Fuzzy logic (FL) was used to operate the MPPT technique on the converter. Conventional and Adaptive Perturb and Observe (P&O) techniques based on variables step-size were also used to operate the MPPT. The performance generated by the FL algorithm outperformed conventional and variable step-size P&O. It is evident that the oscillation caused by the FL algorithm is more petite than variables step-size and conventional P&O. Furthermore, FL's tracking speed algorithm for tracking MPP is twice as fast as conventional P&O.

KEYWORDS

Maximum power point tracking (MPPT), Artificial Intelligence, Fuzzy logic control, Perturb and Observe (P&O), Variable step size P&O

1 | INTRODUCTION

The need for electrical energy for homes and industries has shown a significant increase in the last few decades. Many power plants were built to meet the demand for electrical energy. However, in addition to their dwindling resources, these power plants have a lot of adverse side effects on the environment, such as water, soil, and air pollution due to solid and liquid waste produced from burning fossil materials as raw materials [1,2]. Recently, due to the shared awareness that has arisen in various circles, various radical efforts have been made to overcome these problems to provide a healthier environment.

Renewable energy is one of the significant issues predicted to be the best alternative to fulfill the demand for electrical energy but without doing harm to the environment. Renewable energy sources such as solar photovoltaic (PV) systems, hydropower, wind-turbine, tidal-turbine, biomass, and biothermal [3,4] are being developed because of their capabilty in optimizing the potential of nature. Solar PV systems are one of the most popular because they are clean, do not cause noise, are cheap, and easy to install and maintain [5,6]. Furthermore, the advantage of solar PV systems as an alternative power plant is that they do not generate noise compared to wind turbines [7].

However, due to the direct relationship and dependence on nature, solar PV-based power generation is non-linear. As when the irradiation on the PV array changes drastically, at that time, an instantaneous shift in the peak power point occurs [8]. The non-linear nature resulting from changes in irradiation and temperature affecting the PV causes the efficiency of the PV itself to be lower [9,10]. It is even reported that PV loss of energy reaches up to 25% [11]. This loss of energy is one of the problems in optimizing energy harvesters with solar PV. Various efforts have been made to optimize energy harvesting from solar PV. One of the most effective ways to increase efficiency is to achieve solar PV power production under any conditions [12]. This technique is known as maximum power point tracking (MPPT), which works by feeding an appropriate duty cycle (D) to DC/DC converter in the PV system.

Various methods can be used to operate MPPT, ranging from conventional methods such as Perturb and Observe (P&O) [13–15], Incremental Conductance (IncCond) [16–18], Hill Climbing (HC) [19–21], and their improved methods such as Learning based P&O (LPO) [22], Self-tuned P&O (SPO) [23], Learning-based ncCond (LIC) [24,25], Learning-based HC (L-HC) [26], which is based on the perturbation process in hill-climbing, to methods based on artificial intelligence algorithms such as fuzzy logic (FL) [27–31], artificial neural network (ANN) [32,33] and adaptive neuro-fuzzy inference systems (ANFIS) [34–36]. In general, a suitable MPPT implementation considers several aspects such as the type of application, efficiency, cost, lost energy, and suitability of the converter [37,38].

There are various types of DC/DC converters developed for various applications, generally boost, buck, buck-boost converters. For applications that require high voltage conversion, a DC/DC converter that can compensate for these needs is required. The boost converter can achieve high voltages by providing a large D. However, the voltage increment multiplication is not more than 5, and at the expense of efficiency, increasing the voltage on the switch and causing electromagnetic inference [39–41]. A Coupled-inductor converter can provide high voltage gain. Nevertheless, the efficiency is low due to increased chopper losses in inductors and conduction losses in semiconductors [42]. Another converter topology that provides high gain voltage is the cascaded converter [43,44]. However, the efficiency is also low due to the need for two processes. Another alternative is to connect two converters in series with only one switch, which is often called a quadratic boost converter (QBC) [45–47]. This converter topology produces the same voltage ratio as the cascaded converter, but the efficiency is lower than the boost converter.

The new high gain voltage DC/DC converter [48] provides a high voltage ratio and efficiency with lower current and voltage ripples. However, this converter still needs to be tested with MPPT to determine its suitability for PV systems. This paper employs the FL algorithm in a high gain voltage DC/DC converter for stand-alone PV systems.

2 | MODELING OF SOLAR CELLS

As a fundamental element of a PV system, basic knowledge of solar cells is essential. Solar arrays commonly used consist of a combination of series and/or parallel PV cells to produce a specific value. Different circuit models of PV cells are presented by [49]. As in Figure 1, the single diode is the most common and most straightforward model, while the PV module characteristic curves are shown in Figure 2. The relationship between the voltage-current of the PV module is modeled as

$$I = I_{PH} - I_{sat} \times \left[exp\left\{q \times \frac{V_{PV}+I_{PV}\times R_S}{A\times K\times T}\right\} - 1\right] - \frac{V_{PV}+I_{PV}\times R_S}{R_{SH}} \quad (1)$$

where I_{PH} and I_{sat} are light-generated and reverse saturation current, respectively, q is the electron charge (1.66022×10^{-19} C), V_{PV} and I_{PV} are the output voltage and current of the solar cells, respectively, R_S and R_{SH} are shunt and series resistances, respectively, A is the p-n ideally factor, K is the Boltzmann's constant (1.38×10^{-23} J/K), and T is the cell temperature in Kelvin.

The I_{PH} value is strongly influenced by the ambient temperature, T, as well as the irradiance, G, which is expressed as

$$I_{PH} = \{I_{SC}^* + k_i(T - T^*)\}\frac{G}{G^*} \quad (2)$$

where I_{SC}^* is the short-circuit current at 25 °C, $T^* = 298$ °K and $G = 1000\text{W/m}^2$. While k_i is the short-circuit current temperature coefficient. The * sign is the value at standard test conditions (STC).

I_{sat} is affected by ambient temperature as

$$I_{sat} = \frac{I_{SC}^*+k_i(T-T^*)}{exp\left[\frac{V_{OC}^*+k_V(T-T^*)}{V_t}\right]-1} \quad (3)$$

where V_{OC}^* is the open-circuit voltage at 25°C with k_V as the coefficient of open-circuit voltage, while $V_t = K \times T/q$ is the thermal voltage.

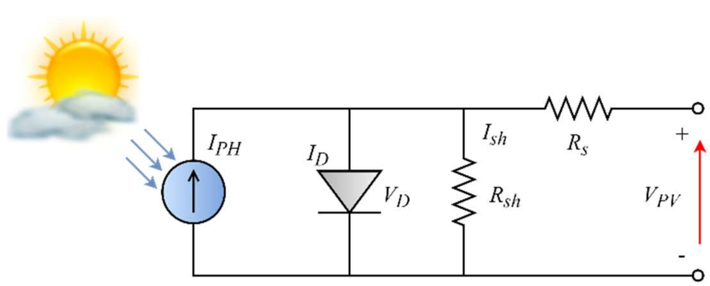


FIGURE 1 Single diode PV model.

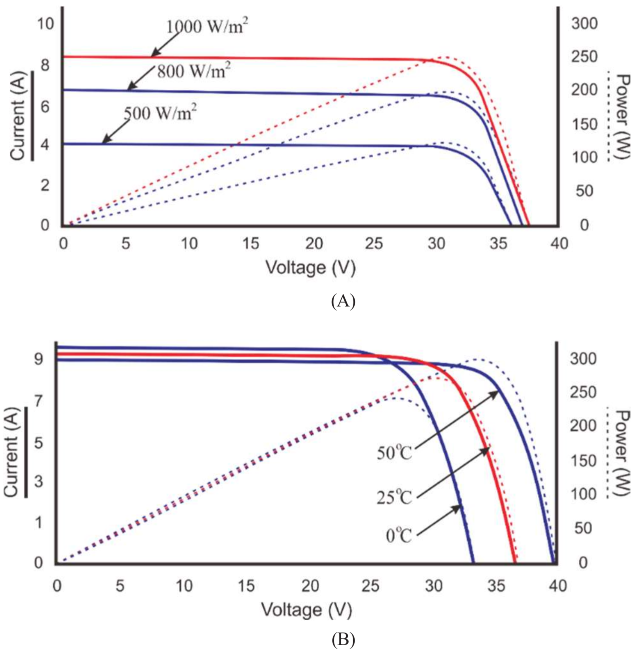


FIGURE 2 Trina Solar TSM-250PA05.08 PV module characteristic curves (a) under irradiation variation and (b) under temperature variation.

The amount of current in the series-connected module per setting is N_{ser}, and the parallel connection is N_{par}, then

$$I = N_{par}I_{PH} - N_{par}I_{sat}\left[exp\left\{q\frac{\frac{V}{N_{ser}}+I\frac{R_S}{N_{par}}}{AKT}\right\}-1\right]-\frac{\left(\frac{N_{par}}{N_{ser}}\right)+IR_S}{R_{SH}} \quad (4)$$

3 | MAXIMUM POWER POINT TRACKING

The maximum power transfer theorem forms the basis for the working principle of the MPPT technique. The theorem states that when the load resistance matches the source, it is possible to transfer the maximum power. Therefore, the working principle of the MPPT technique is to ensure the load resistance with PV at the maximum power point (MPP), which is calculated by [50]

$$R_{mpp} = \frac{V_{mpp}}{I_{mpp}} \quad (5)$$

where R_{mpp}, V_{mpp}, and I_{mpp} are the resistance, voltage, and current in MPP, respectively.

Although the maximum power transfer can be carried out by considering R_{mpp}, in reality, R_{mpp} is not constant because of the $I-V$ curve of PV due to weather dependence where changes in irradiation and temperature are unavoidable. Therefore, a DC/DC converter between the source and voltage connections is required to compensate for this resistance mismatch instead of supplying power directly to the load [51]. Through the MPPT algorithm, the duty cycle, D, is adjusted to ensure load resistance, and the D, which has been modified according to R_{mpp} on PV under varying weather conditions.

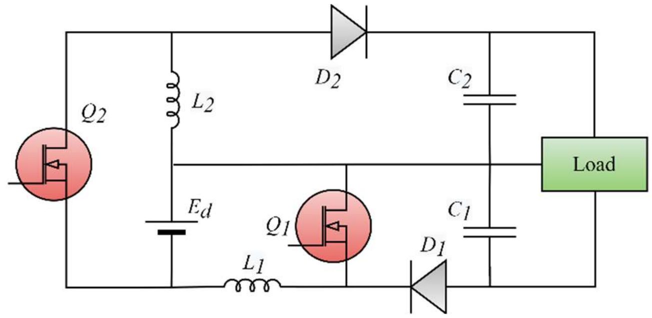


FIGURE 3 Schematic of a converter with a high voltage ratio.

4 | HIGH-GAIN VOLTAGE DC/DC CONVERTER

The DC/DC converter plays a vital role in the source and load interface of PV systems. This paper uses a high-gain voltage DC/DC converter, shown in Figure 3, based on a modified DC/DC buck-boost converter. This converter is capable of producing a high voltage ratio obtained from

$$\frac{V_o}{E_d} = \frac{1}{1-\alpha} \quad (6)$$

where α is the duty factor of the transistor Q.

The RMS value of the voltage ripple is given by (7), while the output voltage ripple when the duty cycle is more than half is given by (8).

$$\tilde{V}_o = \frac{\bar{\iota}_o}{Cf_s}\frac{\alpha(1-2\alpha)}{2\sqrt{3}(1-\alpha)} \quad (7)$$

$$\tilde{V}_o = \frac{\bar{\iota}_o}{Cf_s}\frac{(2\alpha-1)}{2\sqrt{3}} \quad (8)$$

where f_s is the minimum switching of the converter.

5 | MPPT CONTROL ALGORITHMS

There are many variations of the MPPT control algorithm. One of the most frequently applied MPPT control algorithms because of its convenience is P&O. In this paper, conventional and advanced P&O algorithms based on step-size variables will be compared with one of the artificial intelligence algorithms, namely fuzzy logic.

5.1 | Perturb and observe

The P&O algorithm is in great demand in the MPPT technique because it does not require special information related to PV characteristics, so it can be applied to all types of PV modules [52]. Figure 4 shows a flow chart for the conventional P&O method. The working principle is to direct the working point on the MPP by perturbation. If the PV operating point is to the left of the MPP, the perturbation is done to the right, and vice versa. However, this algorithm is affected by the given step size. The wide step size can

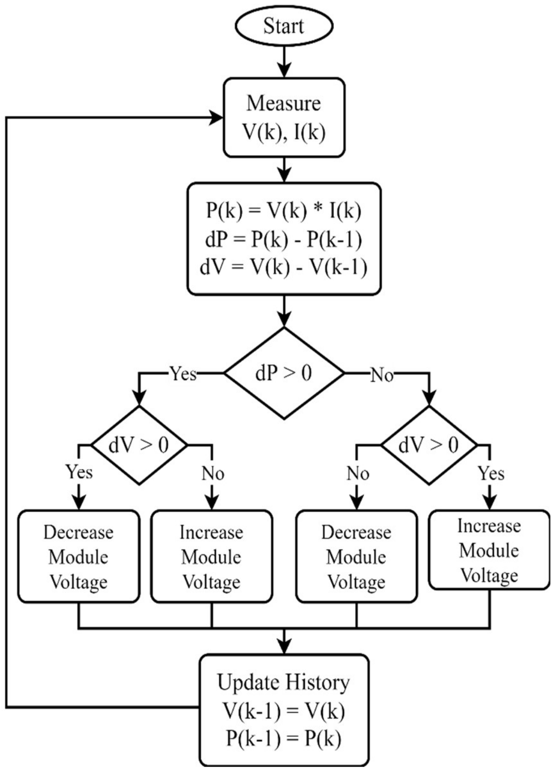


FIGURE 4 Flowchart of conventional P&O algorithm.

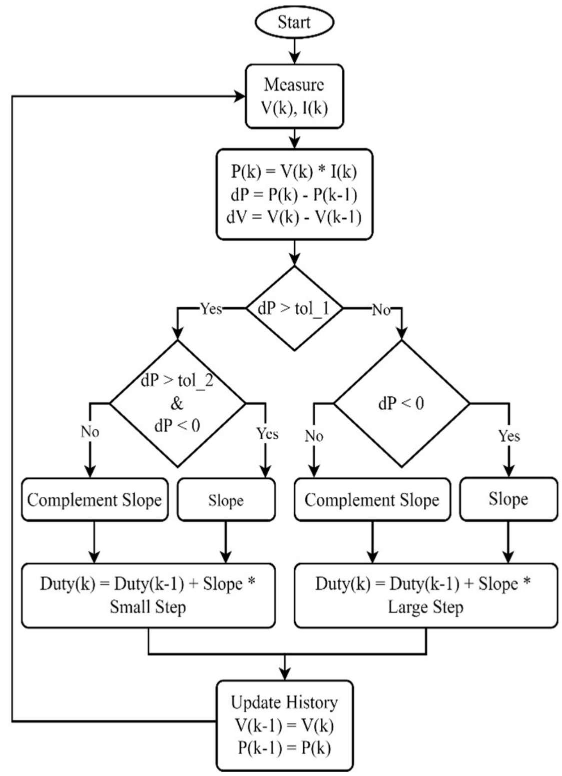


FIGURE 5 Flowchart of P&O variable step size algorithm.

speed up MPP tracking, but the oscillations around the MPP are also large. On the other hand, a small step size reduces oscillations around the MPP but slows down the tracking speed.

Adaptive P&O based on step-size variables was developed to reduce oscillations around the MPP caused by conventional P&O algorithms [53]. The flow chart of the algorithm is shown in Figure 5. In this algorithm, factor (A) is used as a constant whose value is greater than 1. The duty cycle as the control output of the algorithm increases with the multiplication factor (A) when $dP > 0$. Meanwhile, when the condition $dP < 0$, then the duty cycle is divided by (A).

5.2 | Fuzzy logic

The FL algorithm offers advantages in the form of ease of implementation, no requirement for mathematical modeling of data, and robustness in the field of control systems [27,54–56]. In a PV system, the input FL is the Error (E) resulting from the change in the PV output power divided by the change in the output voltage and the Change of Error (ΔE). While the output is the duty cycle which will regulate the PWM converter signal. Both inputs are given by

$$Error,\ E(k) = \frac{\Delta P}{\Delta V} = \frac{P(k)-P(k-1)}{V(k)-V(k-1)} \tag{9}$$

$$Error\ Change,\ \Delta E(k) = E(k) - E(k-1) \tag{10}$$

where k is sample time, $P(k)$ and $V(k)$ are PV power and voltage, $P(k-1)$ and $V(k-1)$ are previous PV power and voltage.

In the fuzzification stage, a triangular subset with five membership functions is used. Both input and output use symmetrical membership functions. Each of these membership

TABLE 1 Knowledge base

E/ΔE	Negative Big (NB)	Negative Small (NS)	Zero (Z)	Positive Small (PS)	Positive Big (PB)
Negative Big (NB)	NB	NB	Z	PB	PB
Negative Small (NS)	NS	NS	Z	PS	PS
Zero (Z)	Z	Z	Z	Z	Z
Positive Small (PS)	PS	PS	Z	NS	NS
Positive Big (PB)	PB	PB	Z	NB	NB

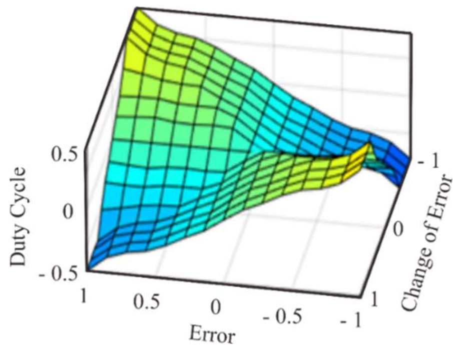


FIGURE 6 Surface inference system stage.

functions is NB (negative big), NS (negative small), Z (zero), PS (positive small), and PB (positive big). The knowledge based on the Mamdani type inference system process is shown in Table 1, while the results of the rule base are depicted by the surface Figure 6. Thus, in the defuzzification process, the center of gravity method is used.

6 | RESULTS AND DISCUSSION

In this paper, the Trina Solar TSM-250PA05.08 PV module with the parameters as described in Table 2 is used. The characteristics of the PV output that are affected by irradiance and ambient temperature are shown in Figure 2. The proposed system is constructed in MATLAB/Simulink for a standalone application with a resistive load which is comprehensively shown in Figure 7.

System testing is done by varying the irradiance into six steps. The irradiance variations given in the sequence of steps 1-6 are 1000, 700, 800, 600, 400, and 200 W/m^2. This test was conducted to determine the agility of the MPPT algorithm employed in high gain voltage converters with varying weather conditions. Figure 8 shows the results of testing the FL algorithm on the MPPT technique when handling variations of simulated weather conditions by varying the irradiance. The FL algorithm was compared with conventional P&O and variable step-size P&O as described.

As shown in Figure 8, both conventional P&O and variable step-size P&O experience an overshoot of the curve. This phenomenon is known as drift caused by a misjudgment of the MPPT algorithm so that the operating point will deviate away from the true MPP [57,58]. Drift is common in algorithms with operations based on hill-climbing, such as P&O, which experience sudden changes in irradiation. In this test, drift also occurs in the step-size P&O variable, but it is not as severe as in conventional P&O.

It is different from the FL algorithm, which does not experience the drift phenomenon at all. The FL algorithm is able to operate the MPPT technique on a high gain voltage converter properly. Besides not experiencing drift, the FL algorithm is also able to track MPP quickly. This is proven by the tracking speed, which is better than the P&O algorithm. It can be seen in Figure 9 that the curve generated by the FL algorithm is more stable than P&O, especially without the step-size variable. When the system is first subjected to high irradiation treatment (Figure 9a), both conventional P&O and variable step-size P&O oscillate around the MPP until they are finally able to track the true MPP. Of course, the process to the actual MPP after this oscillation takes time, causing losses in the system. Likewise, when given low irradiation treatment, the two P&O algorithms drifted, causing the system to be unresponsive. These two disadvantages do not occur in the FL algorithm.

Furthermore, several parameters affecting the performance of the MPPT system were carefully examined from the three algorithms. These parameters are tracking speed, oscillation, and efficiency. Overall, the FL algorithm is able to track MPP faster, namely 0.25

TABLE 2 Trina Solar TSM-250PA05.08 PV module characteristics.

Parameters	Value
Maximum Power, P_{MPP}	249.86 (W)
Cells per module, N_{cell}	60 cells
Open circuit voltage, V_{OC}	37.6 (V)
Short-circuit current, I_{SC}	8.55 (A)
Voltage at maximum power point, V_{MP}	31 (V)
Current at maximum power point, I_{MP}	8.06 (A)
Temperature coefficient of V_{OC}	-0.35 %/°C
Temperature coefficient of I_{SC}	0.06 %/°C

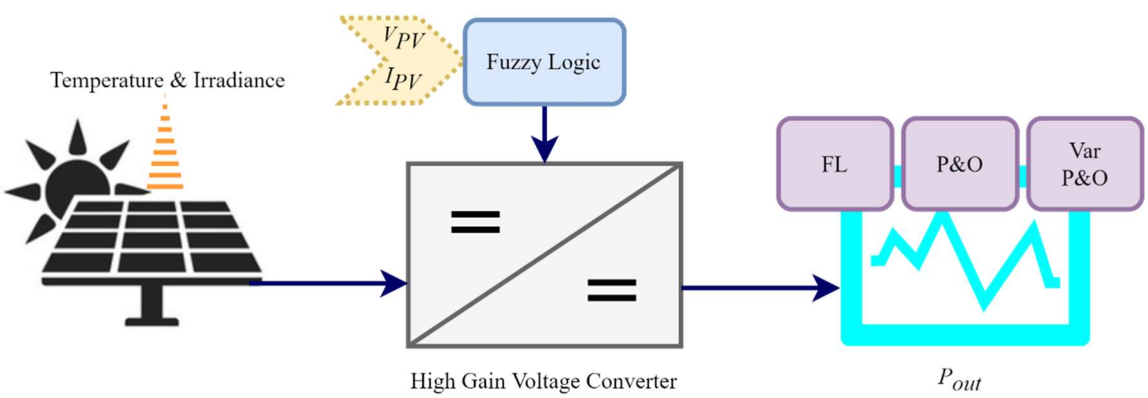


FIGURE 7 The proposed system simulated with MATLAB/Simulink.

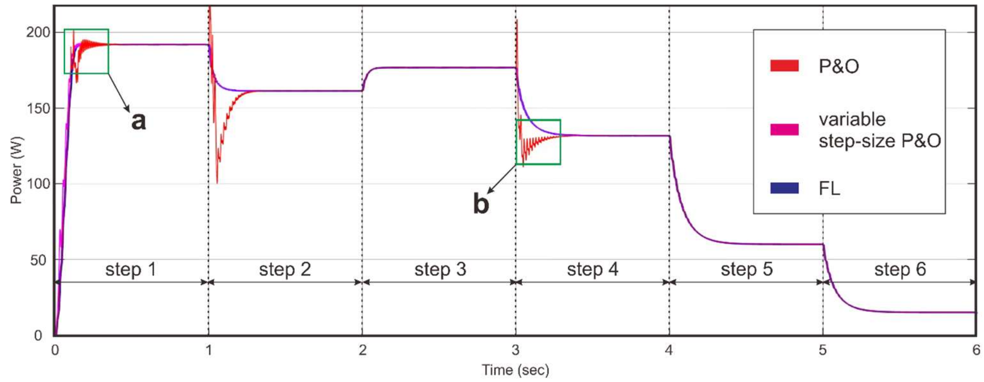
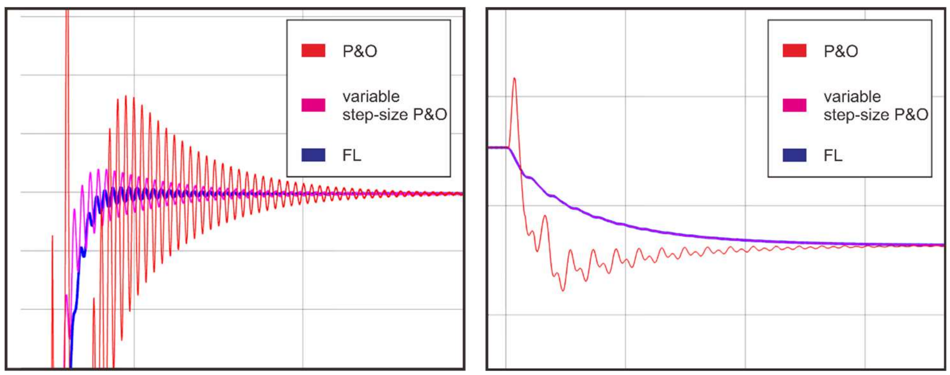


FIGURE 8 P_{out} generated by given the variation of irradiance.



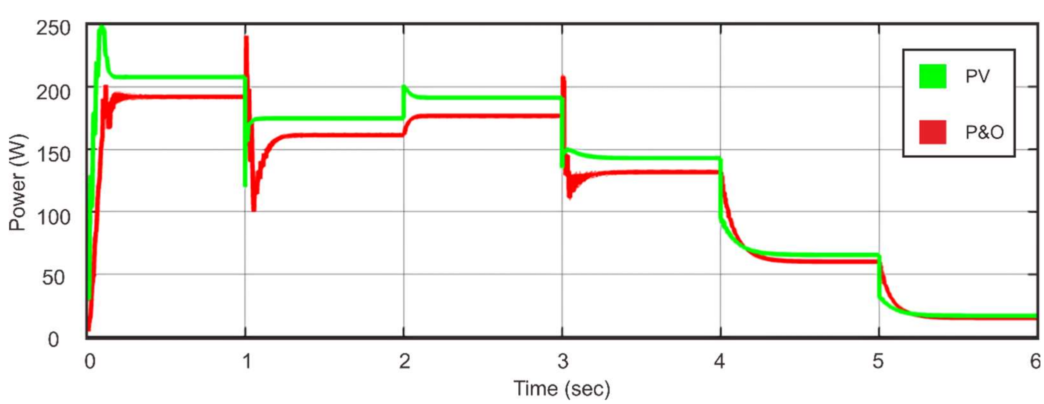
(A) (B)

FIGURE 9 Details of drift and initial oscillation of P_{out} (A) when the irradiation level increases and (B) when the irradiation level decreases

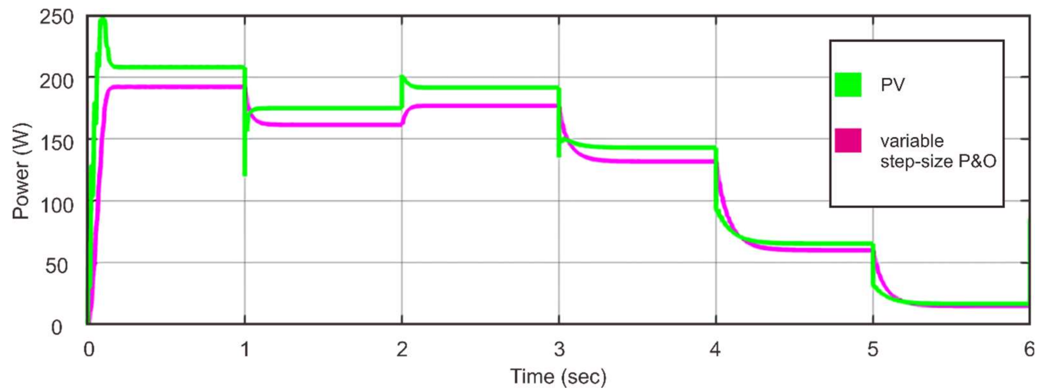
seconds, followed by the step-size P&O variable with a tracking time of 0.41 seconds. At the same time, conventional P&O is only able to track MPP after 0.52 seconds. The oscillations around MPP caused by the FL algorithm are also much smaller, 0.01 V, while the step-size and conventional P&O variables are 0.86 V and 1.22 V, respectively.

However, the efficiency generated by the three algorithms has the same level of 93.66 %. Figure 10 shows the comparison of P_{out} PV against the three MPPT algorithms. Seen in Figure 10a, the P&O algorithm reacts to an extreme when there is a change in irradiation. The P&O algorithm causes an instantaneous drift when the irradiation changes and takes longer to return to a stable state. Different results are shown in the FL algorithm and the step-size P&O variable, where there is no extreme reaction when irradiation changes. Both tend to produce a smoother slope. Also, when viewed in more detail, as shown in Figure 9a, the step-size P&O algorithm tends to have oscillations even though they only look small.

The FL algorithm can track MPP quickly because it does not go through a subtraction and addition process as the P&O algorithm does. MPP as fast as the FL algorithm. On the other hand, the oscillations caused by P&O are also more significant. The perturbation step length causes large oscillations around the MPP. In the conventional P&O algorithm that uses a fixed step-size, the magnitude of the oscillation is the same as the step-size used. This



(A)



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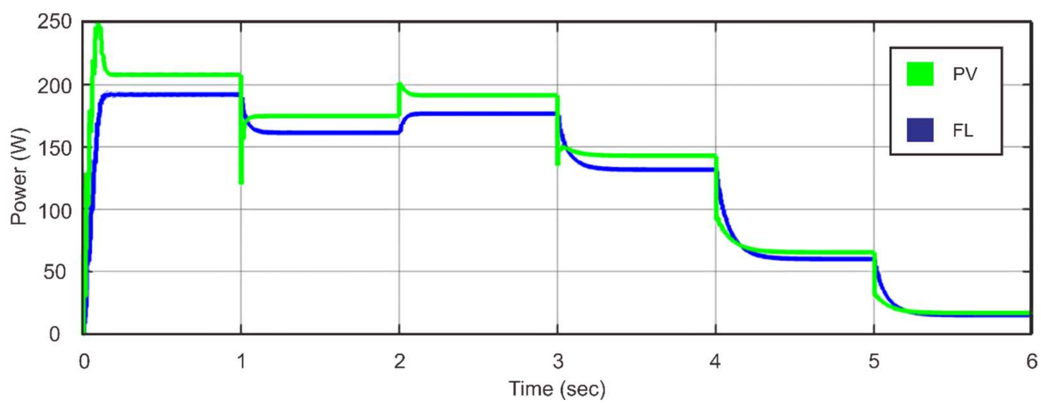

(C)

FIGURE 10 Comparison of P_{out} PV against (A) conventional P&O, (B) variable step-size P&O, and (C) FL.

paradigm of problems occurs in conventional P&O algorithms, where a wide step-size can shorten the MPPT tracking process, but the oscillations around the MPP become large. On the other hand, a small step-size will minimize oscillations, but it will take longer to reach MPP.

In terms of efficiency, the three algorithms do not affect the power harvesting efficiency of the high-gain DC/DC converter used. All three algorithms can actually be applied to the new converter topology. However, the FL algorithm is able to outperform conventional and variable step-size P&O algorithms in terms of tracking speed and oscillation damping.

7 | CONCLUSION

MPPT control with a new topology converter that has never been tested on MPPT PV system techniques has been completed. MPPT is operated using the FL algorithm as one of the various types of intelligent algorithms. MPPT performance with this FL algorithm is compared with the P&O algorithm as the most commonly used algorithm and adaptive P&O, which is based on step-size variables as the development of the P&O algorithm. The test is done by varying the irradiance as a representation of weather changes around the PV module. The results obtained indicate that the FL algorithm is able to outperform conventional P&O algorithms and step-size variables. This is evidenced by the faster tracking speed and smaller oscillations generated by the FL algorithm. The P&O algorithm reacts to extremes when there is a change in irradiation which causes a momentary deviation when the irradiation changes and takes longer to return to a stable state. On the other hand, the FL algorithm shows no extreme reaction when the irradiation changes. Therefore, the MPPT technique becomes more convergent, and the MPP is ensured to be tracked correctly by the FL algorithm. This advantage makes solar energy harvesting through the PV system with the MPPT technique, which is operated by the FL algorithm, more optimum.

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ORIGINAL ARTICLE

Optimum solar energy harvesting system using artificial intelligence

Sunardi Sangsang Sasmowiyono [1,*] | Abdul Fadlil [1,] | Arsyad Cahya Subrata [1,]

[1]Department of Electrical Engineering, Universitas Ahmad Dahlan, Yogyakarta, Indonesia

Correspondence
Sunardi Sangsang Sasmowiyono, Department of Electrical Engineering, Universitas Ahmad Dahlan, Yogyakarta, Indonesia.
Email: sunardi@mti.uad.ac.id

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Abstract

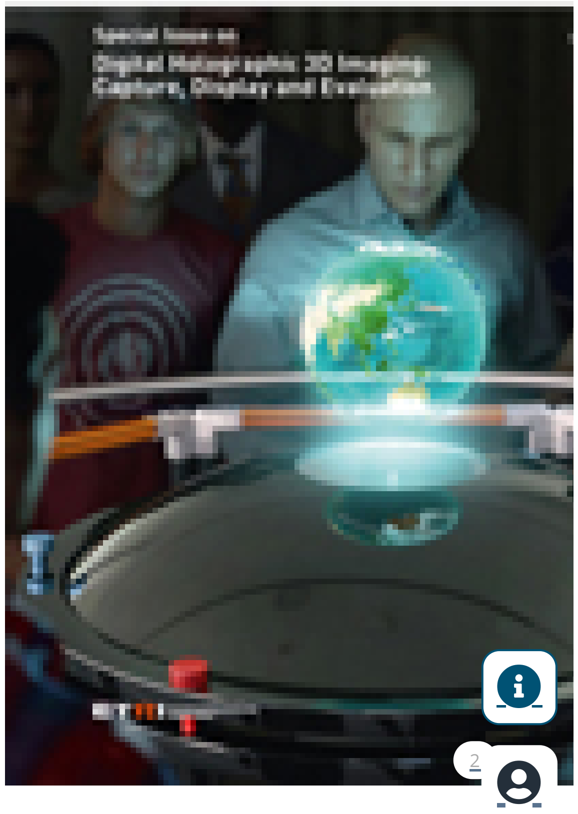
Renewable energy is promoted massively to overcome problems that fossil fuel power plants generate. One popular renewable energy type that offers easy installation is a photovoltaic (PV) system. However, the energy harvested through a PV system is not optimal because influenced by exposure to solar irradiance in the PV module, which is constantly changing caused by weather. The maximum power point tracking (MPPT) technique was developed to maximize the energy potential harvested from the PV system. This paper presents the MPPT technique, which is operated on a new high-gain voltage DC/DC converter that has never been tested before for the MPPT technique in PV systems. Fuzzy logic (FL) was used to operate the MPPT technique on the converter. Conventional and adaptive perturb and observe (P&O) techniques based on variables step size were also used to operate the MPPT. The performance generated by the FL algorithm outperformed conventional and variable step-size P&O. It is evident that the oscillation caused by the FL algorithm is more petite than variables step-size and conventional P&O. Furthermore, FL's tracking speed algorithm for tracking MPP is twice as fast as conventional P&O.

Keywords

artificial intelligence | fuzzy logic control | maximum power point tracking (MPPT) | perturb and observe (P&O) | variable step-size P&O

1 | INTRODUCTION

The need for electrical energy for homes and industries has significantly increased in the last few decades. Many power plants have been built to meet the demand for electrical energy. However, in addition to their dwindling resources, these power plants have several adverse side effects on the environment, such as water, soil, and air pollution caused by solid and liquid waste produced from burning fossil materials as raw materials [1, 2]. However, due to the shared awareness in various circles, radical efforts have been made to overcome these problems and provide a healthier environment.



harming the environment. gy sources such as solar photovoltaic (PV) systems, hydropower, wind turbine, tidal turbine, biomass, and biothermal [3, 4] are being developed because of their ability to optimize the potential of nature. Solar PV systems are one of the most popular because they are clean, do not cause noise, are cheap, and easy to install and maintain [5, 6]. Furthermore, the advantage of solar PV systems as an alternative power plant is that they do not generate noise compared to wind turbines [7].

However, due to the direct relationship and dependence on nature, solar PV-based power generation is nonlinear. As when the irradiation on the PV array changes drastically, at that time, an instantaneous shift in the peak power point occurs [8]. The nonlinear nature resulting from changes in irradiation and temperature affecting the PV causes the efficiency of the PV itself to be lower [9, 10]. PV energy loss has reached up to 25% [11]. This energy loss is one of the problems in optimizing energy harvesters with solar PV. Various efforts have been made to optimize energy harvesting from solar PV. One of the most effective ways to increase efficiency is to achieve solar PV power production under any conditions [12]. This technique is known as maximum power point tracking (MPPT), which works by feeding an appropriate duty cycle to DC/DC converter in the PV system.

Various methods can be used to operate MPPT, ranging from conventional methods such as perturb and observe (P&O) [13–15], incremental conductance (IncCond) [16–18], hill climbing (HC) [19–21], and their improved methods such as learning-based P&O (LPO) [22], self-tuned P&O (SPO) [23], learning-based ncCond (LIC) [24, 25], learning-based HC (L-HC) [26], which is based on the perturbation process in HC, to methods based on artificial intelligence algorithms such as fuzzy logic (FL) [27–31], artificial neural network (ANN) [32, 33], and adaptive neuro-fuzzy inference systems (ANFIS) [34–36]. Generally, a suitable MPPT implementation considers several aspects such as the type of application, efficiency, cost, lost energy, and suitability of the converter [37, 38].

There are various types of DC/DC converters developed for various applications, namely, boost, buck, and buck–boost converters. For applications that require high-voltage conversion, a DC/DC converter that can compensate for these needs is required. The boost converter can achieve high voltages by providing a large D. However, the voltage increment multiplication is not more than five and at the expense of efficiency, increasing the voltage on the switch and causing electromagnetic inference [39–41]. A coupled-inductor converter can provide high-voltage gain. Nevertheless, the efficiency is low due to increased chopper losses in inductors and conduction losses in semiconductors [42]. Another converter topology that provides high-gain voltage is the cascaded converter [43, 44]. However, the efficiency is also low due to the need for two processes. Another alternative is connecting two converters in series with only one switch, which is often called a quadratic boost converter (QBC) [45–47]. This converter topology produces the same voltage ratio as the cascaded converter, but the efficiency is lower than the boost converter.

The new high-gain voltage DC/DC converter [48] provides a high-voltage ratio and efficiency with lower current and voltage ripples. However, this converter still needs to be tested with MPPT to determine its suitability for PV systems. Therefore, this paper employs the FL algorithm in a high-gain voltage DC/DC converter for standalone PV systems.

2 | MODELING OF SOLAR CELLS

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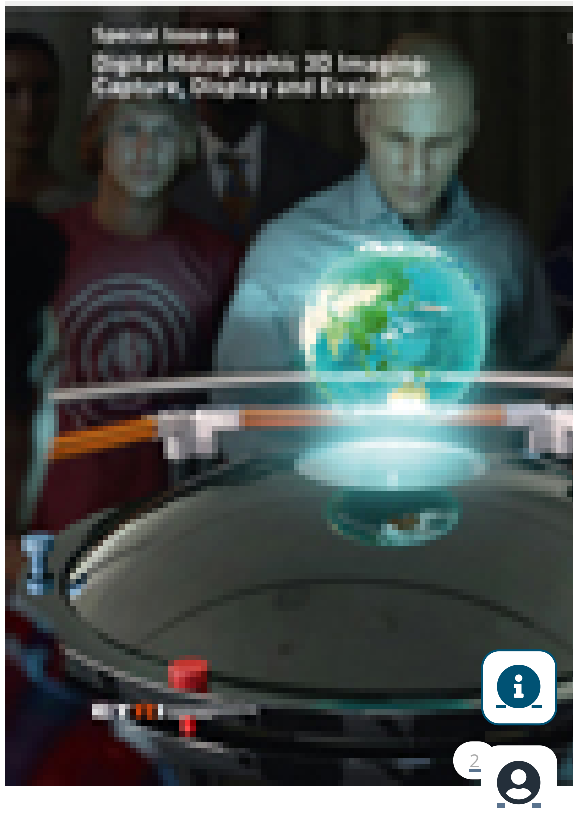

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combination of series and/... ...lls to produce a specific value. Different circuit models of PV cells are presented by Jordehi [49]. As in Figure 1, the single diode is the most common and most straightforward model, whereas the PV module characteristic curves are shown in Figure 2. The relationship between the voltage–current of the PV module is modeled as

$$I = I_{\mathrm{PH}} - I_{\mathrm{sat}} \times \left[\exp\left\{q \times \frac{V_{\mathrm{PV}} + I_{\mathrm{PV}} \times R_{\mathrm{S}}}{A \times K \times T}\right\} - 1\right] - \frac{V_{\mathrm{PV}} + I_{\mathrm{PV}} \times R_{\mathrm{S}}}{R_{\mathrm{SH}}}, \quad (1)$$

where I_{PH} and I_{sat} are light-generated and reverse saturation current, respectively, q is the electron charge (1.66022 $\times$ 10^{-19} C), V_{PV} and I_{PV} are the output voltage and current of the solar cells, respectively, R_{S} and R_{SH} are shunt and series resistances, respectively, A is the p-n ideal factor, K is the Boltzmann's constant (1.38$\times$ 10^{-23} J/K), and T is the cell temperature in Kelvin.

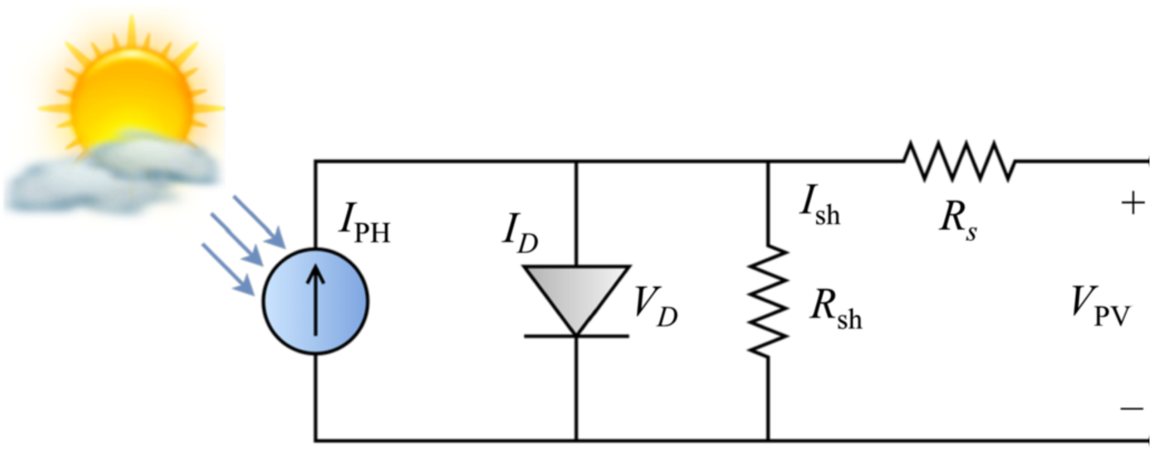


FIGURE 1.
Single-diode PV model

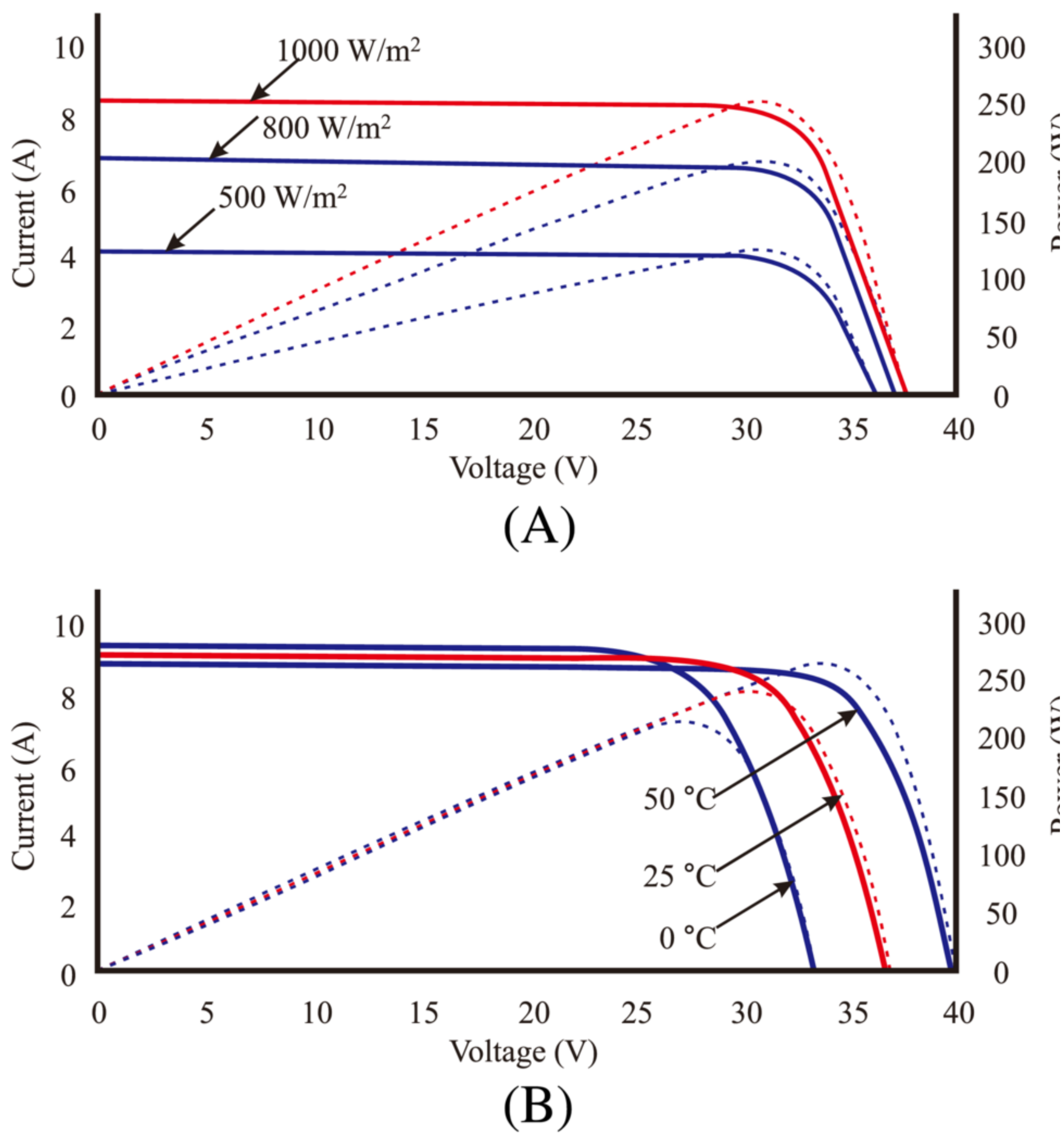
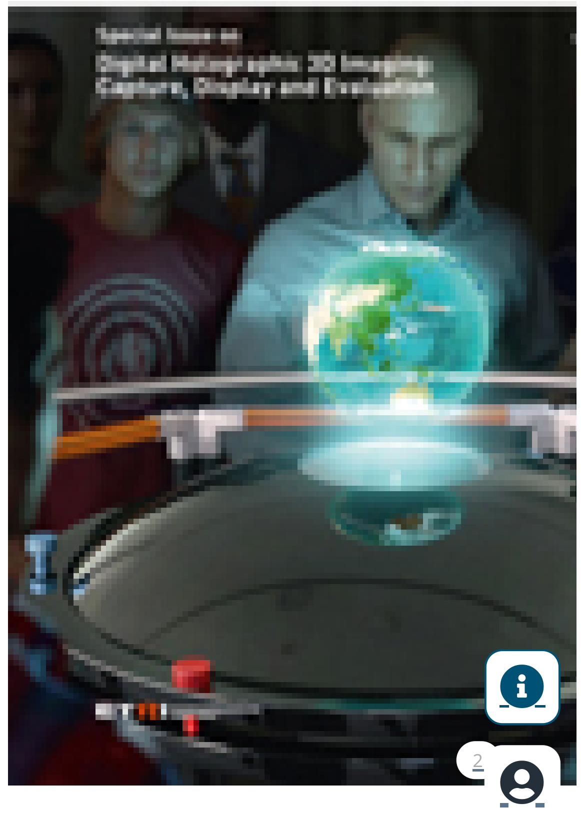


FIGURE 2.
Trina Solar TSM-250PA05.08 PV module characteristic curves (A) under irradiation variation and (B) under temperature variation



$$I_{\mathrm{PH}} = \left\{I_{\mathrm{SC}}^{*} + k_i\left(T - T^{*}\right)\right\}\frac{G}{G^{*}}, \quad (2)$$

where I_{SC}^{*} is the short-circuit current at 25°C, T^{*} = 298$^{\circ}K$ and G = 1000 W/m^2. Although k_i is the short-circuit current temperature coefficient. The * sign is the value at standard test conditions.

I_{sat} is affected by ambient temperature as

$$I_{\mathrm{sat}} = \frac{I_{\mathrm{SC}}^{*} + k_i\left(T - T^{*}\right)}{\exp\left[\frac{V_{\mathrm{OC}}^{*} + k_{\mathrm{V}}\left(T - T^{*}\right)}{V_{\mathrm{t}}}\right] - 1}, \quad (3)$$

where V_{OC}^{*} is the open-circuit voltage at 25°C with k_{V} as the coefficient of open-circuit voltage, whereas $V_{\mathrm{t}} = K \times T/q$ is the thermal voltage.

The amount of current in the series-connected module per setting is N_{ser}, and the parallel connection is N_{par}, then

$$I = N_{\mathrm{par}}I_{\mathrm{PH}} - N_{\mathrm{par}}I_{\mathrm{sat}}\left[\exp\left\{q\frac{\frac{V}{N_{\mathrm{ser}}} + I\frac{R_S}{N_{\mathrm{par}}}}{AKT}\right\} - 1\right] - \frac{\left(\frac{N_{\mathrm{par}}}{N_{\mathrm{ser}}}\right) + IR_{\mathrm{S}}}{R_{\mathrm{SH}}}. \quad (4)$$

3 | MPPT

The maximum power transfer theorem forms the basis for the working principle of the MPPT technique. The theorem states that when the load resistance matches the source, it can transfer the maximum power. Therefore, the working principle of the MPPT technique is to ensure the load resistance with PV at the maximum power point (MPP), which is calculated by Green [50].

$$R_{\mathrm{mpp}} = \frac{V_{\mathrm{mpp}}}{I_{\mathrm{mpp}}}, \quad (5)$$

where R_{mpp}, V_{mpp}, and I_{mpp} are the resistance, voltage, and current in MPP, respectively.

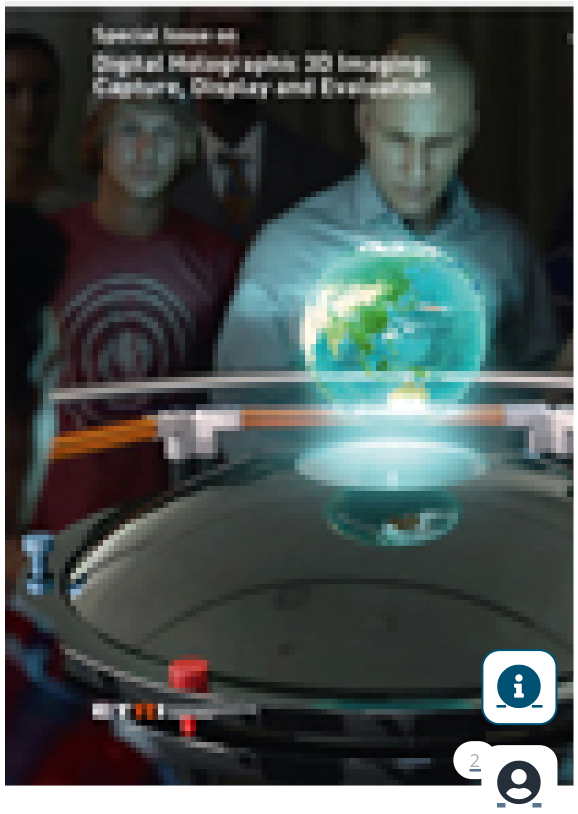
Although the maximum power transfer can be carried out by considering R_{mpp}, in reality, R_{mpp} is not constant because of the $I-V$ curve of PV due to weather dependence where changes in irradiation and temperature are unavoidable. Therefore, a DC/DC converter between the source and voltage connections is required to compensate for this resistance mismatch instead of supplying power directly to the load [51]. Through the MPPT algorithm, the duty cycle, D, is adjusted to ensure load resistance, and the D, which has been modified according to R_{mpp} on PV under varying weather conditions.

4 | HIGH-GAIN VOLTAGE DC/DC CONVERTER

The DC/DC converter plays a vital role in the source and load interface of PV systems. This paper uses a high-gain voltage DC/DC converter, shown in Figure 3, based on a modified DC/DC buck–boost converter. This converter is capable of producing a high-voltage ratio obtained from

$$\frac{V_{\mathrm{o}}}{E_{\mathrm{d}}} = \frac{1}{1-\alpha} \quad (6)$$

where α is the duty factor of the transistor Q.



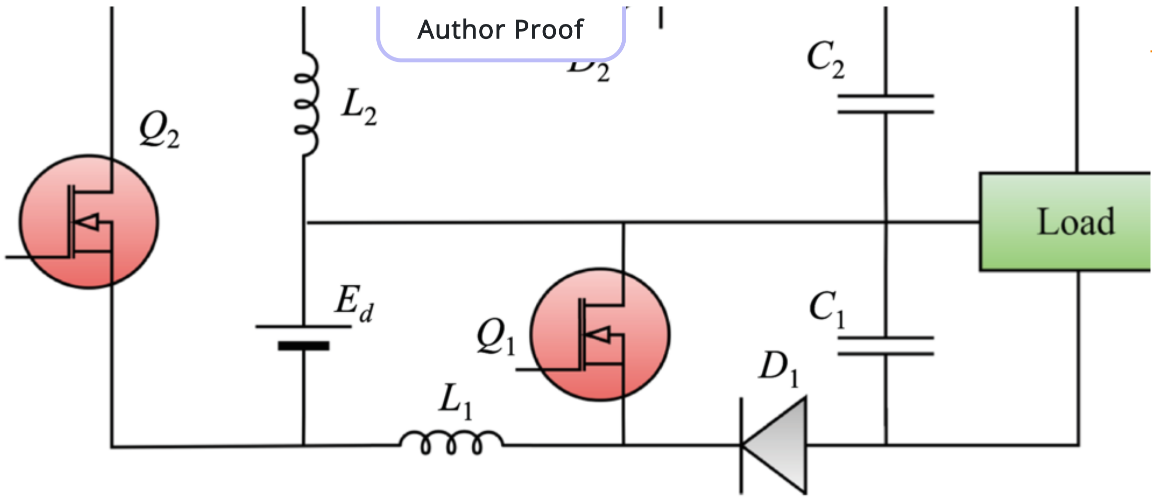


FIGURE 3.
Schematic of a converter with a high-voltage ratio

The RMS value of the voltage ripple is given by Bahrami et al. (7), whereas the output voltage ripple when the duty cycle is more than half is given by Baba et al.(8).

$$\tilde{V}_{\mathrm{o}} = \frac{\bar{i}_{\mathrm{o}}}{Cf_{\mathrm{s}}} \frac{\alpha(1-2\alpha)}{2\sqrt{3}(1-\alpha)}, \quad (7)$$

$$\tilde{V}_{\mathrm{o}} = \frac{\bar{i}_{\mathrm{o}}}{Cf_{\mathrm{s}}} \frac{(2\alpha-1)}{2\sqrt{3}}, \quad (8)$$

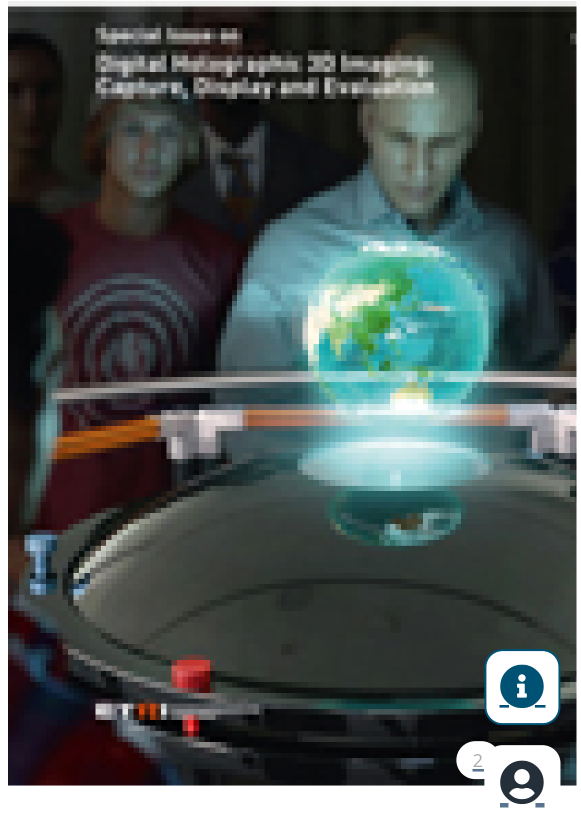
where f_{s} is the minimum switching of the converter.

5 | MPPT CONTROL ALGORITHMS

There are many variations of the MPPT control algorithm. However, one of the most frequently applied MPPT control algorithms because of its convenience is P&O. In this paper, conventional and advanced P&O algorithms based on step-size variables will be compared with one of the artificial intelligence algorithms, namely, FL.

5.1 | P&O

The P&O algorithm is in great demand in the MPPT technique because it does not require special information related to PV characteristics, so it can be applied to all types of PV modules [52]. Figure 4 shows a flowchart for the conventional P&O method.



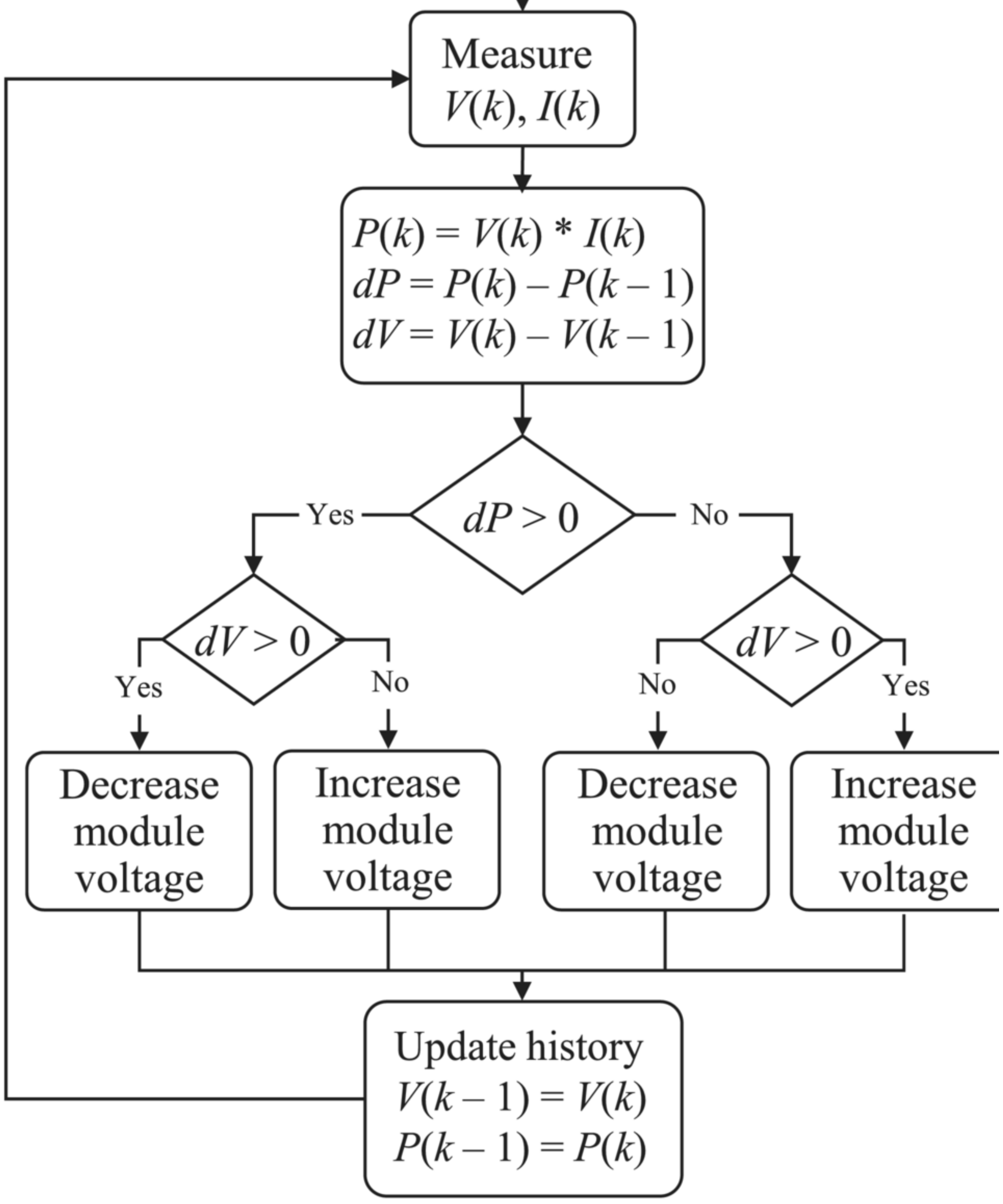
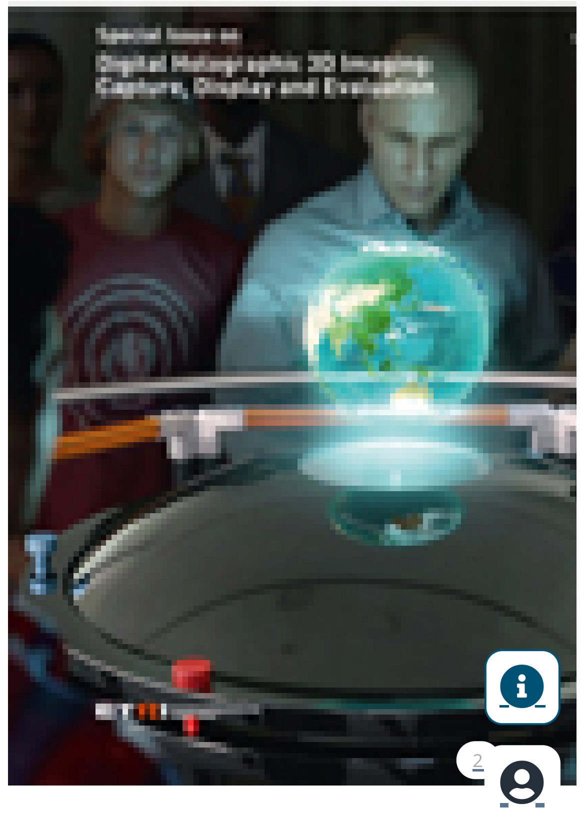


FIGURE 4.
Flowchart of conventional P&O algorithm

The working principle is to direct the working point on the MPP by perturbation. If the PV operating point is to the left of the MPP, the perturbation is done to the right, and vice versa. However, this algorithm is affected by the given step size. The wide step size can speed up MPP tracking, but the oscillations around the MPP are also large. On the other hand, a small step size reduces oscillations around the MPP but slows down the tracking speed.

Adaptive P&O based on step-size variables was developed to reduce oscillations around the MPP caused by conventional P&O algorithms [53]. The flowchart of the algorithm is shown in Figure 5. In this algorithm, factor (A) is used as a constant whose value is greater than 1. The duty cycle as the control output of the algorithm increases with the multiplication factor (A) when $dP > 0$. Meanwhile, when the condition $dP < 0$, then the duty cycle is divided by (A).



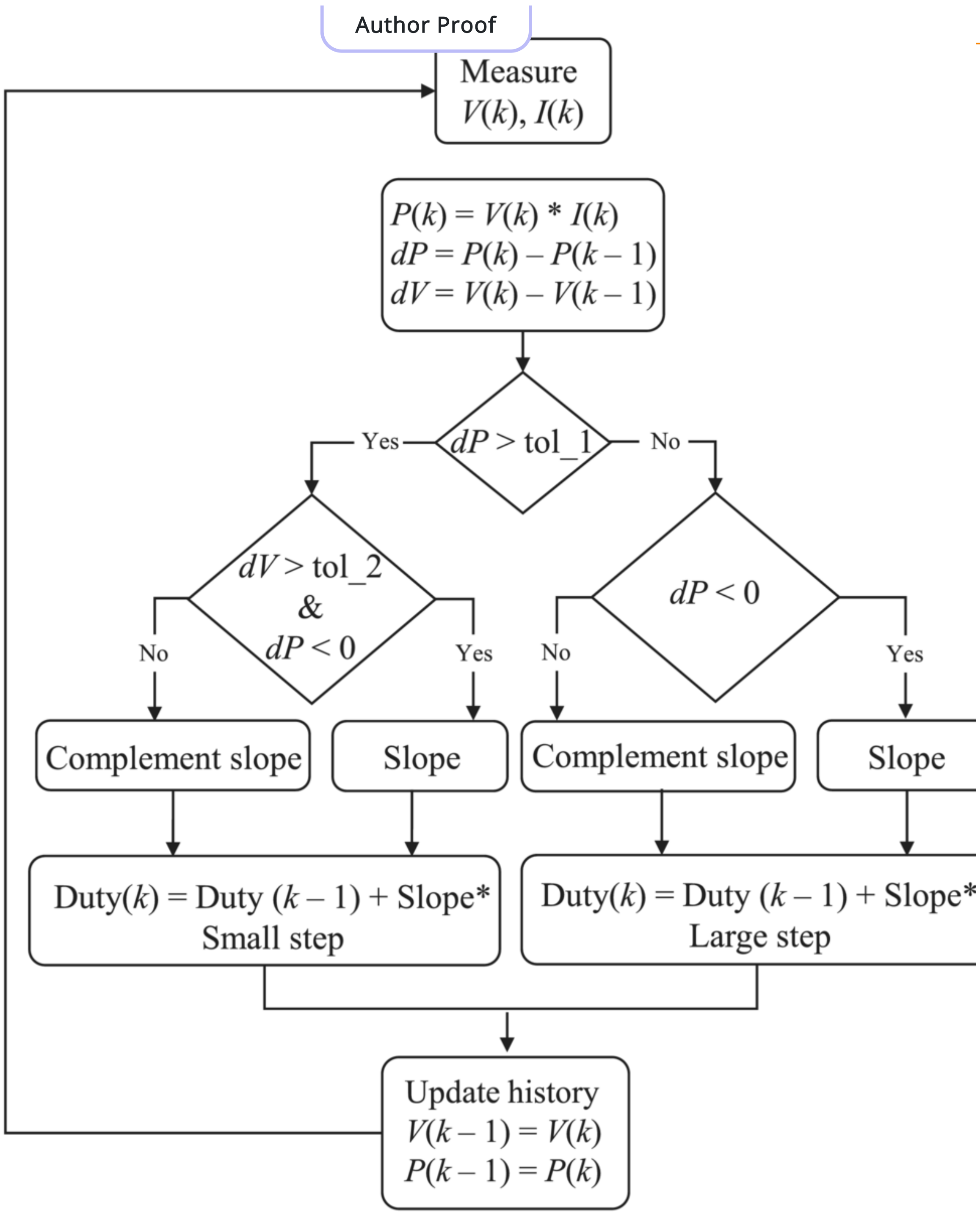


FIGURE 5.
Flowchart of P&O variable step-size algorithm

5.2 | FL

The FL algorithm offers advantages in the form of ease of implementation, no requirement for mathematical modeling of data and robustness in the field of control systems [27, 54–56]. In a PV system, the input FL is the Error (E) resulting from the change in the PV output power divided by the change in the output voltage and the Change of Error (ΔE). Although the output is the duty cycle which will regulate the PWM converter signal. Both inputs are given by.

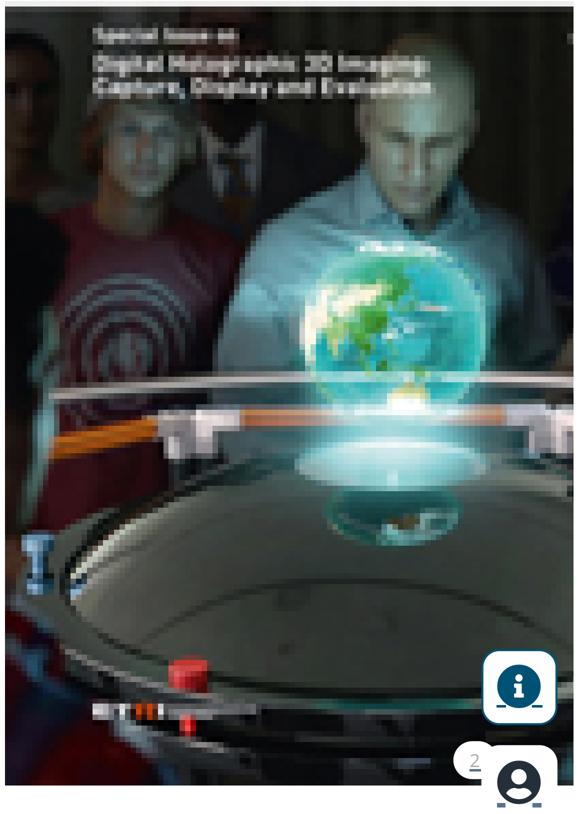
$$\text{Error,}\quad E(k) = \frac{\Delta P}{\Delta V} = \frac{P(k) - P(k-1)}{V(k) - V(k-1)}, \tag{9}$$

$$\text{Error Change,}\quad \Delta\, E(k) = E(k) - E(k-1), \tag{10}$$

where k is sample time, $P(k)$ and $V(k)$ are PV power and voltage, $P(k-1)$ and $V(k-1)$ are previous PV power and voltage.

In the fuzzification stage, a triangular subset with five membership functions is used. Additionally, symmetrical membership functions are used for input and output. Each of these membership functions is negative big (NB), negative small (NS), zero (Z), positive small (PS), and positive big (PB). The knowledge based on the Mamdani-type inference system process is shown in Table 1, whereas the results of the rule base are depicted by the surface Figure 6. Thus, in the defuzzification process, the center of gravity method is used.

TABLE 1. Knowledge base



Negative big (NB)	NB			PB	PB
Negative small (NS)	NS	NS	Z	PS	PS
Zero (Z)	Z	Z	Z	Z	Z
Positive small (PS)	PS	PS	Z	NS	NS
Positive big (Pb)	PB	PB	Z	NB	NB

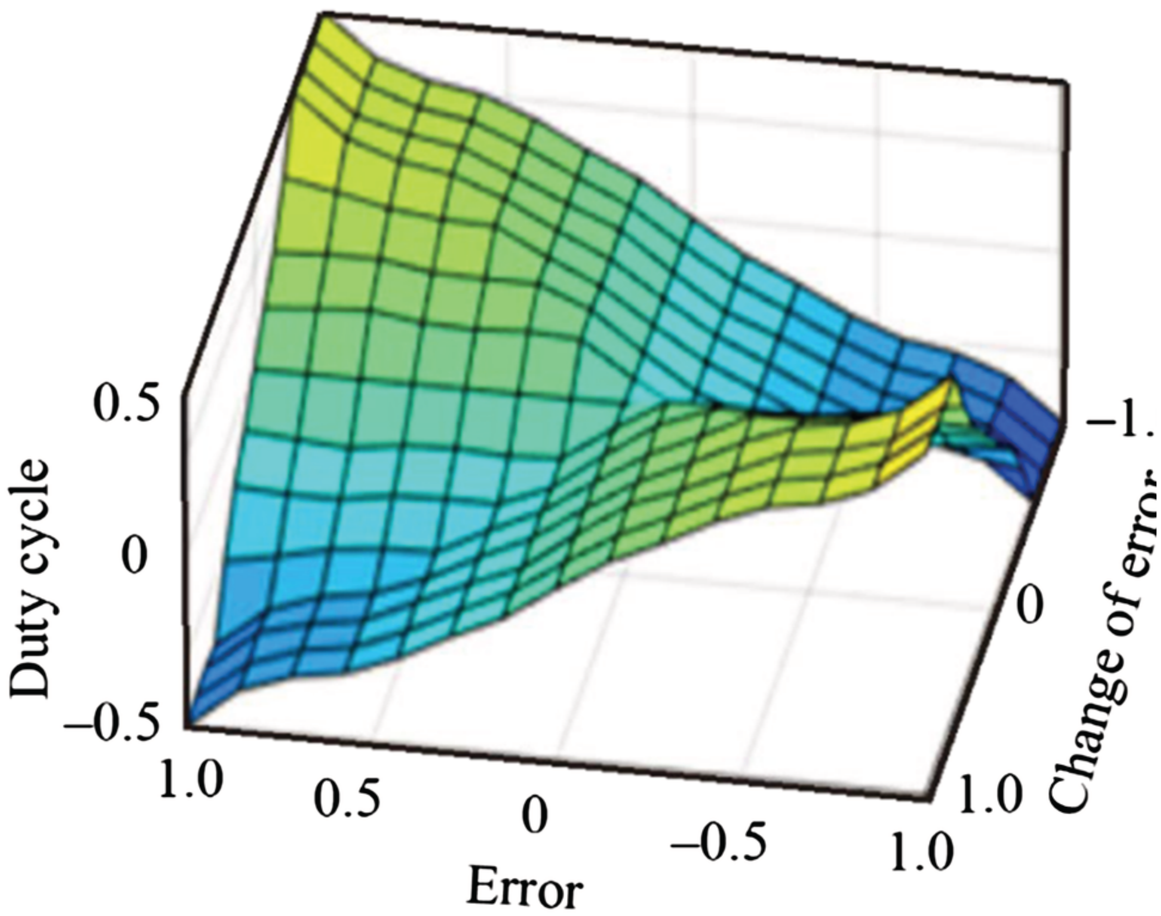


FIGURE 6.
Surface inference system stage

6 | RESULTS AND DISCUSSION

In this paper, the Trina Solar TSM-250PA05.08 PV module with the parameters as described in Table 2 is used. The characteristics of the PV output that are affected by irradiance and ambient temperature are shown in Figure 2. The proposed system is constructed in MATLAB/Simulink for a standalone application with a resistive load, which is comprehensively shown in Figure 7.

TABLE 2. Trina Solar TSM-250PA05.08 PV module characteristics

Parameters	Value
Maximum power, P_{MPP}	249.86 (W)
Cells per module, N_{cell}	60 cells
Open-circuit voltage, V_{OC}	37.6 (V)
Short-circuit current, I_{SC}	8.55 (A)
Voltage at maximum power point, V_{MP}	31 (V)
Current at maximum power point, I_{MP}	8.06 (A)
Temperature coefficient of V_{OC}	−0.35%/°C

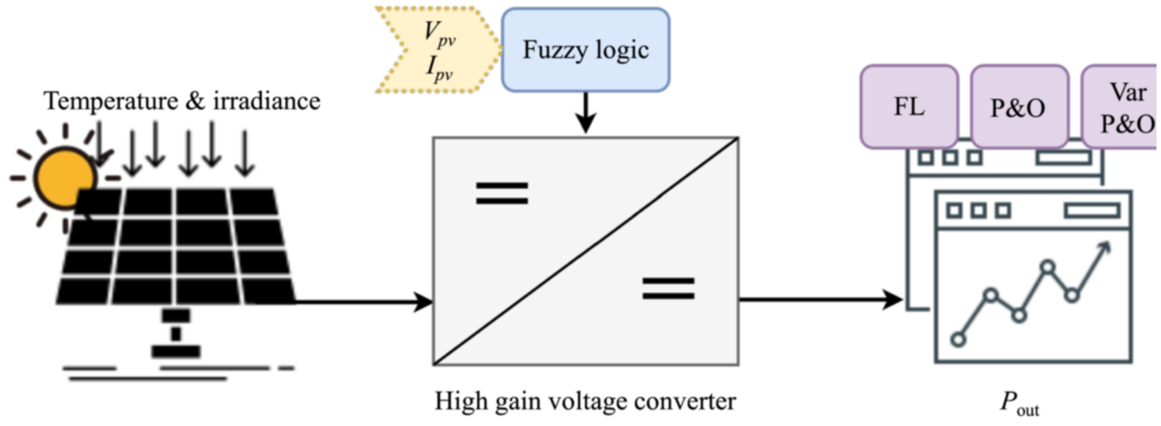


FIGURE 7.
The proposed system simulated with MATLAB/Simulink

System testing is done by varying the irradiance into six steps. The irradiance variations given in the sequence of steps 1–6 are 1000, 700, 800, 600, 400, and 200 W/m^2. This test was conducted to determine the agility of the MPPT algorithm employed in high-gain voltage converters with varying weather conditions. Figure 8 shows the results of testing the FL algorithm on the MPPT technique when handling variations of simulated weather conditions by varying the irradiance. The FL algorithm was compared with conventional P&O and variable step-size P&O as described.

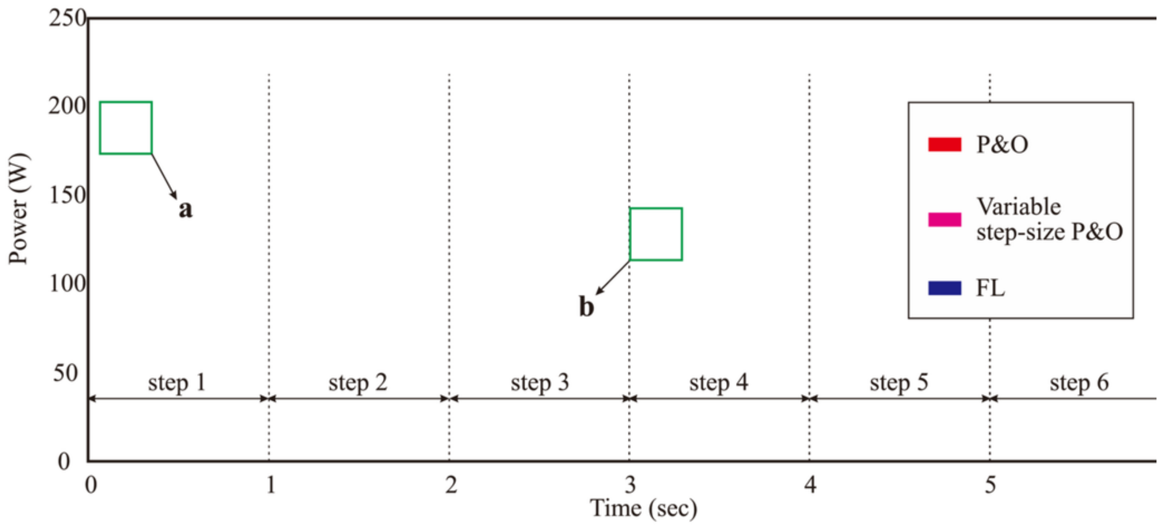
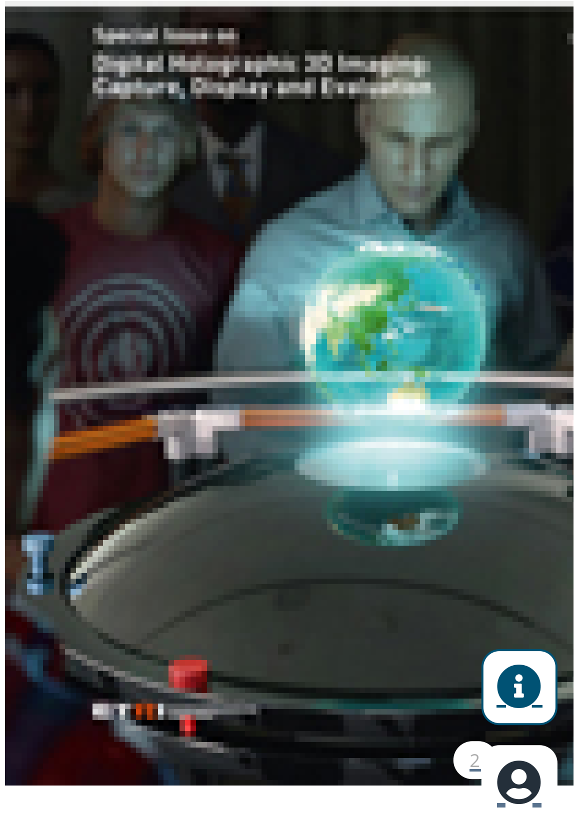


FIGURE 8.
P_{out} generated by given the variation of irradiance

As shown in Figure 8, conventional P&O and variable step-size P&O experience an overshoot of the curve. This phenomenon is known as drift, which is caused by a misjudgment of the MPPT algorithm so that the operating point will deviate from the true MPP [57, 58]. Drift is common in algorithms with operations based on hill climbing, such as P&O, which experience sudden changes in irradiation. In this test, drift also occurs in the step-size P&O variable, but it is not as severe as in conventional P&O.

AQ1 It is different from the FL algorithm, which does not experience the drift phenomenon at all. The FL algorithm is able to operate the MPPT technique on a high-gain voltage converter properly. Besides not experiencing drift, the FL algorithm is also able to track MPP quickly. This is proven by the tracking speed, which is better than the P&O algorithm. It can be seen in Figure 9 that the curve generated by the FL algorithm is more stable than P&O, especially without the step-size variable. When the system is first subjected to high irradiation treatment (Figure 9A), both conventional P&O and variable step-size P&O oscillate around the MPP until they are finally able to track the true MPP. ~~Of course, t~~The process to the actual MPP after this oscillation takes time, causing losses



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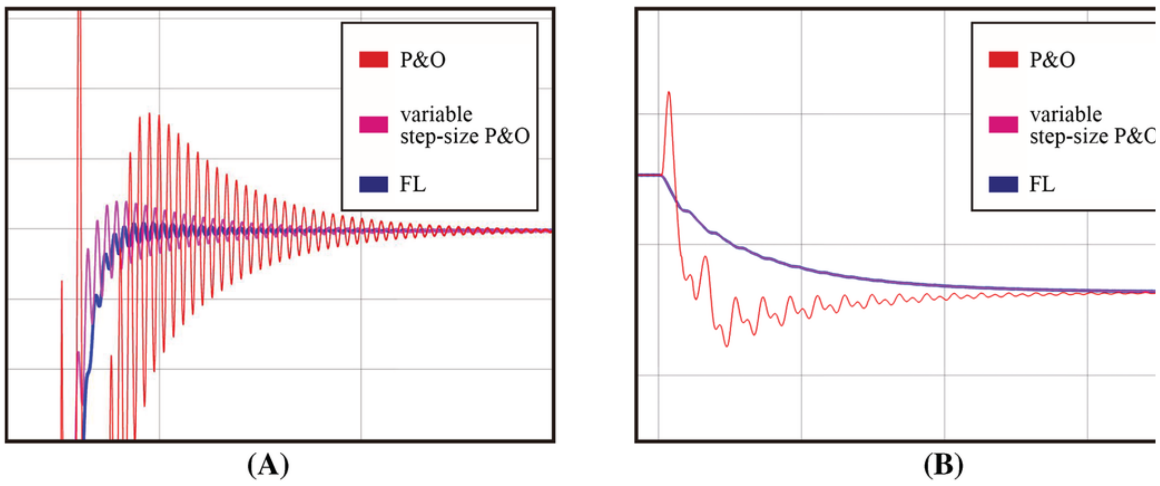

FIGURE 9.
Details of drift and initial oscillation of P_{out} (a) when the irradiation level increases and (B) when the irradiation level decreases

Furthermore, several parameters affecting the performance of the MPPT system were carefully examined from the three algorithms. These parameters are tracking speed, oscillation, and efficiency. Overall, the FL algorithm can track MPP faster, namely, 0.25 s, followed by the step-size P&O variable with a tracking time of 0.41 s. At the same time, conventional P&O can only track MPP after 0.52 s. The oscillations around MPP caused by the FL algorithm are also quite small (0.01 V), whereas the step-size and conventional P&O variables are 0.86 and 1.22 V, respectively.

However, the efficiency generated by the three algorithms has the same level of 93.66%. Figure 10 shows the comparison of P_{out} PV against the three MPPT algorithms. Seen in Figure 10A, the P&O algorithm reacts to an extreme when there is a change in irradiation. The P&O algorithm causes an instantaneous drift when the irradiation changes and takes longer to return to a stable state. Different results are shown in the FL algorithm and the step-size P&O variable, where there is no extreme reaction when irradiation changes. Both tend to produce a smoother slope. Also, when viewed in more detail, as shown in Figure 9A, the step-size P&O algorithm tends to have oscillations even though they only look small.

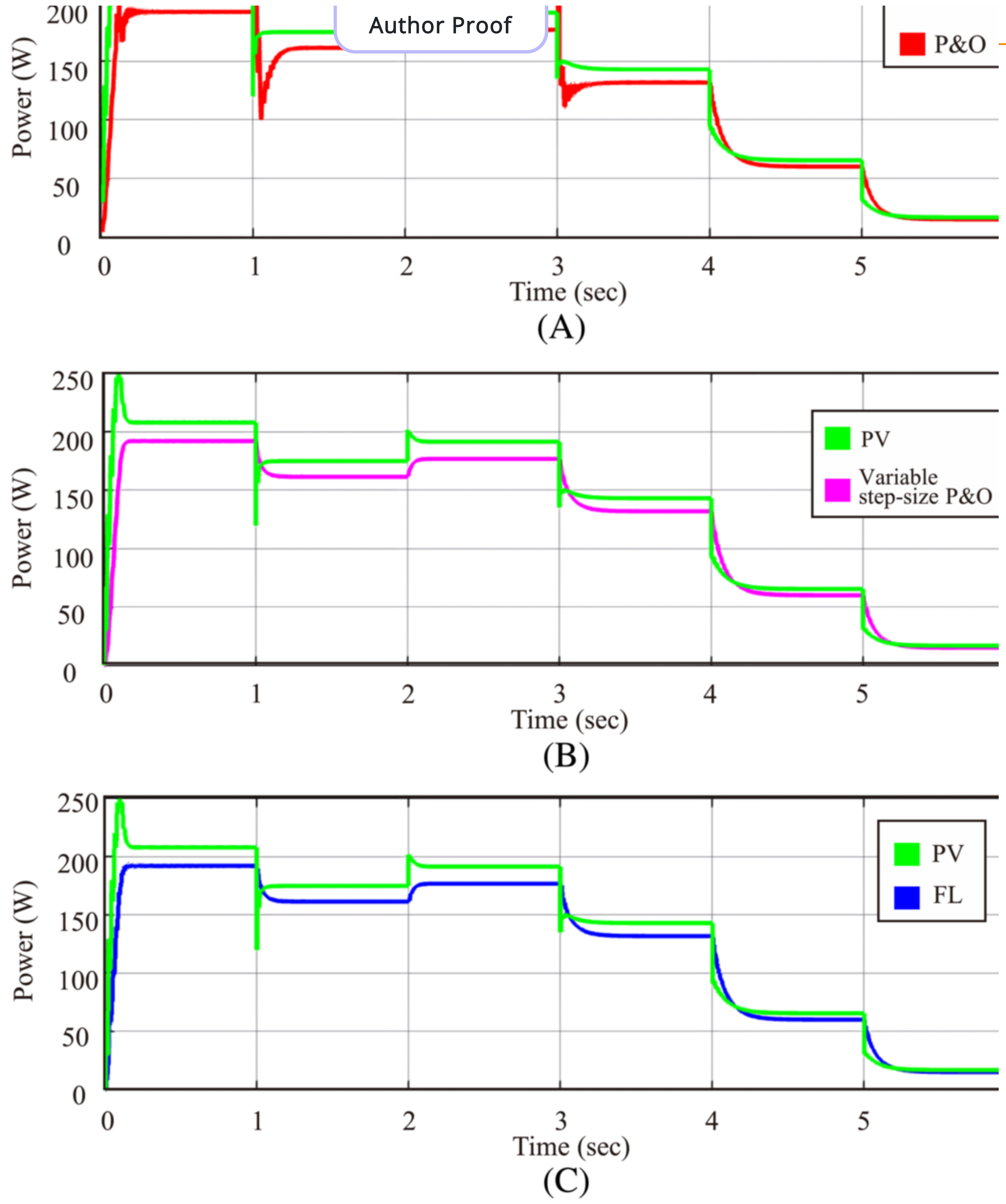

FIGURE 10.
Comparison of P_{out} PV against (A) conventional P&O, (B) variable step-size P&O, and (C) FL

AQ2 The FL algorithm can track MPP quickly because it does not go through a subtraction and addition process as the P&O algorithm does. Although the variable step-size P&O can provide large step perturbations away from MPP, it still needs to track MPP as fast as the FL algorithm. Furthermore, the oscillations caused by P&O are more significant. The perturbation step length causes large oscillations around the MPP. In the conventional P&O algorithm that uses a fixed step size, the magnitude of the oscillation is the same as the step size used. This paradigm of problems occurs in conventional P&O algorithms, where a wide step size can shorten the MPPT tracking process, but the oscillations around the MPP become large. On the other hand, a small step size will minimize oscillations, but it will take longer to reach MPP.

In terms of efficiency, the three algorithms do not affect the power harvesting efficiency of the high-gain DC/DC converter used. All three algorithms can actually be applied to the new converter topology. However, the FL algorithm is able to outperform conventional and variable step-size P&O algorithms in terms of tracking speed and oscillation damping.

7 | CONCLUSION

MPPT control with a new topology converter that has never been tested on MPPT PV system techniques has been completed. MPPT is operated using the FL algorithm as one of the various types of intelligent algorithms. MPPT performance with this FL algorithm is compared with

P&O algorithm. The test is performed by varying the irradiance to represent weather changes around the PV module. The results indicate that the FL algorithm can outperform conventional P&O algorithms and step-size variables. This is evidenced by the faster tracking speed and smaller oscillations generated by the FL algorithm. The P&O algorithm reacts to extremes when there is a change in irradiation, which causes a momentary deviation when the irradiation changes and takes longer to return to a stable state. However, the FL algorithm shows no extreme reaction when the irradiation changes. Therefore, the MPPT technique becomes more convergent, and the MPP is ensured to be tracked correctly by the FL algorithm. This advantage makes solar energy harvesting through the PV system with the MPPT technique, which is operated by the FL algorithm, more optimum.

CONFLICT OF INTEREST

The authors declare that there are no conflicts of interest.

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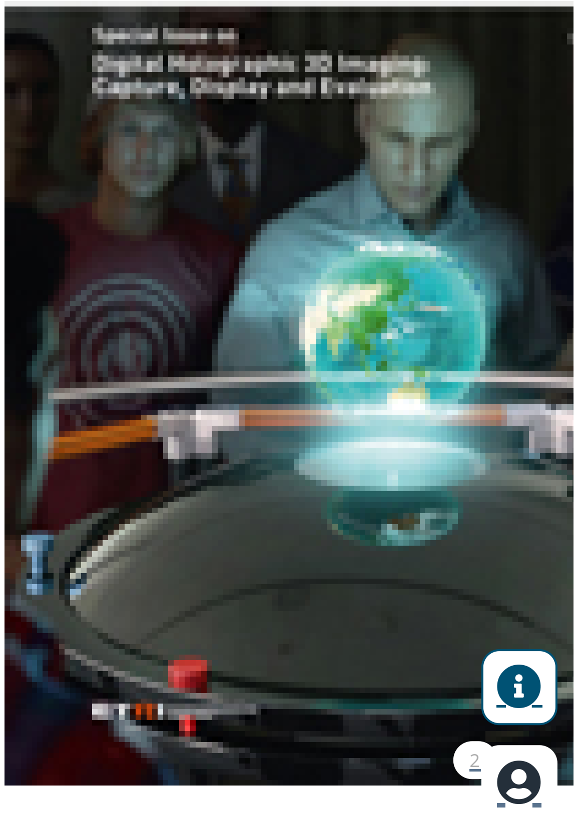

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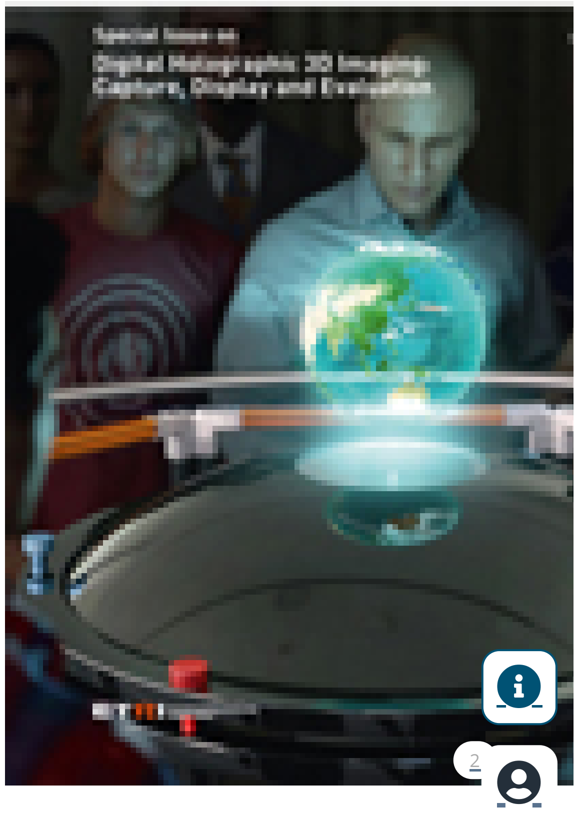

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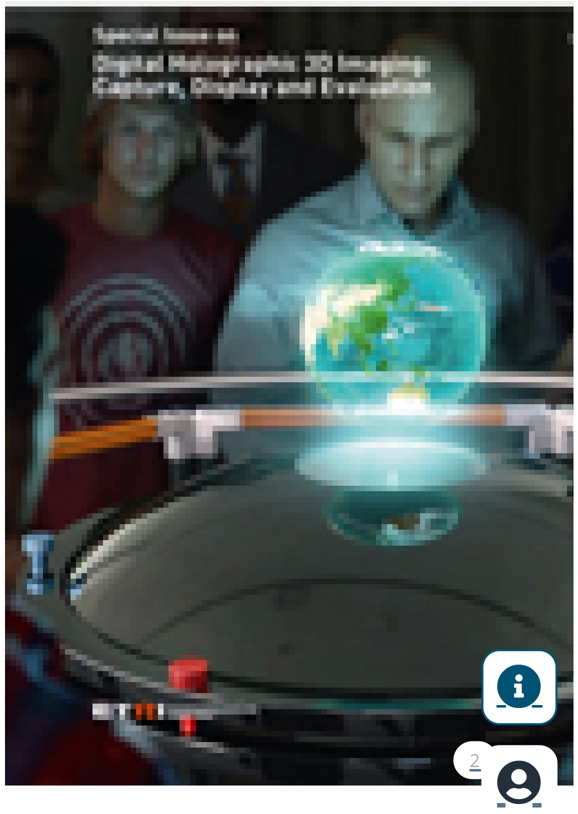

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AUTHOR BIOGRAPHIES

Sunardi Sangsang Sasmowiyono ~~Sunardi~~ received his B.E. and M.E. in Electrical Engineering from Universitas Gadjah Mada and Institut Teknologi Bandung in 1999 and 2003, respectively. He also received his Ph.D. degree in Electrical Engineering from Universiti Teknologi Malaysia in 2011. He is currently working as an Associate Professor with the Electrical Engineering Department, Universitas Ahmad Dahlan (UAD), Yogyakarta, Indonesia. His current research interests include signal processing, image processing, and artificial intelligence. He can be contacted at email: sunardi@mti.uad.ac.id.

Abdul Fadlil received his B.E. in Physics—Electronics ~~Electrical~~ and Instrumentation and M.E. in Electrical Engineering from Universitas Gadjah Mada in 1992 and 2000, respectively. He also received his Ph.D. degree in Electrical Engineering from Universiti Teknologi Malaysia in 2006. He is currently as Associate Professor with the Electrical Engineering Department, Universitas Ahmad Dahlan (UAD), Yogyakarta, Indonesia. His current research interests include pattern recognition, image processing, and artificial intelligence. He can be contacted at email: fadlil@mti.uad.ac.id.

Arsyad Cahya Subrata received his B.E. and M.E. in Electrical Engineering from Universitas Ahmad Dahlan, Indonesia ,and Universitas Diponegoro, Indonesia, in 2016 and 2020, respectively. He has been the Head of Technology at a start-up company engaged in automation in agriculture-livestock, health, aerial monitoring, and industrial automation since 2017. Currently, he is a member of the Embedded Systems and Power Electronics Research Group (ESPERG) research team since 2018 and has been a Lecturer with the Electrical Engineering Department, Universitas Ahmad Dahlan (UAD), Yogyakarta, Indonesia, since 2021. His research interests include renewable energy, robotics, artificial intelligence, control instrumentation, intelligent control, and Internet of Things. He can be contacted at email: arsyad.subrata@te.uad.ac.id.

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