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Comparison of Maximum Power Point Tracking Algorithms in the Presence of Boost and SEPIC Converters

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ABSTRACT

The Maximum Power Point Tracking (MPPT) control system is a method that can bring a photovoltaic (PV) system closer to its maximum achievable efficiency. Given the various algorithms and classifications available, comparing methods in a specific situation can help select the appropriate algorithm. This paper first provides a comprehensive categorization of MPPT methods and then tracks the maximum power point using three algorithms: P&O, IC, and Fuzzy-PI, in the presence of Boost and SEPIC converters. The P&O, IC, and Fuzzy-PI algorithms are executed once with the Boost converter and once with the SEPIC converter. In both cases, the accuracy and speed of tracking the algorithms and the impact of the converters on output power are examined. By comparing oscillations around the desired point and the settling time in each scenario, the use of a PI algorithm, with coefficients calculated by the Fuzzy method and applied to the SEPIC converter, demonstrates better performance than others. Analysis and simulation of the system were conducted using the Simulink unit in MATLAB software.

1. INTRODUCTION

In recent years, with the increase in population and subsequent rise in electricity demand, environmental issues and chronic diseases have prompted the application of renewable energy sources. Solar, wind, and hydro energies are replacing fossil fuels and natural gas. Among the renewable sources used for electricity generation, solar energy has the highest efficiency. The ability to generate energy from the sun's heat and radiation is a feature of this source, but the most common and efficient type is the photovoltaic system.

Photovoltaic systems consist of solar cells, power electronics converters, batteries (if necessary), and power transmission devices that directly convert solar radiation into electricity. In this conversion process, weather conditions (radiation and sunlight) play a crucial role. When the sunlight intensity on the cells decreases, the system output also reduces. Since climatic conditions are unchangeable, the development and advancement of each part of the photovoltaic system can help improve its performance.

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A typical photovoltaic system comprises several main components: solar cells, an MPPT controller, a DC-DC converter to apply the control signal to the system, and a load. One step in increasing the efficiency of the photovoltaic system is maintaining the system's operation at maximum achievable efficiency. Since the output power of the PV system depends on radiation and temperature, a controller is essential to receive maximum power. Studies on solar cells have shown that the output characteristics (voltage and current) are nonlinear [1-2]. The curves related to the solar cell's features and the impact of radiation and temperature changes are shown in Figure 1. The point where the solar cell reaches its highest value is called the Maximum Power Point (MPP). Since this point constantly changes and the cell's characteristics are nonlinear, there is a need for a maximum power point tracker.

Given the importance of MPPT, many methods have been proposed to improve controller performance, known as Maximum Power Point Tracking algorithms; Constant Voltage, Open Circuit Voltage, Short Circuit Current, Perturb and Observe (P&O), and Incremental Conductance (IC). These traditional methods often have simple circuits and implementation, and to enhance the control system's performance, these algorithms are combined with intelligent methods like fuzzy logic, neural networks, and PSO [3-4].

The P&O algorithm is one of the most widely used MPPT methods due to its adaptability with various PV modules, no need for module information, easy execution, and low cost [5]. However, oscillation around the maximum power point, low tracking accuracy, and speed are its drawbacks. One way to address this problem is using a variable step size, which is also applicable under partial shading conditions [6-7].

If issues like non-convergence and slight oscillations around the point occur (disadvantages of the P&O method), they can be resolved using the IC algorithm. However, this method is more complex and requires more time for its operations [8]. It has also shown appropriate performance under static and dynamic weather conditions [9]. A variable step size can also be used to reduce oscillations around the maximum power point [10].

Compared to the two previously mentioned methods, the fuzzy logic algorithm (Fuzzy Logic) performs better in response time, stability, tracking speed, and fewer oscillations. This algorithm has also shown good performance under partial shading conditions, indicating its flexibility against changes [11]. The performance of a fuzzy control system depends on its rules and membership functions, and optimizing these can lead to overall control system performance improvement [12]. Another way to increase this algorithm's efficiency is combining it with other methods, which has also performed very well under partial shading conditions [13-14].

Grid-connected PV systems must use two conversion stages; the first stage increases the output voltage level from the photovoltaic arrays (DC-DC), and the second stage converts from DC to AC. In DC load-connected systems, the presence of a DC-DC converter is also necessary. The control signals output from the MPPT, after combining with the modulation unit, are applied to the control pins of the switches used in the converters, completing the control process. Various categorizations have been presented for DC-DC converters, such as with or without transformers and whether they are step-up or step-down. Some converters include Buck, Boost, Buck-Boost, SEPIC, Cúk, Flyback, etc. [15]. With advances in power electronics and the introduction of new high-gain converters, these converters have been used in PV systems to increase the output voltage level [16].

In this paper, an MPPT control unit for a photovoltaic system under normal radiation conditions is presented. The control system uses three maximum power point tracking algorithms: P&O, IC, and Fuzzy-PI. For the control signal application, two converters, Boost and SEPIC, are presented, and the performance of all three algorithms with these two converters is compared. Following the introduction, the stages of this paper are as follows: Section 2: Description of the circuit model of a solar cell, Section 3: Review of maximum power point tracking algorithms, Section 4: Introduction of DC-DC converters, and Section 5: Simulation and results obtained from this research.

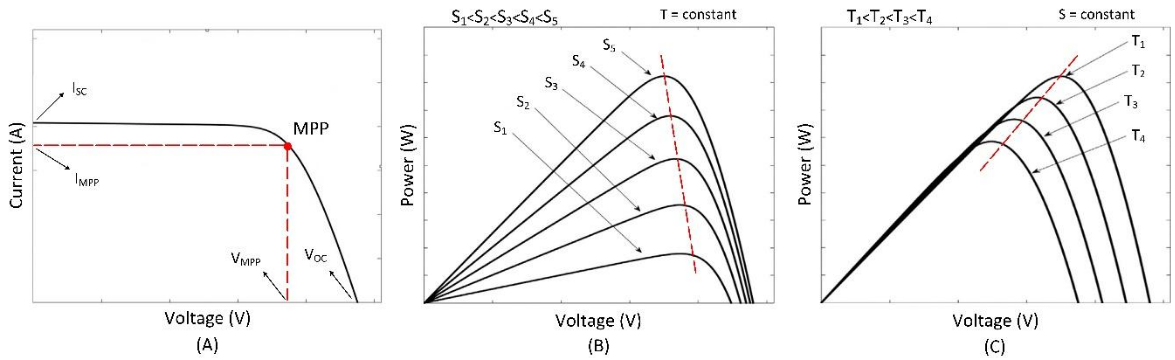

Fig.1. Characteristics of a solar cell, a) Voltage-Current b) Power-Voltage constant temperature c) Power-Voltage constant radiation

2. SOLAR CELL MODEL

The single-diode mathematical model of a solar cell is shown in Figure 2 [17]. Connecting cells forms a module, connecting modules forms a panel, and connecting panels forms a solar array. The relationship between the voltage and current of a solar cell is defined by Equation (1).

$$I = I_L - I_D - I_{SH} = I_L - I_o\left[e^{\frac{q(V+R_S I)}{nKT}} - 1\right] - \frac{V+R_S I}{R_{SH}} \tag{1}$$

In these equations, q is the electric charge of an electron in Coulombs, k is the Boltzmann constant in Joules per Kelvin, T is the cell temperature, V is the diode voltage, n is the ideality factor, RS and RSH are the series and parallel resistances, respectively, IL is the photon-generated current, IO is the reverse saturation current, ID is the diode current, ISH is the current passing through the parallel branch, and I is the output current of the cell.

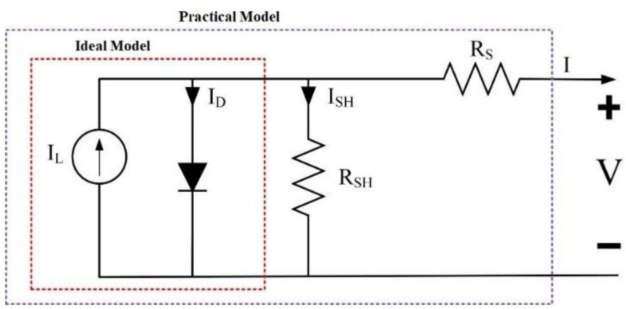

Fig.2. Equivalent circuit of a single-diode solar cell

3. MAXIMUM POWER POINT TRACKING ALGORITHMS

Reaching the operating point to the MPP is a significant topic in a PV system. For this purpose, methods have been presented to track the desired point. The algorithm specifications, such as complexity, number of sensors, digital or analog execution, convergence speed, precise tracking ability, and cost, vary. This paper provides a new categorization for algorithms, which is as follows:

Measurement-Based Tracking Methods

These methods measure the cell parameters and the characteristics of the produced sunlight. Algorithms operate based on calculations and comparisons with previous results or predefined values. Open Circuit Voltage (OCV), Short Circuit Current (SCC), Temperature Method (TA), and Perturb and Observe (P&O) are some of these methods.

Calculation-Based Tracking Methods

To determine the MPP, the algorithms in this method use calculations of their specific equations. Linear Reoriented Coordinates Method (LRCM), Sliding Mode (SM), Parasitic Capacitance (PC), and Incremental Conductance (IC) are among these methods.

Intelligent Design-Based Tracking Methods

New optimization designs based on intelligent methods can also be used in the MPPT control system. Fuzzy Logic (FL), Neural Networks (NN), Particle Swarm Optimization (PSO), and Ant Colony Optimization (ACO) are among these methods.

Hybrid Design-Based Tracking Methods

Combining traditional and intelligent algorithms is one of the new methods for tracking the maximum power point. These methods increase tracking speed and accuracy and perform very well under partial shading conditions. FLC/P&O, PSO/P&O, ANN/IC, and ANN/FLC are among these methods.

In this paper, an MPPT control system using three algorithms, P&O, IC, and Fuzzy-PI, is examined.

3.1. Perturb and Observe Algorithm (P&O)

This algorithm is one of the most common methods among researchers and is widely used in both industry and laboratory settings. For each operational period, it measures the PV cell parameters and then perturbs the voltage to adjust the operating point towards achieving the Maximum Power Point (MPP). After performing the calculations, if the power difference from the previous sample is positive, the voltage perturbation should continue in the same direction (indicating it is to the left of the MPP). Conversely, if the power difference is negative, the perturbation should be in the opposite direction (indicating it is to the right of the MPP). When the power difference is zero, the desired point is found. Essentially, the operating voltage is constantly changing. The advantages of this method include compatibility with various modules, no need for module configuration information, ease of implementation, and low cost. However, due to the fixed perturbation step size, this method faces three significant issues: oscillation around the MPP, lack of precise tracking, and low tracking speed. Methods such as P&O with variable step size have been introduced to mitigate these issues to some extent and have shown satisfactory performance even under partial shading conditions [6, 18, 17].

3.2. Incremental Conductance Algorithm (IC)

This method utilizes the slope of the power-voltage characteristic curve to track the MPP. At the desired point, the slope is zero; to the left of the point, the slope is positive; and to the right, the slope is negative. The mathematical relationships and the operation of this algorithm are depicted in Figure 3. This algorithm generally aims to address the problems of the P&O method and has somewhat succeeded in overcoming them. The main advantage of this method is its flexibility with rapid changes in weather conditions. However, the IC algorithm requires a complex control circuit to perform its calculations. Calculations related to the step size adjustment and operation under partial shading conditions are provided in reference [19].

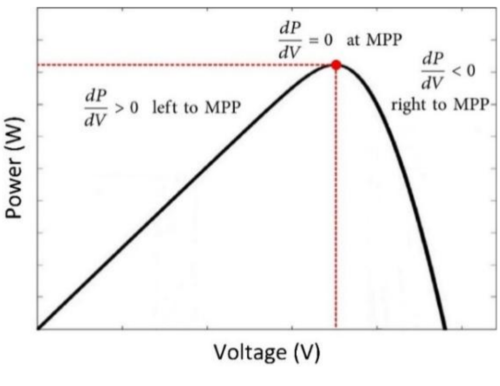

Fig.3. Performance of the Incremental Conductance Algorithm

3.3. Fuzzy-PI Algorithm

Fuzzy logic control is highly capable of handling nonlinear systems. However, a major drawback of this method is the continuous integral calculations that produce cumulative error. The PI controller is also widely used in various fields because the relationship between control and response is well-defined. However, if operating conditions change, its performance deteriorates due to its fixed gain [20]. Therefore, the Fuzzy-PI algorithm is proposed to cover each other's errors. The block diagram of this controller is shown in Figure 4.

A fuzzy controller consists of fuzzification units, membership functions, fuzzy rules, fuzzy inference, and defuzzification operations. In fuzzy logic, defining inputs, outputs, and membership functions are crucial steps. In this study, the inputs to the fuzzy block are the measured voltage and current from the PV module, and the output is the PI controller coefficients.

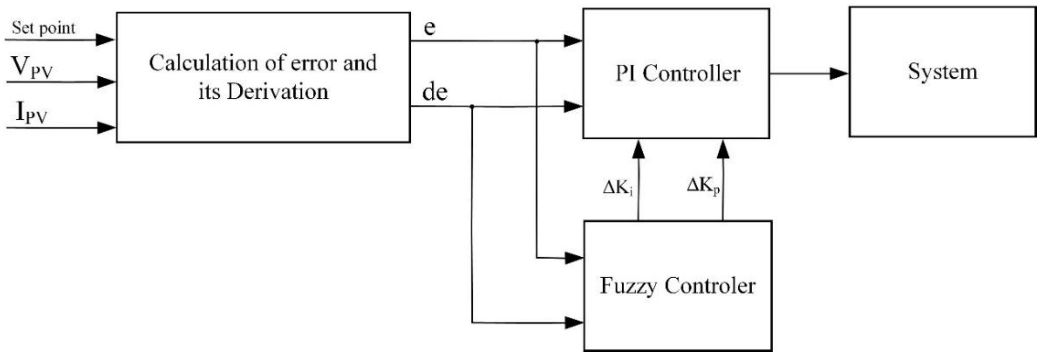

Fig.4. Overview of the Fuzzy-PI Algorithm

4. DC-DC CONVERTERS

Photovoltaic (PV) systems connected to the grid must use two stages of conversion. The first stage increases the output voltage level (DC-DC converter) and the second stage converts from DC to AC. Even in DC load-connected systems, a voltage step-up is essential. The control signals from the MPPT system, combined with the modulation unit, can reach the converter and regulate it. These signals are applied to the switches used in the converters. Various classifications for DC-DC converters exist, such as with or without transformers or being step-up and step-down types. Some of these converters include Boost, Buck, Buck-Boost, SEPIC, Cuk, Flyback, etc. With advances in power electronics and the introduction of new high-gain converters, these converters are also used in PV systems [21].

4.1. Boost Converter

A boost converter is a DC-DC step-up switching converter. The topology of this converter is shown in Figure 5. It consists of a switch, a diode, an inductor, and a capacitor, forming a simple structure. When the switch is on, the current flows through the source to the inductor, storing energy in it. When the switch is off, the stored energy in the inductor is delivered to the other parts of the circuit. It is evident that the switching on or off is controlled by the MPPT controller.

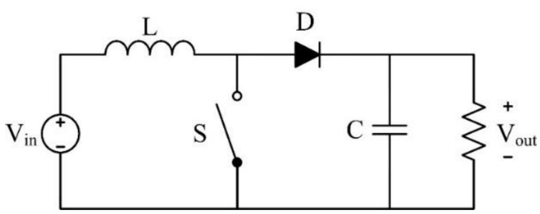

Fig.5. Topology of the Boost Converter

4.2. SEPIC Converter

The SEPIC converter (Single Ended Primary Inductance Converter) is a multi-mode converter, meaning it can be used as a step-up, step-down, or step-up/down converter depending on the application. It has a more complex structure than the boost converter, consisting of a switch, a diode, two inductors, and two capacitors. The topology of this converter is shown in Figure 6. When the switch is off, the diode is on, and the first inductor charges from the source while the second inductor charges the capacitor. When the switch is on, the diode is off, the first inductor charges the first capacitor, and the second inductor supplies current to the load.

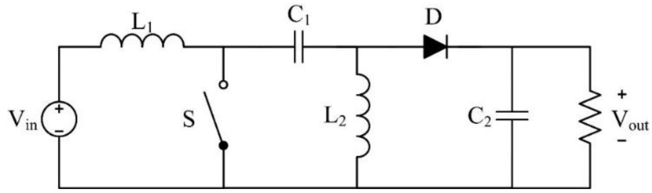

Fig.6. Topology of the SEPIC Converter

5. SIMULATION

The proposed PV system is shown in Figure 7, modeled using MATLAB/Simulink. The parameters of the PV module are taken from the Canadian Solar Clean Power CS5T-130, and the related information is provided in Table 1. The simulation results are presented using the P&O, IC, and Fuzzy-PI tracking algorithms and the Boost and SEPIC converters. To better understand the system's performance, the responses of the methods and system dynamics under four different irradiance levels (800, 300, 900, and 400 W/m²) are used as module inputs. The output results, delivered powers to the resistive load, are compared using the described algorithms and converters.

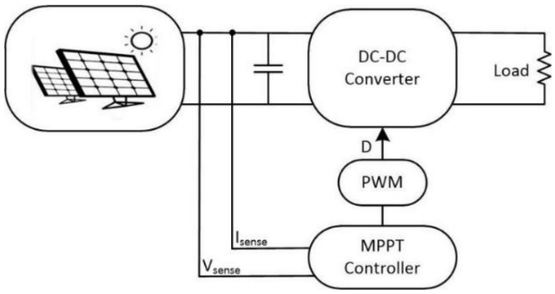

Fig.7. Proposed System

Table 1. Calculated Parameters at Two Points

Parameter	Description	Value
P_{max}	Maximum Power	130 W
V_{OC}	Open Circuit Voltage	36.3 V
I_{SC}	Short Circuit Current	4.82 A
V_{MPP}	Voltage at Maximum Power Point	29.2 V
I_{MPP}	Current at Maximum Power Point	4.45 A
N_S	Number of Series Modules	1
N_P	Number of String Modules	1
R_S	Series Resistance	1.0362 ohms
n_{VocT}	Temperature Coefficient of Open Circuit Voltage	-0.35 %/°C
n_{IscT}	Temperature Coefficient of Short Circuit Current	0.06 %/°C

According to the simulation results, the oscillations around the MPP in the P&O algorithm are more significant than those in the other algorithms. These ripples result in energy loss in the steady state and the identification of local MPPs. The IC algorithm shows better flexibility during irradiance changes and quickly reaches its final value from the transient state. Although the P&O algorithm improves with step size adjustments, the IC oscillations remain lower. However, the performance of both methods depends on their step size, and optimizing the step size under rapid weather condition changes remains a major issue. The combination of Fuzzy and PI algorithms, covering each other's deficiencies, has demonstrated satisfactory performance compared to the other two algorithms. The reduced oscillations around the desired point and the rapid response of the algorithm to irradiance changes support this claim. The SEPIC converter has a topology similar to the Buck-Boost converter, with the distinction that its output polarity remains the same as the input polarity. Since a relatively large inductor is used at its input, its input current is continuous, reducing ripple. It also reduces noise and prevents interference with other circuit components in the MPPT system, offering better performance than the Boost converter. A comparison of the converter performance with the Fuzzy-PI algorithm is also presented in Figure 12.

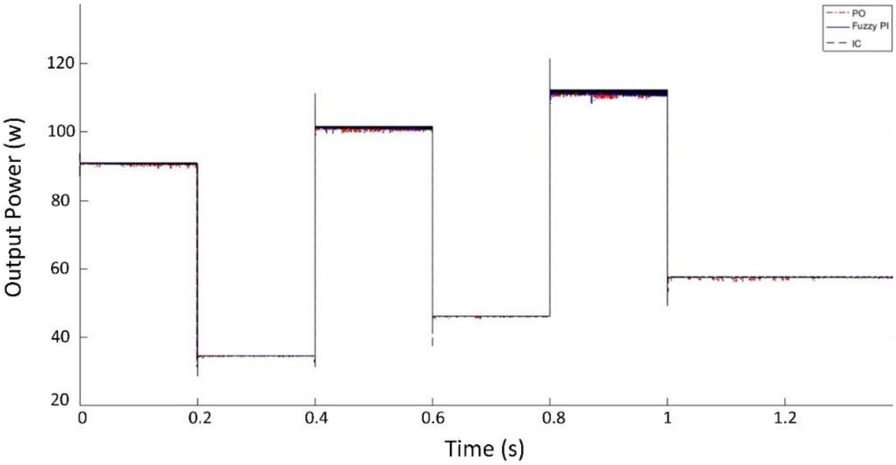

Fig.8. Output Power of P&O, IC, and Fuzzy-PI Algorithms with Boost Converter

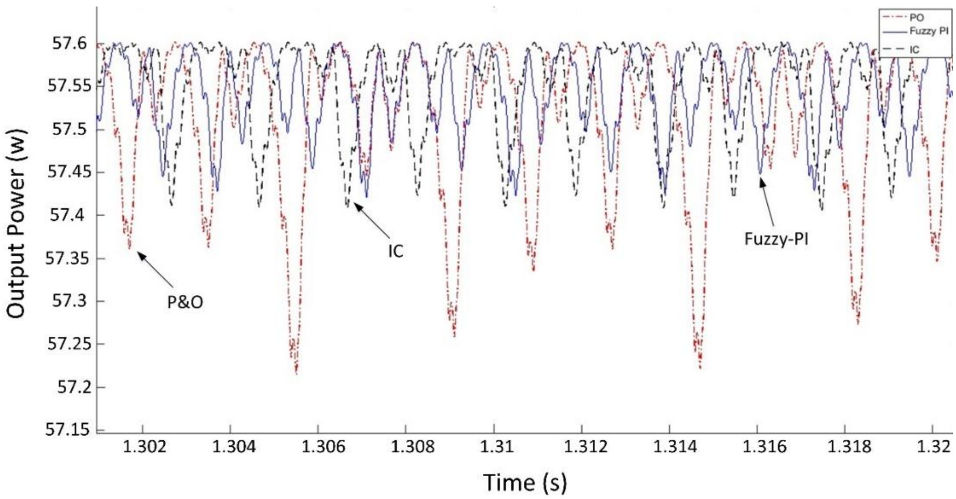

Fig.9. Close-up View of Figure 8

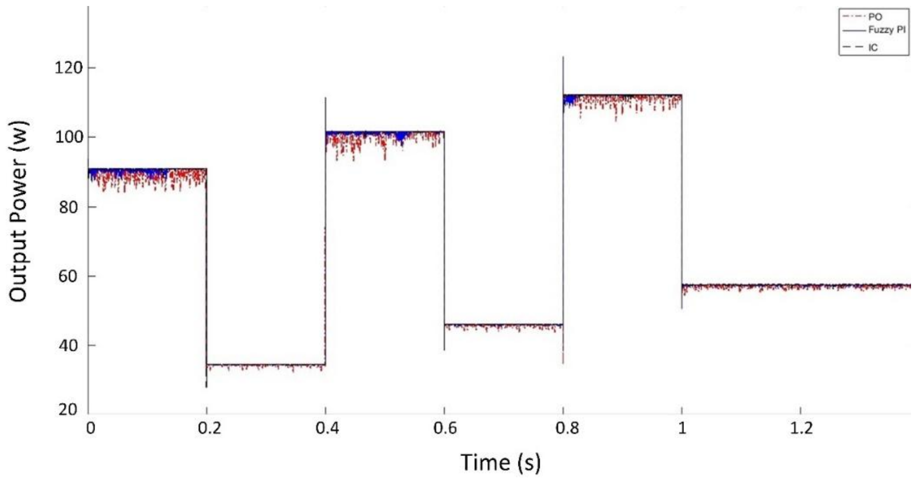

Fig.10. Output Power of P&O, IC, and Fuzzy-PI Algorithms with SEPIC Converter

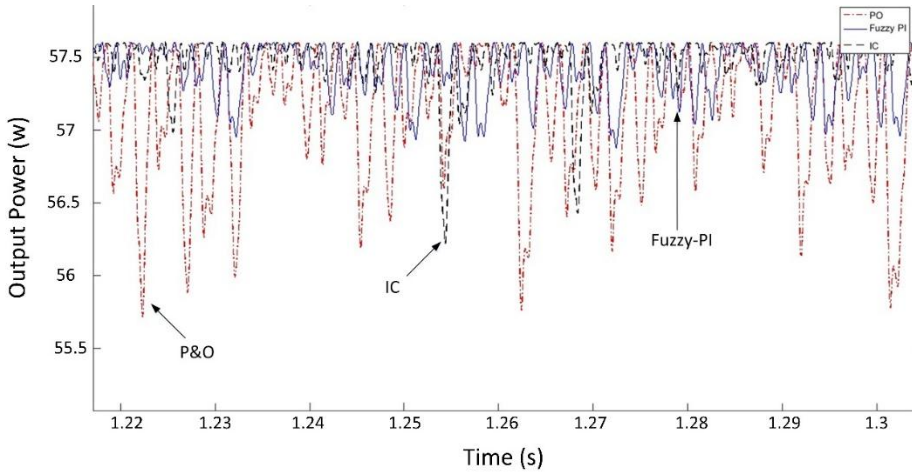

Fig.11. Close-up View of Figure 10

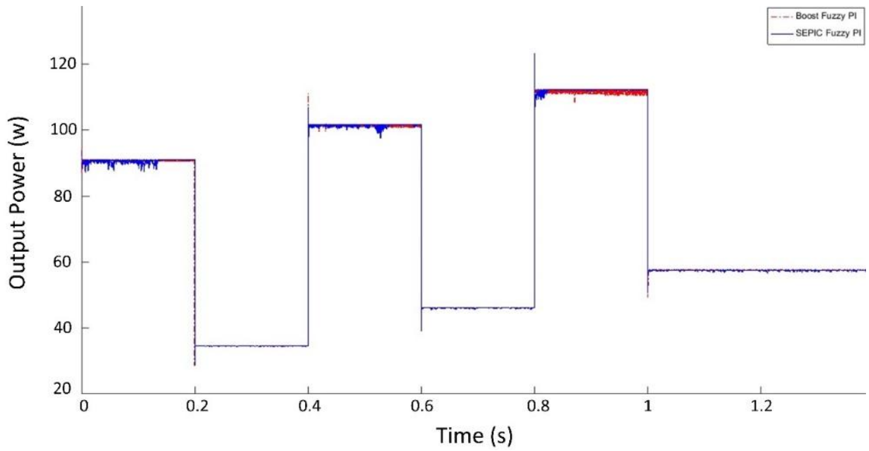

Fig.12. Output Power of Fuzzy-PI Algorithm with Boost and SEPIC Converters

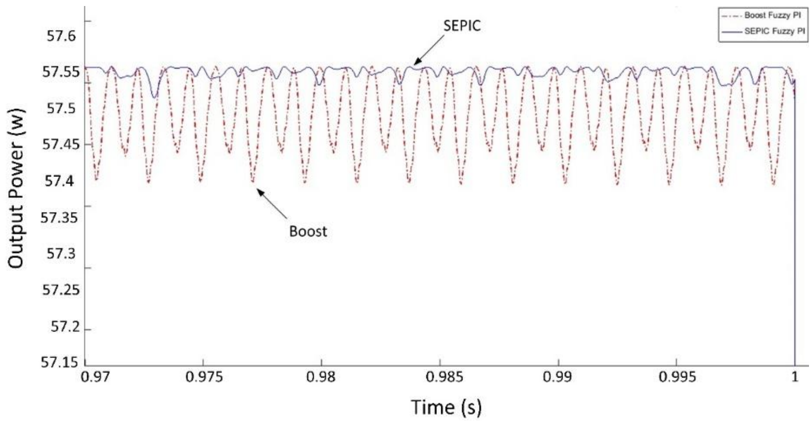

Fig.13. Close-up View of Figure 12

6. CONCLUSION

In this article, after introducing the photovoltaic system and the components utilized within it, each of these units has been individually introduced and examined. Following the introduction of solar cells, a comprehensive classification of MPPT algorithms has been provided, and then two DC-DC converters have been presented. Using three algorithms, P&O, IC, and Fuzzy-PI, and two converters, Boost and SEPIC, an off-grid PV system was simulated, and the obtained results have been presented. The key considerations in this study were overshoot, oscillations around the MPP, settling time, and the ability to track the maximum power point under various conditions. The analyses showed that the Fuzzy-PI algorithm exhibited fewer oscillations and reached the MPP in less time compared to the other two algorithms. Additionally, with varying irradiation levels (performance under changing weather conditions), this algorithm demonstrated superior capability in aligning the system's operating point to the desired conditions, possessing higher accuracy and tracking speed. The inclusion of the SEPIC converter alongside this algorithm for applying control signals significantly reduced system oscillations and stabilized the steady-state conditions. Given the ongoing advancements in photovoltaic systems, areas of interest for enthusiasts in this field include examining system performance under partial shading conditions, combining tracking algorithms to enhance operation speed and accuracy, and employing DC-DC converters with high gain.

Transparency Statement

The data supporting this study are available upon reasonable request to the corresponding author, subject to ethical and confidentiality considerations.

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Declaration of Interest

The authors declare that they have no competing interests.

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REFERENCES

[1] Li, S., Yang, K., Hu, L., Zhong, J., & Nguyen, H. (2017). A MPPT strategy with variable weather parameters through analyzing the effect of the DC/DC converter to the MPP of PV system. Solar Energy, 144, 175-184. https://doi.org/10.1016/j.solener.2017.01.002

[2] Bradai, R., Stambouli, T., Bouchafaa, F., Ramdani, M., & Haddad, S. (2017). Experimental assessment of new fast MPPT algorithm for PV systems under non-uniform irradiance conditions. Applied Energy, 199, 416-429. https://doi.org/10.1016/j.apenergy.2017.05.045

[3] da Silva, S. A. O., Oliveira, C. C., Oliveira, L. E., & da Silva, E. B. (2016). Feed-forward DC-bus control loop applied to a single-phase grid-connected PV system operating with PSO-based MPPT technique and active power-line conditioning. IET Renewable Power Generation, 11(1), 183-193. https://doi.org/10.1049/iet-rpg.2016.0120

[4] da Rocha, M. V., Sampaio, L. P., & da Silva, S. A. O. (2020). Comparative analysis of MPPT algorithms based on Bat algorithm for PV systems under partial shading condition. Sustainable Energy Technologies and Assessments, 40, 100761. https://doi.org/10.1016/j.seta.2020.100761

[5] Ahmed, J., & Salam, Z. (2015). An improved perturb and observe (P&O) maximum power point tracking (MPPT) algorithm for higher efficiency. Applied Energy, 150, 97-108. https://doi.org/10.1016/j.apenergy.2015.04.006

[6] Ahmed, J., & Salam, Z. (2018). An enhanced adaptive P&O MPPT for fast and efficient tracking under varying environmental conditions. IEEE Transactions on Sustainable Energy, 9(3), 1487-1496. https://doi.org/10.1109/TSTE.2018.2791968

[7] Amir, A., Terzioğlu, M., Gani, A., & Köseer, K. (2017). Conventional and modified MPPT techniques with direct control and dual scaled adaptive step-size. Solar Energy, 157, 1017-1031. https://doi.org/10.1016/j.solener.2017.09.004

[8] Mirbagheri, S. Z., Mekhilef, S., & Mirhassani, S. M. (2013). MPPT with Inc. Cond method using conventional interleaved boost converter. Energy Procedia, 42, 24-32. https://doi.org/10.1016/j.egypro.2013.11.002

[9] Tey, K. S., & Mekhilef, S. (2014). Modified incremental conductance algorithm for photovoltaic system under partial shading conditions and load variation. IEEE Transactions on Industrial Electronics, 61(10), 5384-5392. https://doi.org/10.1109/TIE.2014.2304921

[10] Necaibia, S., Arab, A. H., Talha, A., Kebir, R. H., Tazerout, M., & Belgacem, K. (2019). Enhanced auto-scaling incremental conductance MPPT method, implemented on low-cost microcontroller and SEPIC converter. Solar Energy, 180, 152-168. https://doi.org/10.1016/j.solener.2019.01.028

[11] Al Nabulsi, A., & Dhaouadi, R. (2012). Efficiency optimization of a DSP-based standalone PV system using fuzzy logic and dual-MPPT control. IEEE Transactions on Industrial Informatics, 8(3), 573-584. https://doi.org/10.1109/TII.2012.2192282

[12] Khabou, H., Souissi, M., & Aitouche, A. (2020). MPPT implementation on boost converter by using T-S fuzzy method. Mathematics and Computers in Simulation, 167, 119-134. https://doi.org/10.1016/j.matcom.2018.05.010

[13] Harrag, A., & Messalti, S. (2019). IC-based variable step size neuro-fuzzy MPPT improving PV system performances. Energy Procedia, 157, 362-374. https://doi.org/10.1016/j.egypro.2018.11.201

[14] Priyadarshi, N., Modi, N. S., Das, D., & Josyula, S. (2019). An experimental estimation of hybrid ANFIS-PSO-based MPPT for PV grid integration under fluctuating sun irradiance. IEEE Systems Journal, 14(1), 1218-1229. https://doi.org/10.1109/JSYST.2019.2949083

[15] Lakshmi, M., & Hemamalini, S. (2019). Coordinated control of MPPT and voltage regulation using single-stage high gain DC-DC converter in grid-connected PV system. Electric Power Systems Research, 169, 65-73. https://doi.org/10.1016/j.epsr.2018.12.011

[16] Reddy, K. J., & Sudhakar, N. (2018). High voltage gain interleaved boost converter with neural network based MPPT controller for fuel cell based electric vehicle applications. IEEE Access, 6, 3899-3908. https://doi.org/10.1109/ACCESS.2017.2785832

[17] Mehta, H. K., Karimi, D., Jain, A. K., Murthy, A. S., & Oberoi, P. S. (2019). Accurate expressions for single-diode-model solar cell parameterization. IEEE Journal of Photovoltaics, 9(3), 803-810. https://doi.org/10.1109/JPHOTOV.2019.2896264

[18] Jiang, Y., Abu Qahouq, J. A., & Haskew, T. A. (2012). Adaptive step size with adaptive-perturbation-frequency digital MPPT controller for a single-sensor photovoltaic solar system. IEEE Transactions on Power Electronics, 28(7), 3195-3205. https://doi.org/10.1109/TPEL.2012.2220158

[19] Kumar, R., Arya, S., & Meena, R. K. (2019). Global maximum power point tracking using variable sampling time and PV curve region shifting technique along with incremental conductance for partially shaded photovoltaic systems. Solar Energy, 189, 151-178. https://doi.org/10.1016/j.solener.2019.07.029

[20] Bouchakour, A., Borni, A., & Brahami, M. (2019). Comparative study of P&O-PI and fuzzy-PI MPPT controllers and their optimisation using GA and PSO for photovoltaic water pumping systems. International Journal of Ambient Energy. https://doi.org/10.1080/01430750.2019.1614988

[21] Reddy, K. J., & Sudhakar, N. (2018). High voltage gain interleaved boost converter with neural network based MPPT controller for fuel cell based electric vehicle applications. IEEE Access, 6, 3899-3908. https://doi.org/10.1109/ACCESS.2017.2785832