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Optimizing PV System Performance with FLC and P&O MPPT Controllers Using SEPIC and Boost Converters

Fotovoltaikus rendszer teljesítményének optimalizálása FLC és P&O MPPT vezérlőkkel SEPIC és boost konverterek alkalmazásával

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Abstract — **The growing reliance on renewable energy systems necessitates maximizing efficiency, reducing costs, and improving reliability. In photovoltaic (PV) systems, Maximum Power Point Tracking (MPPT) and converter design are critical to achieving these goals. This study models a PV module integrated with MPPT controllers using SEPIC and boost converters to compare their performance under varying environmental conditions. Using MATLAB/SIMULINK, two control techniques, Fuzzy Logic Controller (FLC) and Perturb and Observe (P&O), and two converters - SEPIC and Boost -were simulated and compared. Results indicate that the SEPIC converter outperformed the boost converter in terms of response time and ripple reduction (1.20% vs. 3.40%). As for the controllers, FLC demonstrated superior performance in tracking maximum power compared to P&O, achieving higher efficiency (92.5% vs. 91.7%) and faster response (~0.004 s), delivering better current, voltage, and power outputs. The case studyanalysed system performance under variable solar irradiation and temperature, with efficiencies reaching 93.1% and 91.9%. These results emphasize the potential of enhancing PV system efficiency for real applications.**

Keywords: Photovoltaic Systems (PV), Maximum Power Point Tracking (MPPT), Fuzzy Logic Controller (FLC), Perturb and Observe technique (P&O), SEPIC converter, boost converter.

Összefoglalás — **A megújuló energiaforrások növekvő alkalmazása megköveteli a fotovoltaikus (PV) rendszerek hatékonyságának, megbízhatóságának és gazdaságosságának folyamatos javítását, amelyben az MPPT technikák és a teljesítményelektronikai konverterek kulcsszerepet játszanak. A MATLAB/SIMULINK alapú vizsgálat során a SEPIC és Boost konvertereket, valamint az FLC és P&O szabályozási módszereket hasonlították össze különböző környezeti feltételek mellett, és az eredmények azt mutatták, hogy a SEPIC konverter alacsonyabb hullámosságot, nagyobb stabilitást és jobb dinamikus viselkedést biztosít, míg az FLC szabályozó gyorsabb válaszidőt, pontosabb maximális teljesítménykövetést és magasabb hatásfokot nyújt a P&O módszerhez képest. Az esettanulmány kimutatta, hogy a rendszer hatásfoka elérheti a 93,1% és 91,9% értékeket, ami világosan rámutat arra, hogy a környezeti tényezők (mint a besugárzás és hőmérséklet) és a megfelelő vezérlési, illetve konvertertechnológiák döntő szerepet játszanak a PV rendszerek teljesítményének növelésében és gyakorlati optimalizálásában.**

Kulcsszavak: Fotovoltaikus rendszerek (PV), maximális teljesítménypont-követés (MPPT), fuzzy logikai vezérlő (FLC), perturbáció és megfigyelés módszer (P&O), SEPIC konverter, boost konverter.

1 INTRODUCTION

Solar energy is the most popular system among renewable energy sources and could be considered one of the most valuable sources as it has many features, including pollution-free as well as low operating and maintenance costs, which promise to grow its share in the near future. The World Commission for Environment and Development described four key components of sustainability in relation to energy: capacity to scale. Energy supplies to meet growing human needs, energy efficiency and conservation, public health and safety, protection of the biosphere, and the prevention of further local pollution [1]. The efficiency of solar energy systems remains a critical factor that directly affects their widespread adoption and practical viability. A comprehensive understanding of the various factors influencing system efficiency is essential for optimizing performance and increasing their contribution to the global energy mix. These factors include environmental conditions, system design, and operational strategies. Furthermore, technological advancements play a significant role in improving the efficiency of solar energy systems [2]. As the output power of a photovoltaic cell is susceptible to fluctuations stemming from environmental variables such as light intensity and temperature, rapid changes in these factors directly impact the actual output power of the photovoltaic system [3]. Therefore, efficient MPPT techniques are essential to ensure that the PV system continuously operates at its maximum power point under varying conditions. So Artificial intelligence (AI) can be used as a powerful tool in addressing complex problems, and its application in renewable energy systems has shown great potential. By leveraging AI techniques, it is possible to enhance the performance, efficiency, and reliability of solar energy systems. Therefore, this paper aims to explore the role of artificial intelligence techniques in improving the performance of solar energy systems on different converters.

MPPT is utilized to identify the maximum power point in a photovoltaic (PV) system. The efficiency of MPPT is influenced by both the control algorithm and the circuit used. Typically, the MPPT control algorithm is implemented in a DC-DC converter, which serves as the MPPT circuit. This paper presents several MPPT methods for maximizing the power extracted from photovoltaic systems. These methods can be classified into classical methods, like Perturb & Observe (P&O), or intelligent control methods, like fuzzy logic [4]. These methods differ in effectiveness, speed of tracking, sensor required, complexity, and cost [5]. The system is modeled and simulated using MATLAB/Simulink.

Fig. 3 illustrates the proposed system designed to maximize solar energy extraction. It uses photovoltaic (PV) panels as the main power source, and two DC-DC converters (SEPIC and boost) to efficiently output power. Intelligent control, like fuzzy logic and P&O technique for maximum power point tracking (MPPT), This helps capture as much energy as possible from the solar panels, improving system flexibility.

The main novelty of this study lies in the integrated and comparative evaluation of intelligent and conventional MPPT techniques (FLC and P&O) combined with different DC–DC converter topologies (SEPIC and boost) within a unified MATLAB/Simulink framework. Furthermore, the study incorporates real environmental data from Yemen (Sana'a and Aden), providing practical validation under realistic operating conditions. This combined approach offers a more comprehensive performance assessment compared to existing studies, which typically focus on either control strategies or converter topologies separately. The main objectives of this study are to compare the performance of FLC and P&O MPPT techniques, evaluate the effectiveness of SEPIC and Boost converters, and analyze system performance under realistic environmental conditions in Yemen, with the aim of identifying the most efficient configuration for improving photovoltaic system performance.

2 PV TECHNOLOGY

The sun is a renewable energy source. Photovoltaic modules convert light into electricity. The word photovoltaic comes from Greek words meaning light and electromotive power. Commercial panels usually have an efficiency of 17% to 23%, while advanced crystalline silicon cells can reach up to 50% efficiency under laboratory conditions.

PV technology converts sunlight directly into electricity using semiconductor materials. It is a clean and renewable energy source widely adopted in residential, commercial, and industrial applications. Advances in PV materials, such as monocrystalline, polycrystalline, and thin-film technologies, have improved efficiency, reduced costs, and enhanced performance under varying environmental conditions. Modern PV systems often integrate Maximum Power Point Tracking (MPPT) techniques and energy storage solutions to optimize energy harvesting and system reliability [4].

Solar Cell Current Equation:

$$I = I_{ph} - I_0\left(e^{\frac{qV}{nkT}} - 1\right),$$

where I_{ph}: photogenerated current. I_0: reverse saturation current. **q**: electron charge **V**: voltage. **n**: ideality factor. **k**: Boltzmann constant. **T:** temperature in kelvin.

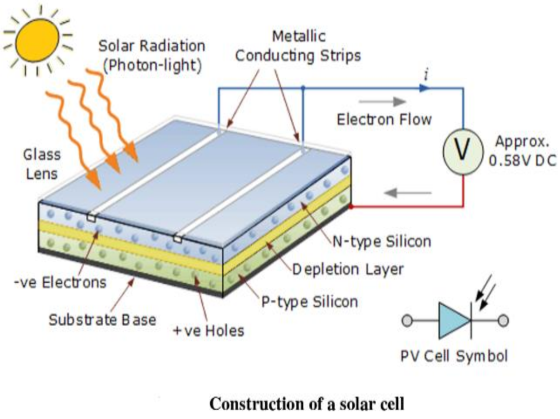


Figure 1: Solar cell diagram [5]

3 AI TECHNIQUES FOR MPPT IN PV SYSTEMS

There is a point in a curve where the power can be maximized, which is called the Maximum Power Point (MPP). This point usually changes depending on conditions such as irradiation, temperature, or the state of the PV cell. These conditions can change the shape of the curve, making the problem nonlinear and time-varying due to the changes produced by the atmospheric and load conditions [6]. In PV systems, MPPT is crucial for maximizing energy output. AI techniques can greatly improve the efficiency and effectiveness of MPPT algorithms. In the following, a few prominent AI approaches used in MPPT are presented.

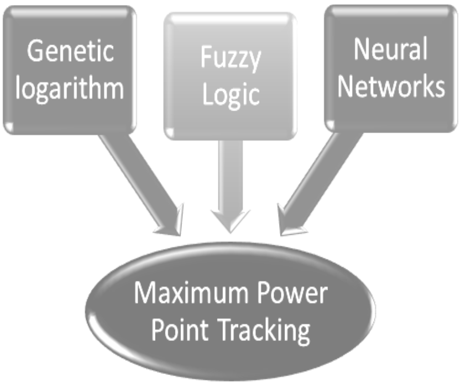


Figure 2. Most commonly used AI methods for MPPT

3.1 Fuzzy Logic FLC

The systems provide quick responses to changes and low oscillations near MPP that reduce power loss compared with traditional systems. The combination with FCN or the initial estimation of the MPP voltage further improves the results [7].

3.2 Genetic Algorithms (GA)

Genetic Algorithms (GA) are valuable metaheuristics used to find optimal solutions and improve the performance of AI techniques. They have been applied to optimize training data and neuron numbers in Artificial Neural Networks (ANNs), as well as to optimize membership functions [8].

3.3 Neural Networks

Neural Networks have shown excellent adequacy and high capabilities for complex learning problems; thus, they are ideal for tracking the MPP. They can be used alone or helped by other methods. The hybrid techniques are usually focused on improving the performance of the neural networks by optimizing the hyper-parameters of the networks, since it is a complex task [9].

4 OPERATING SYSTEM OF THE PROPOSED SYSTEM

The proposed system, illustrated in Fig. 3, is comprehensively modeled to include several key components: the PV module based on the ARE230W model, the environmental input parameters including temperature and solar irradiance, and the implementation of both intelligent and conventional control strategies, namely the FLCand the P&O algorithm. In addition, DC–DC power conversion is achieved through the integration of boost and SEPIC converter topologies to evaluate their impact on system performance. A switching mechanism is incorporated to enable dynamic selection between the FLC and P&O controllers, facilitating a direct and systematic comparison under identical operating conditions. This integrated modeling framework is designed to enhance the efficiency, adaptability, and reliability of the photovoltaic system while providing a robust platform for performance evaluation and optimization.

The parameters listed in Table 1 are selected based on the PV module specifications and implemented in the MATLAB/Simulink environment to ensure realistic system behavior under varying environmental conditions.

Table 1. System parameters used in the proposed model

Parameter	Value	Parameter	Value
PV Module Power	230 W	Switching Frequency	20 kHz
Open Circuit Voltage	37.2 V	Inductor (Boost)	0.0004 H
Maximum Voltage	30.5 V	Capacitor (Boost)	0.0012 F
Maximum Current	7.54 A	Inductor (SEPIC)	0.0004 H
Irradiance Range	200–1000	Coupling Capacitor	0.004 F
Temperature Range	15–45 °C	Output Capacitor	0.0012 F

Converters are essential components in MPPT systems. In this simulation we will compare two converters. The first, SEPIC converter (Single-Ended Primary Inductance Converter) offers the advantage of providing both step-up and step-down voltage capabilities, ensuring flexibility in a variety of conditions. It is particularly useful when the PV voltage fluctuates above or below the desired operating point. The second, boost converter, on the other hand, is designed to step up the voltage, which is beneficial when the PV output is lower than the required voltage for optimal system performance. With varying atmospheric conditions, the duty cycle of the DC-DC converter must be adjusted to extract maximum power from PV module [7]. For the operation, during Ton, the SEPIC inductor L4 and C5 are charged by the switched inductance (L1 and L2) with half of the DC link voltage since these switched capacitors become parallel due to the reverse bias of D12 and forward bias of D5 and D6. However, during Toff, the L1 and L2 are charged in series with the DC link voltage since D12 becomes forward bias. Furthermore, current in the SEPIC inductor L4 continuing through the freewheeling diode D3 charges the output capacitor C5. During the operation of the boost converter during the Ton, the transistor is switched on, allowing current to flow from the input voltage source through the inductor. This results in energy storage within the inductor in the form of a magnetic field, causing the inductor current to increase linearly.

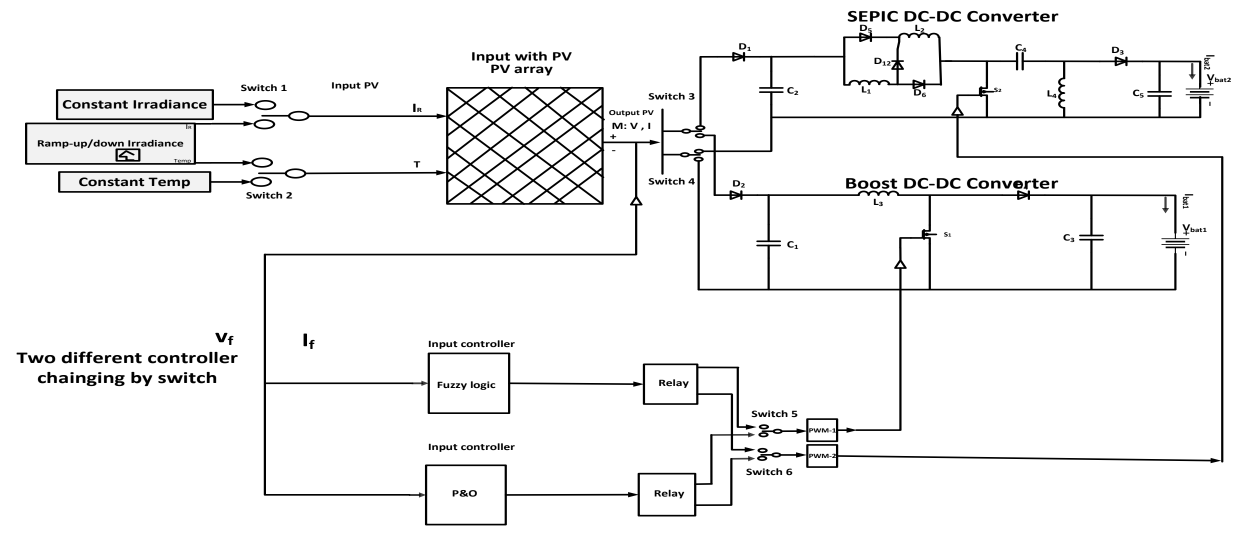


Figure 3: Proposed Photovoltaic System with MPPT Controllers and DC-DC Converters

During the Toff, the transistor is switched off, preventing current flow through it. Consequently, the inductor discharges its stored energy through the diode and into the load, effectively increasing the output voltage.

Continuous energy transfer ensures that the voltage across the load remains higher than the input voltage.

The model incorporates inputs for temperature and solar irradiation, which influence the output power of the PV panel. These inputs can be dynamically adjusted within the simulation to monitor the performance of the panel under real conditions. Fig. 4 shows the internal structure of the PV panel module.

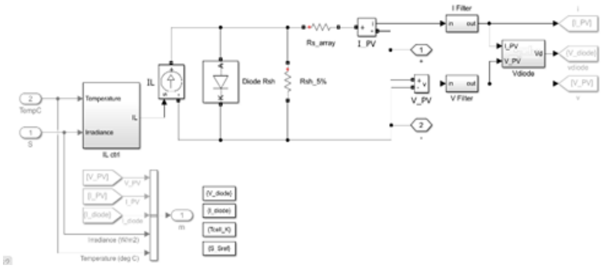
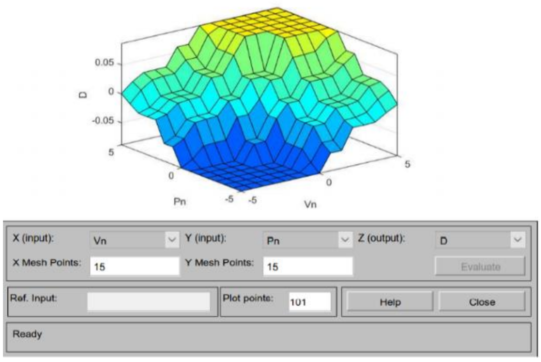


Figure 4. Structure of the PV panel module

The controller component is also worth highlighting, and it is noted that two techniques were used: fuzzy logic and perturbation and observation. To clarify the fuzzy logic technique, Fig. 5 shows the surface of the base rules used in FLC, which represents the input and output values of the controller in three dimensions.



X (input): Vn
Y (input): Pn
Z (output): D
X Mesh Points: 15
Y Mesh Points: 15
Ref. Input:
Plot points: 101
Ready

Figure 5. The surface of the base rules

To adjust duty cycles, monitor power variations, and achieve MPPT in photovoltaic systems. The P&Oalgorithm used in PV systems tracks the MPP by slightly changing the PV voltage and observing how the output power responds. In a single power–voltage (PV) graph, the power increases with voltage until it reaches the peak point (MPP) and then decreases afterward. The controller perturbs (slightly increases or decreases) the operating voltage and measures the change in power. If the perturbation causes the power to increase ($\Delta P > 0$), the algorithm continues changing the voltage in the same direction because it means the operating point is moving toward the MPP [10][11]. If the perturbation causes the power to decrease ($\Delta P < 0$), the algorithm reverses the direction of the voltage change because it has moved away from the MPP. By continuously repeating this process, the operating point moves back and forth around the peak of the P–V curve as shown in Fig. 6, allowing the PV system to operate very close to the maximum available power.

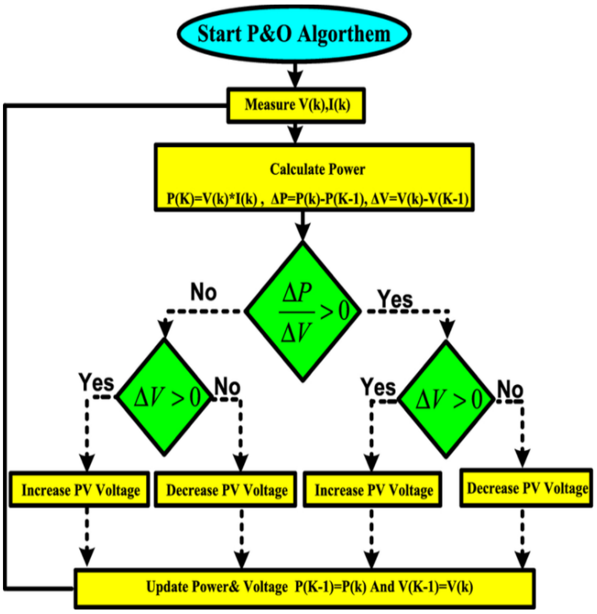


Figure 6. Flowchart of perturb and observe scheme [**10**]

The FLC system is represented in the MATLAB/Simulink software which there is a Mamdani-type system with two inputs and a single output. There are two inputs as shown in Fig. 7. The input E represents the power the input CE represents the change in voltage of the PV generator and output D represents the duty cycle which will generate the control signal to the converter of the PV generator.

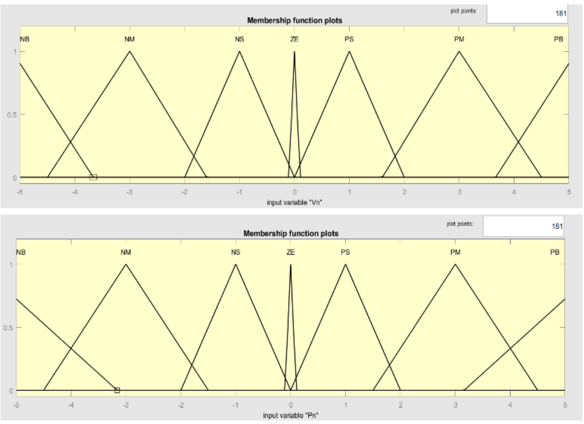


Figure 7. Membership function (MF) of Vn, Pn

The fuzzy rules of the proposed system have been derived from the behavior of the system and tested in Simulink/MATLAB. Table 2 presents the fuzzy logic rule base that defines the relationship between the error (E) and the change in error (ΔE) and their effect on the control output (duty cycle). The rules use seven linguistic variables ranging from Big Negative (BN) to Big Positive (BP) to determine the appropriate control action. When both E and ΔE indicate that the operating point is far from the MPP, strong adjustments (BN or BP) are applied to rapidly move the system toward the optimum. Conversely, when the system is close to the MPP, smaller control actions (SN, SP, or Zero) are used to minimize oscillations and maintain stability. This rule-based mechanism enables smooth and adaptive tracking of the MPP under varying environmental conditions.

Table 2. Fuzzy logic rule-based

ΔE/E	BN	MN	SN	Zero	SP	MP	BP
BN	BN	BN	MN	MN	SN	SN	Zero
MN	BN	MN	MN	SN	SN	Zero	SN
SN	MN	MN	Zero	SN	Zero	SP	SP
Zero	MN	SN	SN	Zero	SP	SP	MP
SP	SN	SN	Zero	SP	Zero	MP	MP
MP	SP	Zero	MP	SP	MP	MP	BP
BP	Zero	SN	MP	MP	MP	BP	BP

5 RESULTS AND DISCUSSION

5.1 *Comparison of controllers*

The simulation results demonstrate that the FLC outperforms the P&O controller in managing the power output of PV systems. The FLC consistently achieved higher efficiency levels, exceeding those of the P&O controller by 2-5% under fluctuating environmental conditions (Fig. 8).

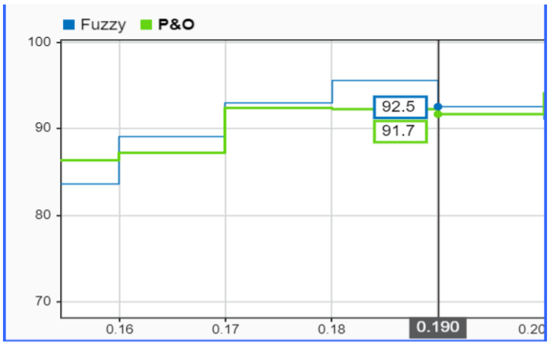


Figure 8. Efficiency comparison of FLC and P&O controllers

As shown in Fig. 9, the FLC exhibited superior responsiveness to changes in sunlight and temperature, quickly optimizing energy extraction. This adaptability was particularly evident during rapid irradiance variations, where the FLC maintained stable power output, while the P&O controller lagged, resulting in temporary power losses.

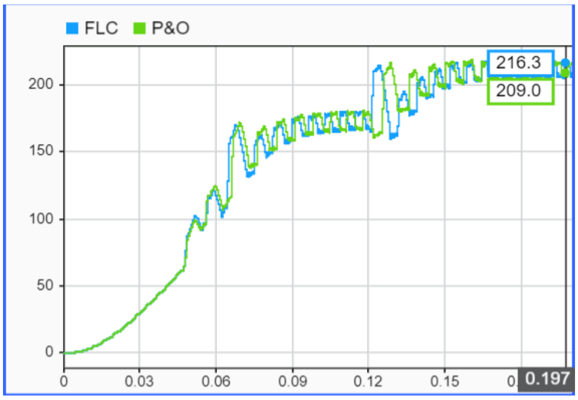


Figure 9. Power comparison of FLC and P&O controllers

As a conclusion to the controller comparison, FLC outperformed P&O with slightly higher efficiency (2–5%) and faster response to environmental changes, ensuring more stable power output as shown in Table 3.

Table 3. Performance comparison of FLC and P&O controllers

Performance Indicator	(FLC)	(P&O)
Response Time	Faster adaptation	Slower adaptation
Efficiency	92.5%	91.7%
Peak Value (W)	228.3	227.6

5.2 *Comparison of converters*

To evaluate the performance of SEPIC and Boost converters, various parameters such as ripple, voltage stability, and battery charging were analyzed.

5.2.1 *Pulse Width Modulation*

Fig. 10 shows the Pulse Width Modulation (PWM) signals for both converters. SEPIC exhibited more stable signals with fewer oscillations, indicating better feedback loop performance. In contrast, Boost showed significant variations, suggesting potential instability or noise in the system.

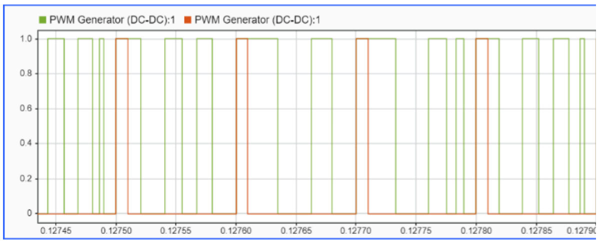


Figure 10: PWM comparison of SEPIC and boost converters

5.2.2 *Ripple Analysis*

Fig. 11. compares the ripple levels of the converters. SEPIC demonstrated smaller ripples (1.20%), indicating superior voltage stability and current regulation due to its advanced design and filtering components. Boost, with larger ripples (3.40%), reflects lower stability, potentially leading to power losses and adverse effects on sensitive loads.

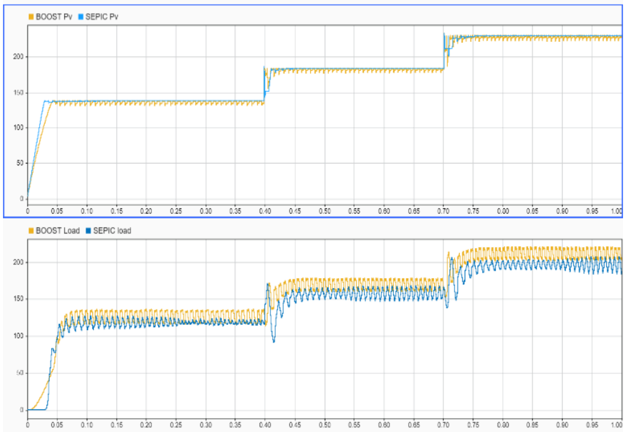


Figure 11: Ripple comparison of SEPIC and boost converters

5.2.3 *Performance Summary*

The performance metrics of SEPIC and boost converters, including battery charging, stability, output voltage, ripple, and peak value. While Boost achieved a slightly higher output voltage (61.5 V vs. 59 V), SEPIC outperformed in battery charging, stability, and ripple reduction, making it a more reliable choice for applications requiring stable and efficient operation as shown in Table 4.

Table 4. Performance Comparison of SEPIC and Boost Converters

Characteristic	SEPIC Converter	Boost Converter
Battery charging	*Fast value*	*Medium value*
Stability	*More stable*	*less stable*
Output Voltage (V)	*59*	*61.5*
Ripple (%)	*1.20%*	*3.40%*
Peak Value (W)	*229.8*	*227*

The simulation results demonstrate that the FLC significantly outperforms the conventional P&O method in photovoltaic applications, achieving approximately 2–5% higher efficiency, faster dynamic response to variations in solar irradiance and temperature, and reduced steady-state oscillations, resulting in more stable power output. In parallel, the comparative analysis of DC–DC converters indicates that the SEPIC converter provides superior overall performance compared to the boost converter, exhibiting lower output voltage ripple (1.20% versus 3.40%), enhanced stability, and more efficient battery charging characteristics, despite the Boost converter delivering a slightly higher output voltage (61.5 V compared to 59 V). These results are supported by a rigorously designed simulation framework, where parameters were selected based on the ARE230W photovoltaic module specifications and standard PV design practices, with a switching frequency of 20 kHz to ensure stable converter operation. Furthermore, the FLC was implemented using a Mamdani inference system with two inputs (error and change in error) and one output (duty cycle), employing triangular membership functions and a rule base validated through iterative simulations, thereby ensuring accurate, robust, and adaptive maximum power point tracking under varying environmental conditions.

6 Case Study

This section presents a case study on the solar energy potential in Yemen, with particular focus on the cities of Sana'a and Aden [12]. Due to the high levels of solar irradiation and favorable climatic conditions of the country, solar energy represents a viable alternative energy source. By examining relevant environmental factors and applying advanced MPPT methods, including FLC and P&O technique, this section evaluates the capability of photovoltaic systems to contribute to addressing Yemen’s ongoing energy challenges.

6.1 *Analysis of Solar Energy Potential*

Environmental and climatic factors significantly influence the performance of PV systems in Yemen. We seek to highlight the importance of adapting PV technology to conditions to enhance energy power and reliability in Yemen's diverse climates [13].

6.1.1 *Sana’a – Yemen*

The direct normal irradiation (DNI) in Sana'a is 2344.2 kWh/m² annually, highlighting its significant potential for solar energy system implementation. Monthly solar energy production data reveal that the highest radiation levels occur in December and January. The average annual air temperature of the city is approximately 18.6 °C further supports the efficient performance of photovoltaic systems, as it provides optimal operating conditions without excessive heat that could reduce efficiency.

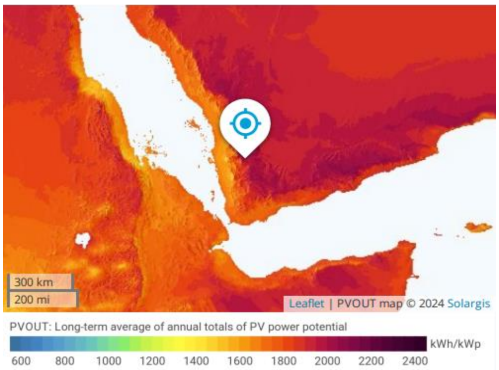


Figure 12. Sana'a location with map of solar potential distribution in Yemen [12]

6.1.2 *Aden – Yemen*

The direct normal irradiation (DNI) in Aden measures 1825.6 kWh/m² annually, which is lower than the DNI in Sana'a. The city's average annual air temperature is approximately 28.2 °C, which is higher than Sana'a.

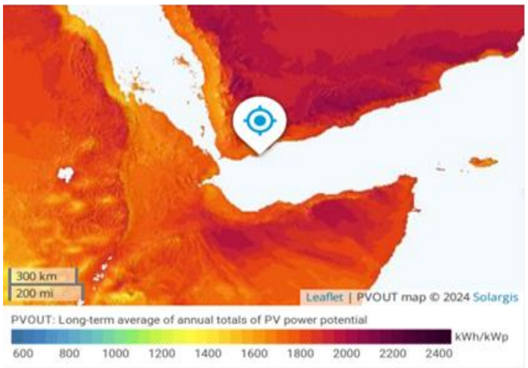


Figure 13. Aden location with map of solar potential distribution in Yemen [12]

The simulation of a solar system utilizing fuzzy logic technology revealed significant insights regarding energy performance in the cities of Sana'a and Aden. By inputting variables of temperature and solar radiation, the analysis demonstrated that Sana'a achieves a higher energy output compared to Aden. Specifically, the energy efficiency in Sana'a is recorded at 91.3%, while Aden lags at 91.9%. This disparity underscores the superior solar energy potential in Sana'a, making it a more favorable location for photovoltaic systems. The findings highlight the importance of local climatic conditions in optimizing solar energy production, further reinforcing the advantages of implementing advanced technologies like fuzzy logic in solar applications.

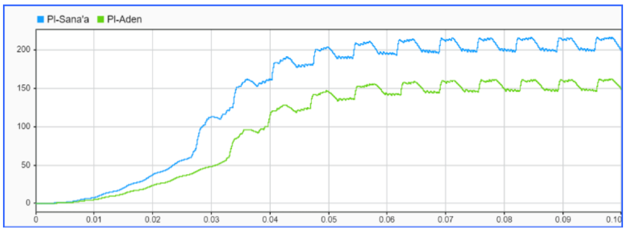


Figure 14. Comparison of power output for Sana'a and Aden

The graphs in Figs. 14 and 15 compare the performance of boost and SEPIC converters using FLC control for photovoltaic systems. SEPIC converter exhibits lower ripple in steady-state operation than boost, indicating improved stability and efficiency under the same conditions.

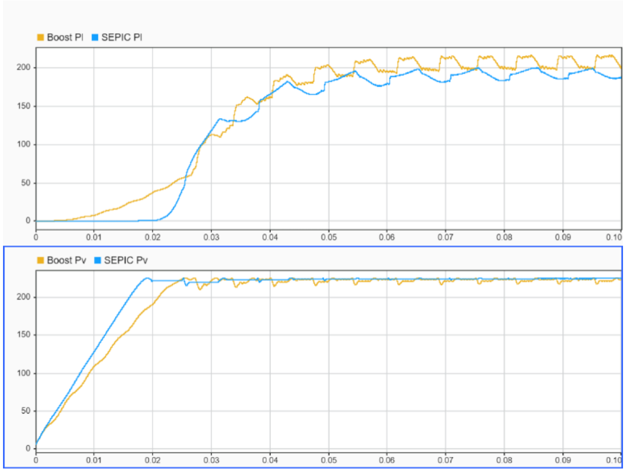
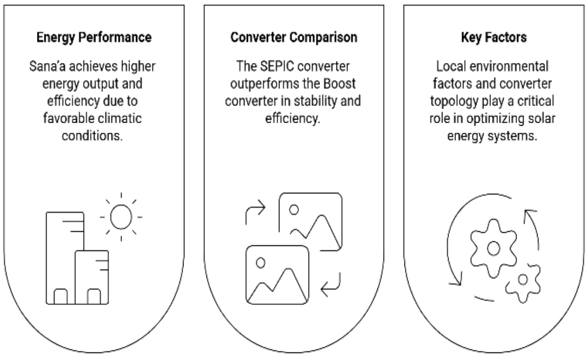


Figure 15: Comparison of power output for boost and SEPIC converters

Sana'a's climatic conditions play a crucial role in enhancing PV system performance due to its relatively high annual solar irradiation of 2344.2 kWh/m² and moderate average temperature of 18.6 °C, which together create an optimal environment for solar energy conversion. Cooler temperatures are particularly beneficial because PV modules generally operate more efficiently under lower thermal stress, reducing energy losses and improving overall electrical output. As shown in Table 5, Sana'a consistently outperforms Aden, which has lower solar irradiation (1825.6 kWh/m²) and significantly higher temperatures (28.2 °C), conditions that can negatively affect PV efficiency due to increased thermal degradation of solar cells. The simulation results confirm this advantage, with Sana'a achieving a higher system efficiency of 93.1% compared to Aden's 91.9%, despite both locations maintaining relatively strong performance. Additionally, the seasonal variation in peak energy production highlights how environmental patterns influence system behavior: highest output in case of Sana'a occurs in December, January, and October, aligning with clearer skies and cooler weather, while peaks in case of Aden in March, April, and October reflect its different solar and temperature dynamics. Overall, the comparison illustrates that while both cities are suitable for solar energy deployment, Sana'a offers a more stable and efficient operating environment, whereas the higher temperatures of Aden introduce performance limitations that slightly reduce system efficiency.

Table 5. Summary of the comparison between Sana'a and Aden

Criterion	Sana'a	Aden
Annual Solar Irradiation	2344.2 kWh/m²	1825.6 kWh/m²
Average Annual Temperature (°C)	18.6 °C	28.2 °C
Months with Highest Output	December, January, October	March, April, October
System Efficiency (Simulation) (%)	93.1%	91.9%



Energy Performance

Sana'a achieves higher energy output and efficiency due to favorable climatic conditions.

Converter Comparison

The SEPIC converter outperforms the Boost converter in stability and efficiency.

Key Factors

Local environmental factors and converter topology play a critical role in optimizing solar energy systems.

Figure 16: Solar System Simulation Insights

7 CONCLUSION

This study investigates the optimization of photovoltaic (PV) system performance through the application of maximum power point tracking (MPPT) techniques and different DC–DC converter topologies. The results demonstrate that the fuzzy logic controller (FLC) outperforms the conventional perturb and observe (P&O) method by achieving higher efficiency in tracking the maximum power point, particularly under rapidly varying solar irradiance and temperature conditions. In addition, the comparative analysis of converter topologies reveals that the SEPIC converter provides superior performance compared to the boost converter, especially in terms of reduced output ripple and improved voltage stability. Although the boost converter produces a slightly higher output voltage, its increased ripple and lower stability make it less suitable for applications requiring consistent power quality. Furthermore, the case study of solar energy potential in Yemen indicates that the integration of advanced MPPT techniques with SEPIC converter topology can significantly enhance the overall energy output of PV systems. This work lies in the development of a comprehensive simulation-based PV model using real environmental data from Sana'a and Aden, the comparative evaluation of FLC and P&O MPPT techniques under realistic climate conditions, the integration of these control strategies with SEPIC and boost converter topologies within a unified simulation framework, and a detailed performance assessment in terms of efficiency, dynamic response, and output stability under varying environmental conditions.

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