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Original Article

Performance Optimization of Photovoltaic Systems in Yemeni Cities: A Comparative Analysis of Fuzzy Logic and Perturb & Observe MPPT under Environmental Variability

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Abstract - *Environmental conditions greatly influence the operational efficiency, lifespan, and reliability of solar photovoltaic (PV) systems. This study exhaustively examines the impact of thermal fluctuations and solar irradiance variation on the performance of PV systems in selected Yemeni cities. A MATLAB-based simulation environment is developed to study the system behavior under these dynamic environmental conditions, exploiting the latest computational techniques. A comparative study of the Fuzzy Logic Controller (FLC) and the conventional Perturb & Observe (P&O) maximum power point tracking (MPPT) algorithm is presented in detail. It is noted that FLC is more adaptive, with 2–5% efficiency improvement and faster convergence against environmental perturbations. The study also examines the effects of these differences on energy yield, conversion efficiency, and system stability in general. By integrating intelligent control strategies, this research underscores the potential of new MPPT methods in optimizing the harnessing of solar energy in the face of Yemen's hostile climatic conditions. The findings suggest the deployment of intelligent energy management systems to enhance the robustness of PV systems, ensuring enhanced performance and sustainability under desert conditions.*

Keywords - *Environmental condition, solar irradiation, Temperature, photovoltaic system, Maximum Power Point Tracking, Fuzzy Logic Controller (FLC), MATLAB Environment and Yemen.*

1. Introduction

The production of electricity and power generation refers to the process of converting initial energy sources such as thermal, wind, solar, and chemical energy into electric energy [1]. Human civilization has depended upon renewable energy resources throughout history.

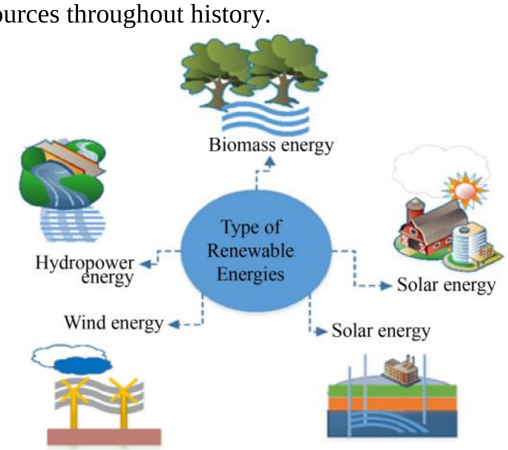

Fig. 1 The types of renewable energy resources [4]

Humans have used biomass for centuries to create steam and generate power for heating and cooking. Water and wind have further been used in transportation and ultimately for electricity generation and power. As illustrated in (Figure 1), most renewable energy technologies are rooted in the Earth's natural energy flows, including solar radiation and geothermal conduction of heat [2-3].

Solar energy, in particular, can convert electrical and thermal energy through photoelectric and thermal conversion processes. Photoelectric conversion is a direct process where solar radiation is converted to electricity by using Photovoltaic (PV) cells. This is achieved through semiconducting materials like silicon and germanium, which enable the photoelectric effect- a phenomenon discovered in the 19th century and later theoretically explained by Albert Einstein, for which he was awarded the Nobel Prize in Physics in 1921 [3].

Solar energy generation efficiency largely depends on climatic conditions; hence, proper Maximum Power Point

Tracking (MPPT) techniques must be used to achieve optimal performance. However, despite significant solar technology progress, there remains a critical research gap to deal with in neutralizing the challenges brought about by environmental variability, particularly where the climatic environment is hostile.

Performance and stability of PV systems are significantly affected in most of the developing world, including Yemen, by extreme temperatures, intermittent solar radiation, and other environmental conditions. Common conditions typically lead to suboptimum energy collection, reduced system efficiency, and higher operation costs.

Yemen, being endowed with rich solar resources, offers the chance to investigate these challenges. However, the nation's unfriendly desert environment presents mainly high temperatures and fluctuating solar irradiance, which are severe hurdles to fully utilizing solar PV systems. Although traditional MPPT methods like Perturb & Observe (P&O) have become very popular, the high likelihood of inability to adjust to high-speed solar irradiance changes introduces inefficiencies and energy loss. Furthermore, the lack of advanced control methods designed to accommodate Yemen's special climatic conditions is a factor in the aggravation of the problem.

In this study, the gap will be bridged through a comparative analysis of two MPPT techniques: the conventional P&O algorithm and the adaptive FLC. Through a simulation platform built on MATLAB, the research compares the performance of these techniques under varying environmental conditions typical of Yemeni cities. Through the integration of smart control methods, this work aims to enhance solar energy utilization with increased performance, sustainability, and resilience of PV systems under the adverse climatic conditions prevailing in Yemen.

The findings bring to the surface the potential of advanced MPPT methods for mitigating the adverse effects of environmental variations, paving the way for more efficient and resilient solar energy systems in arid climatic conditions.

2. Literature Review

Improvement of Photovoltaic (PV) system performance has been a subject of interest for most researchers with the increased demand for clean, renewable energy worldwide. The surrounding conditions, as characterized by solar irradiance and temperature, have tremendous impacts on the reliability and efficiency of PV systems, as posited by experts like Kaygusuz [3] and Hsieh [9]. These researches highlight the importance of optimizing energy harvesting through advanced control methods, particularly Maximum Power Point Tracking (MPPT) techniques, which are crucial in maintaining optimal system performance under fluctuating environmental conditions.

One of the most popular MPPT methods is the Perturb & Observe (P&O) algorithm because it is simple and easy to implement. However, as Athira et al. [12] discussed, the conventional P&O technique suffers from inefficiencies and oscillations around the maximum power point under rapidly changing environmental conditions. In reaction to this limitation, researchers have explored other hybrid MPPT methods that can address the challenges posed by dynamic climatic conditions.

Fuzzy Logic Controllers (FLC), an artificial intelligence (AI)-based control technique, have emerged as a promising solution to ensure the maximum flexibility and resilience of PV systems. Jamshidi et al. [11] mention the capability of FLC to handle nonlinear systems and improve convergence speed and accuracy over traditional MPPT methods. Similarly, Chitturi et al. [6] demonstrated the effectiveness of intelligent control methods for hilly terrain, wherein environmental variations are the primary challenges to PV output. Their research accords with the prevailing focus on the exploitation of novel MPPT algorithms for optimal energy harvesting in challenging climatic conditions.

There have been several studies probing the prospects of solar energy in arid and semi-arid regions, emphasizing the need for geographical and climatic conditions in controlling the energy yield. For instance, Al-Wesabi et al. [5] systematically reviewed Yemen's energy situation and concluded that solar energy effectively addresses the nation's electricity access deficit. They stressed the need for decentralized solar systems and advanced solutions to mitigate the destructive effects of Yemen's arid desert climate. Besides, Avtar et al. [4] used remote sensing and GIS technologies to assess renewable energy resources globally and derive meaningful information about the geographical distribution of solar potential in nations like Yemen.

Despite such advancements, the literature lacks much-needed coverage on utilising advanced MPPT techniques suitably conditioned for local climatic conditions, particularly in developing countries. While studies such as Bangert [1] and Zohuri and McDaniel [2] have touched upon machine learning and AI-based methods in some general frameworks of energy systems, relatively minimal effort has been devoted to specifically applying them to PV systems operating under extreme environmental vagaries. The present investigation attempts to bridge this shortcoming by comparing FLC and P&O algorithms operating under Yemeni city-specific weather conditions.

Drawing on the foundation established by previous researchers, this study contributes to the knowledge about renewable energy systems by addressing the special challenges faced by regions with extreme environmental conditions. The findings validate the superiority of intelligent control approaches like FLC and provide practical recommendations for optimizing PV performance in desert environments. This work emphasizes the significance of adopting better MPPT methods to adapt to environmental conditions on local scales, leading the path to more sustainable and resilient solar-driven systems.

3. Role of Yemen’s Geography and Climate in Shaping Solar Energy Potential and Future Prospects

Yemen's diverse geography and climatic environments are of prime significance in determining the viability and efficiency of solar energy generation. The operation of Photovoltaic (PV) systems is inherently dependent upon environmental conditions because changes in the parameters can profoundly influence power production during the daylight period. Environmental determinants—such as solar irradiance and ambient temperature—directly influence the solar power generation's efficiency and aggregate energy output. The Republic of Yemen is strategically located in the Middle East, between latitudes 13°N and 16°N and longitudes 43.2°E to 53.2°E in Southwest Asia, as shown in (Figure 2). The Republic is characterized by mountainous regions and coastal plains along the south and west. The capital and largest city, Sana'a, is the economic and political center of the country.

Fig. 2 Map of Yemen

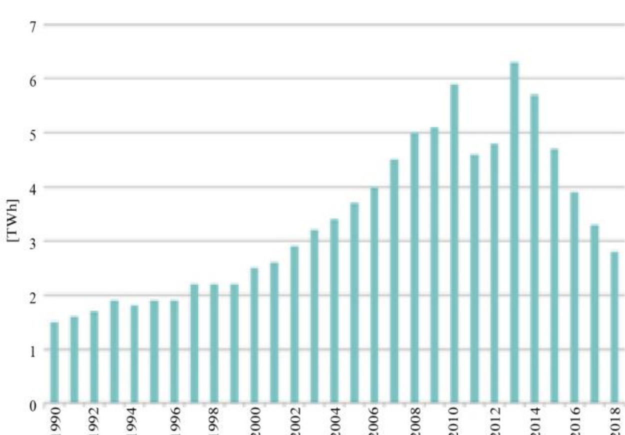

Fig. 3 Yemen's electricity consumption from 1990 to 2018

Yemen's electricity use has demonstrated significant growth since the late 1990s, reaching a peak around 2014 before decreasing due to the ongoing conflict, as indicated in (Figure 3). Total electricity use, measured in terawatt-hours (TWh), indicates a consistent rise over the long term due to population growth, economic development, and industrialization. Despite the recent fall, overall electricity demand remains significant [5].

Historically, electricity generation in Yemen has also been dominated by fossil fuel sources, primarily oil and natural gas, with a steady growth curve of production that peaked around 2014. Since the early 2010s, there has also been a movement towards a gradual transition away from fossil fuels, with a gradual but steady increase in the contribution of solar Photovoltaic (PV) power to the energy mix. The prevailing trend foresees an increasing dependence on hydrocarbons, supported by an emerging trend towards renewable energy sources, as evident from (Figure4).

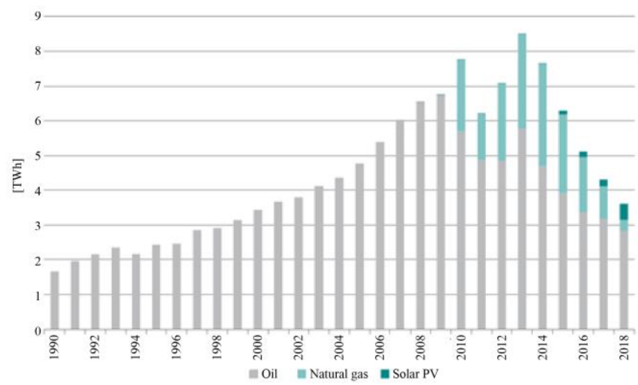

Fig. 4 Yemen's electricity generation from 1990 to 2018

The future development of solar energy in Yemen hinges on numerous factors, from government policy to economic stability and the development of solar technologies. Key drivers of this change are:

Solar Resource Availability: Yemen is exposed to substantial amounts of solar radiation throughout the year, making solar energy a viable and potential renewable resource.

Energy Demand and Access: The country has enormous challenges in ensuring reliable access to electricity. Decentralized solar energy systems can be an efficient solution to fill this energy gap.

Cost Competitiveness: Lowering the cost of solar photovoltaic technology renders solar energy investment more financially viable, inducing mass deployment.

Energy Security and Independence: Solar energy's increased capacity can suppress dependence on imported fossil fuels, rendering Yemen's energy more secure and facilitating long-term sustainability.

Considering these factors, the construction of solar energy infrastructure is a critical opportunity to enhance Yemen's energy resilience and accelerate its transition to a more sustainable energy system [6]

4. Advanced Photovoltaic Technology: Principles, Solar Irradiation, and Thermal Effects

4.1. Photovoltaic Technology

The term "Photovoltaic" (PV) is derived from the Greek words for "light" and "electromotive force." Photovoltaic modules enable the direct conversion of light into electrical energy through the photovoltaic effect in semiconductor material. Commercial PV panels exhibit conversion efficiencies ranging from 17% to 26%, but state-of-the-art crystalline silicon solar cells have reached efficiencies of almost 50% under laboratory conditions. The fundamental principle of PV operation is based on the interaction of incident photons and semiconductor material, predominantly silicon. Photons incident on a PV cell have enough energy to excite electrons, releasing them from their bonds to atoms. This process generates an electric field in the p-n junction, thereby inducing the directional flow of charge carriers, as shown in **(Figure 5)**. For maximum energy harvesting, PV cells are integrated with electrical contacts to facilitate charge collection, while anti-reflective coatings minimize optical losses by reducing light reflection [7].

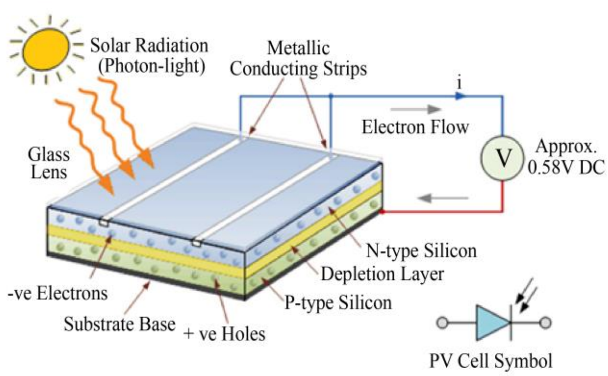

Fig. 5 Construction of a solar cell

4.2. Solar Irradiation

Solar radiation is the total electromagnetic energy from the Sun that reaches a spot on the Earth's surface. Despite the vast total irradiative output of the Sun—estimated at approximately 131 MW/m² at its surface—only an exceedingly small fraction (~1 part in 2 billion) reaches the Earth. Nonetheless, this energy input is the primary driver for terrestrial thermal dynamics and atmospheric activity [8].

The Sun's irradiance at a location on the Earth's surface, typically measured in watts per square meter (W/m²), is regulated by several key parameters, including:

The angle of incidence of the sunlight on the surface.

Air mass, aerosols, and clouds cause losses in the atmosphere.

Time-dependent variations, including diurnal, seasonal, and latitude-dependent changes.

The solar constant represents the intensity of extraterrestrial solar radiation—when received by a perpendicular surface at a mean Earth-Sun distance—and its value is approximately 1361 W/m². The correction factor for day-to-day solar radiation variation is:

$$I = I_0 \left[1 + 0.034 \cos\left(\left(N_j - 2\right)\frac{360}{365}\right)\right] \tag{1}$$

Where

I am the adjusted solar irradiance, I_0 is the solar constant, and N_j represents the Julian day of the year

4.3. Temperature and Its Effect on PV Performance

Temperature is a fundamental physical property for the average kinetic energy of particles in a material, conventionally measured in degrees Celsius (°C), Kelvin (K), or Fahrenheit (°F). The temperature coefficient of a photovoltaic module quantifies the sensitivity of key electrical parameters—such as power output (P), open-circuit voltage (V_{oc}), and short-circuit current (I_{sc})—to changes in temperature [9]. PV module manufacturers typically specify temperature coefficients under Standard Test Conditions (STC), which serve as reference parameters for performance evaluation. A datasheet of a commercial PV module specifies temperature coefficients for the power, V_{oc}, and Isc under STC conditions, as shown in (Figure 6).

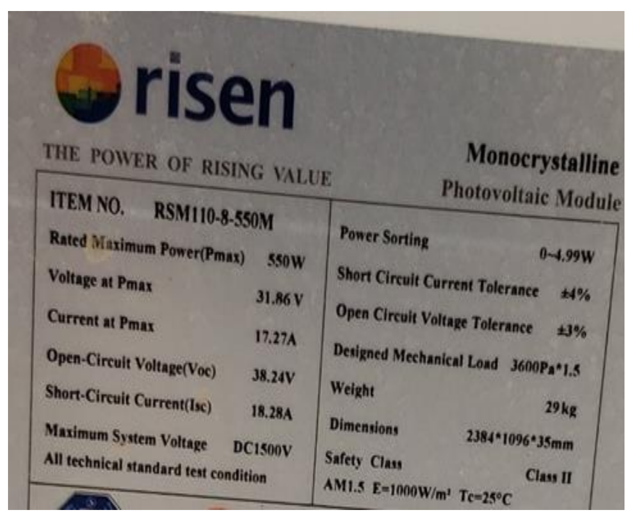

Fig. 6 A datasheet of a commercial PV module

$$V = V_{STC} + V_{T\text{-}coeff} \times (T_{Cell} - 25)^{\circ}C \tag{2}$$

$$P = P_{STC} + P_{T\text{-}coeff} \times (T_{Cell} - 25)^{\circ}C \tag{3}$$

Where:

- V and P represent the voltage and power at a given cell temperature T_{Cell}.
- V_{STC} and P_{STC} denote voltage and power under STC (25°C, 1000 W/m², Air Mass (AM1.5) spectrum).

$V_{T\text{-coeff}}$ and $P_{T\text{-coeff}}$ are the temperature coefficients for voltage and power, respectively.

Understanding and minimising temperature-induced performance loss is crucial to attaining optimum PV system efficiency, particularly in high-temperature climates where excess heat generation can adversely impact module efficiency.

5. Impact of Environmental Conditions on the Efficiency and Optimization of Photovoltaic Systems in Yemen: A Comparative Analysis of Sana'a and Aden

Environmental conditions significantly affect the performance and operation efficiency of Yemen's Photovoltaic (PV) systems. Gaining in-depth insights regarding climatic parameters is essential to ensure high energy output since parameters such as ambient temperature and direct normal irradiation (DNI) directly affect the solar power system's efficiency and reliability.

This study aims to provide an extensive assessment of these environmental factors regarding the implementation of Maximum Power Point Tracking (MPPT) techniques, i.e., Fuzzy Logic Control (FLC) and Perturb and Observe (P&O). Underlying all these analyses, we pinpoint the significant role played by artificial intelligence (AI)-based techniques in enhancing efficiency in energy conversion as well as system dependability in response to climatic uncertainty [10-11]

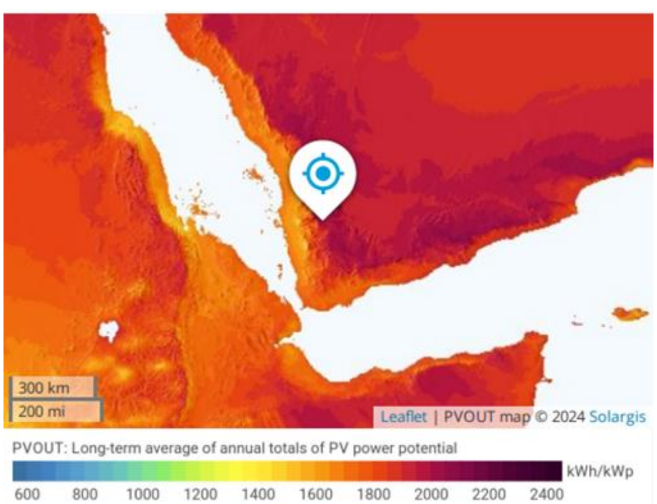

Fig. 7 Sana'a location with Map of Solar Potential Distribution in Yemen [10]

5.1. Sana'a – Yemen

Sana'a, Yemen's capital city, possesses a distinct geographical and climatic profile that greatly influences solar energy production, as observed in (Figure 7). The city receives an annual DNI of 2344.2 kWh/m², reflecting good solar energy potential suitable for photovoltaic use.

The mean monthly solar energy yield in Sana'a varies considerably with the season, as seen from (Figure 8). The solar generation is primarily localized between 8:00 AM and 4:00 PM and occurs at its peak during late morning to early afternoon hours.

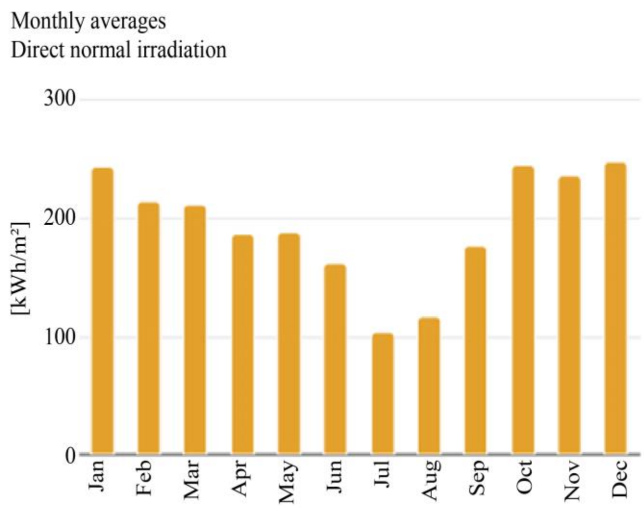

Fig. 8 Monthly average of DNI in Sana'a [10]

The mean temperature of Sana'a is approximately 18.6°C, a relatively intermediate thermal condition to ensure PV performance, as excessive heat is notoriously known to skew photovoltaic efficiency. Therefore, the high DNI and intermediate ambient temperature create an ideal ambience for solar utilization in Sana'a.

These climatic features emphasize the necessity of applying advanced MPPT algorithms, such as FLC and P&O, to maximize energy harvesting and counteract environmental variations affecting system performance.

5.2. Aden – Yemen

Aden, the economic centre of Yemen and a coastal urban area, also has varying climatic conditions compared to Sana'a, as evident in (Figure 9). The city enjoys an average annual DNI of 1825.6 kWh/m², which, though lower than for Sana'a, is quite high for conversion by photovoltaic energy.

The mean DNI of 1825.6 kWh/m² is a considerable solar resource that can be used economically for power production. However, the energy yield in Aden varies considerably throughout the year, as shown in (Figure 10), with the highest production occurring in the late morning and early afternoon.

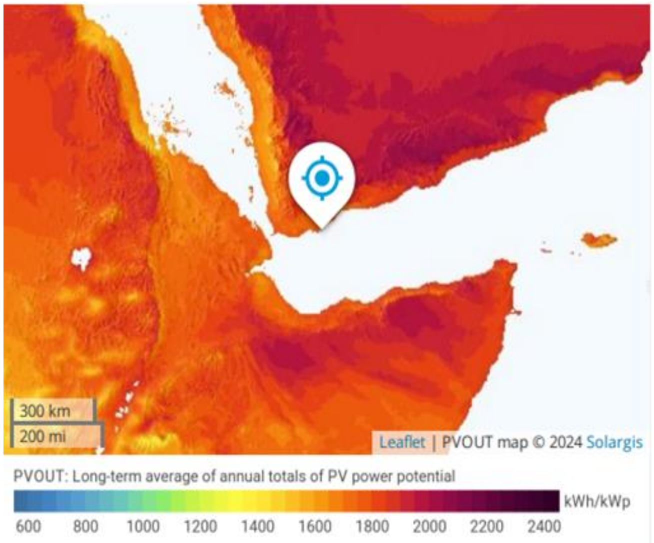

Fig. 9 Aden location with Map of Solar Potential Distribution in Yemen [10]

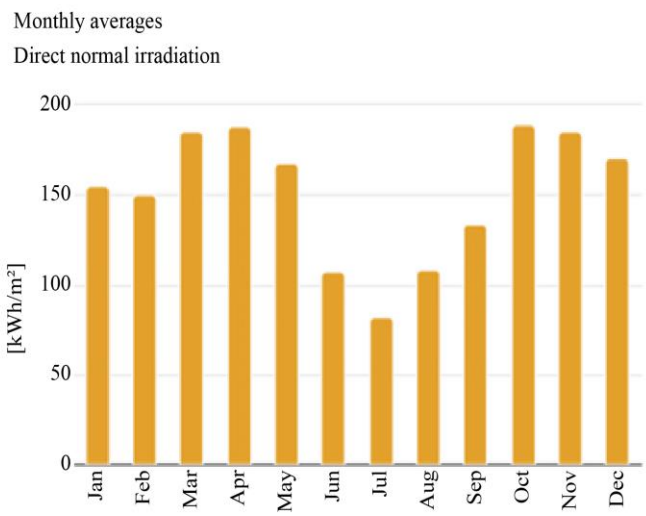

Fig. 10 Monthly average of DNI in Aden [10]

Aden's mean annual temperature is around 28.2°C, significantly larger than that of Sana'a. High temperatures can elevate solar energy conversion efficiency under moderate conditions, but excessive heat leads to thermal losses, thereby reducing the efficiency of PV systems. However, Aden's coastal position can be advantageous in terms of passive cooling of systems, which could partially offset the adverse thermal effects.

5.3. Comparative Analysis

While both cities offer substantial solar energy potential, the higher DNI of Sana'a elevates its photovoltaic efficiency and makes it a more attractive location for solar energy installation, as shown in (Figure 11). However, the oceanic climate of Aden could provide natural cooling benefits that could counterbalance temperature-related degradations in PV system performance.

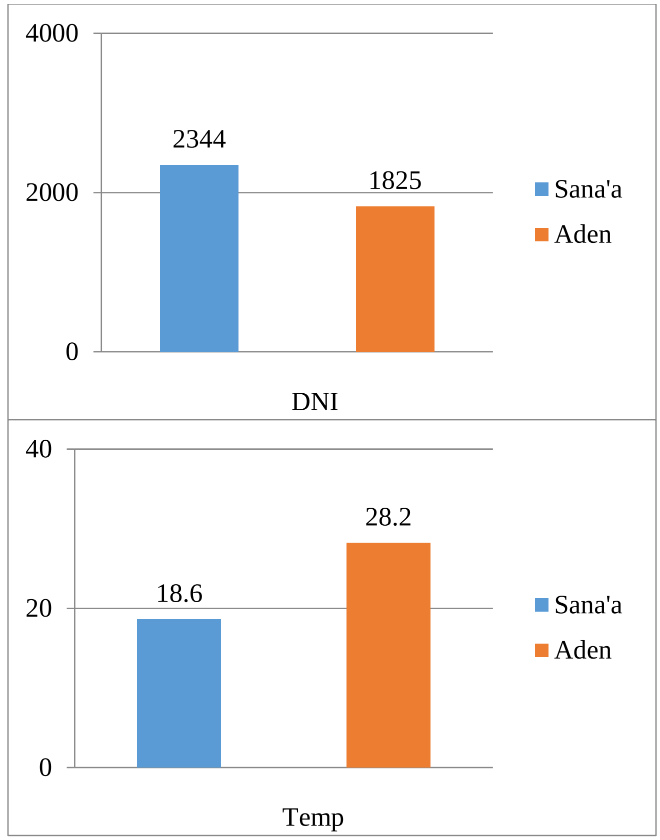

Fig. 11 Comparison between Sana'a and Aden in temperature and solar radiation

Due to climatic uncertainty between the two regions, MPPT techniques must be tailored according to the demands to enhance solar energy conversion efficiency. Intelligent control strategies, such as AI-based MPPT algorithms, can also be incorporated to enhance system adaptability and reliability to varying environmental factors.

6. Advanced Simulation and Performance Analysis of a Hybrid Photovoltaic Control System

The proposed system, illustrated in (Figure 12), is modeled by the following components:

- ARE230W solar panel model.
- Input parameters for the solar panel, i.e., temperature and solar irradiance.
- Fuzzy Logic Controller (FLC).
- Perturb and Observe (P&O) Controller.
- Boost Converter.

Besides, an inter-switch mechanism that switches between the FLC controller and the P&O controller enables performance comparison of control strategies based on performance criteria. This arrangement maximizes the photovoltaic power system's overall efficiency and running reliability.

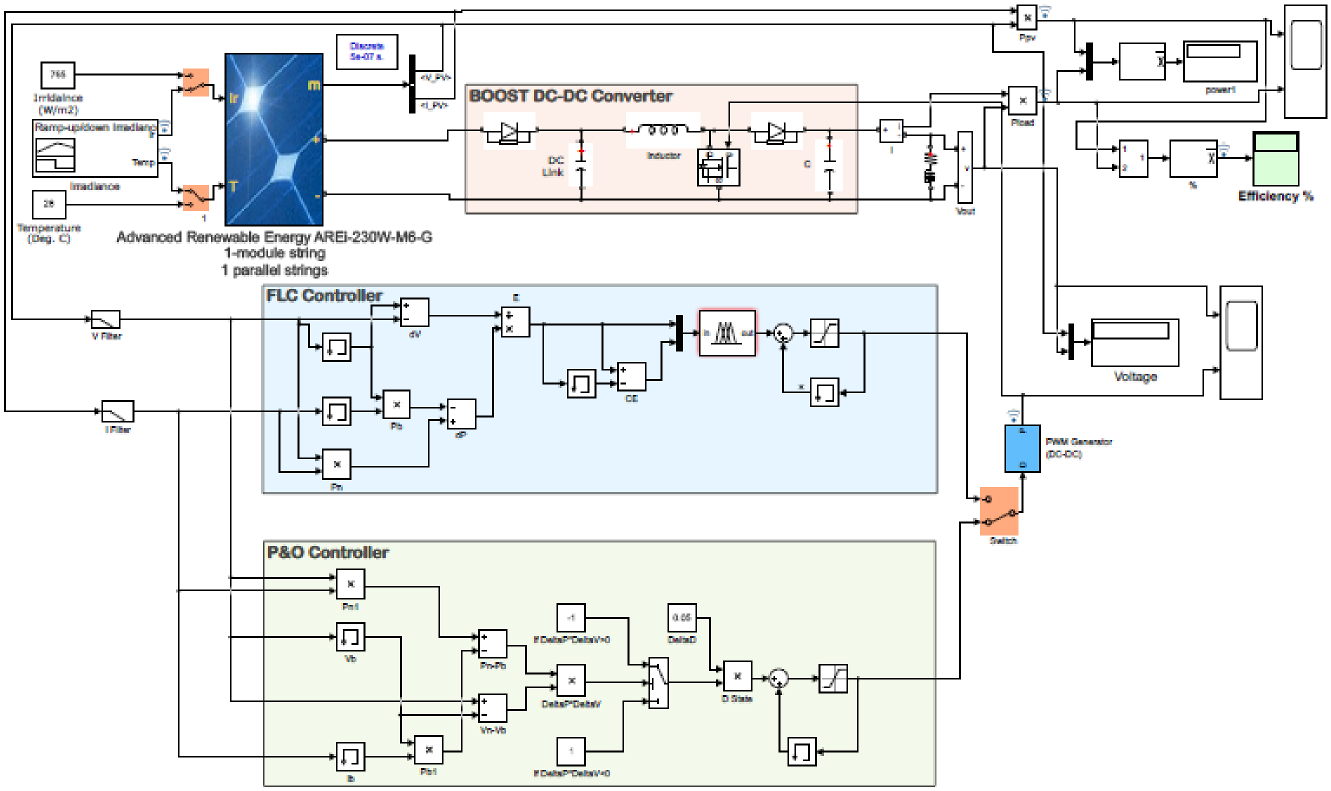

Fig. 12 Simulation of Modeling System

7. Environmental Parameterization and Performance Metrics of a Photovoltaic System

The model incorporates key environmental parameters such as temperature and solar irradiance that directly affect the power output of the photovoltaic (PV) panel. The inputs may be dynamically varied in the simulation environment to determine system performance under varying actual conditions. The study primarily investigates the effect of solar irradiance and temperature on the efficiency and behavior of the system in Sana'a and Aden cities.

7.1. Solar Irradiance

Solar irradiance readings, accessed from climatic data available, were taken in both cities for specific time frames:

Sana'a: The highest solar irradiance recorded was 967 Wh/m² in December.

Aden: The highest solar irradiance was 765 Wh/m² in November.

7.2. Temperature Conditions

Solar irradiance in each city is associated with some midday temperature conditions:

Sana'a: The temperature measured was 21°C.

Aden: The temperature measured was 28°C.

The influence of wind speed and humidity on PV system performance was deemed negligible for this study since their comparatively lesser impact was being compared with solar irradiance and temperature. Although these parameters might affect panel efficiency to a lesser degree, their impact is far less than the impact of irradiance and temperature variations, as shown in earlier studies [12].

8. Results

8.1. Impact of Temperature on the Output Power of PV

Temperature plays a significant role in affecting the performance of solar panels. With an increased ambient temperature, most solar panels' performance decreases, reducing their power output. (Figure 13) illustrates the performance of a 230-watt solar panel as the temperature increases from 5°C to 45°C under constant solar radiation of 1000 W/m².

8.2. Impact of Photovoltaic Radiation on the Output Power of PV

The power output from the photovoltaic panel is directly proportional to the solar irradiance incident upon the panels. Solar panels produce electrical power from sunlight based on the photovoltaic effect and operate based on the intensity of solar radiation. (Figure 14) shows how the variation in the solar radiation levels (600 W/m², 800 W/m², and 1000 W/m²) influences the power output of a 230-watt-rated panel.

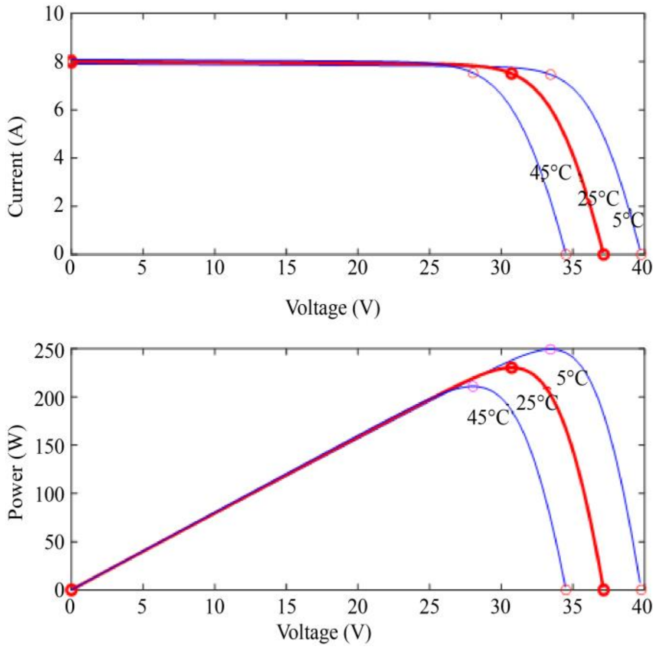

Fig. 13 I-V&P-V characteristics curve at different Temperate with irradiation of 1 kW/m2

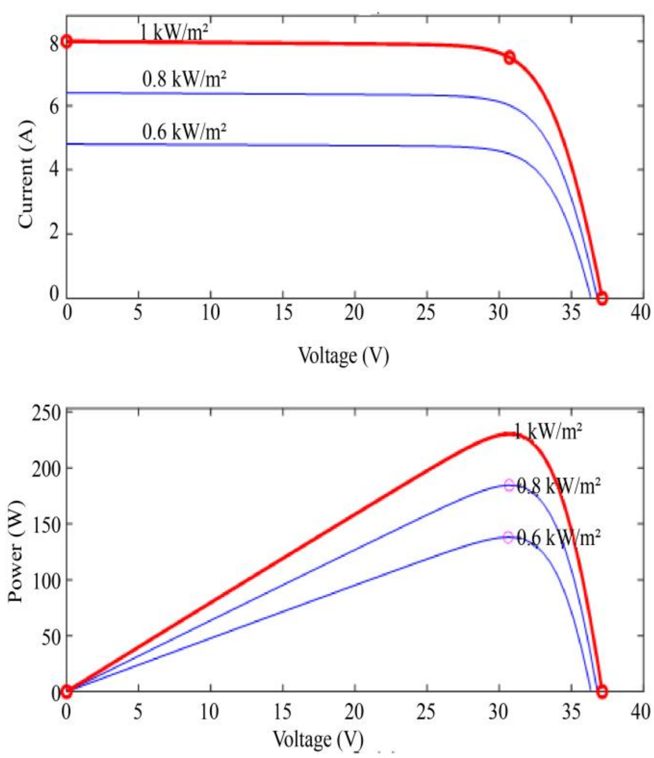

Fig. 14 I-V & P-V characteristics curve with different irradiation at Temperature of 25 °C

8.3. Comparative Analysis between Sana'a and Aden

Including temperature and solar irradiance variables, the simulation results indicate that Sana'a has a greater energy output than Aden. More specifically, the energy efficiency in Sana'a is 93.1%, whereas a lower efficiency of 91.9% is found in Aden, as shown in (Figure 15).

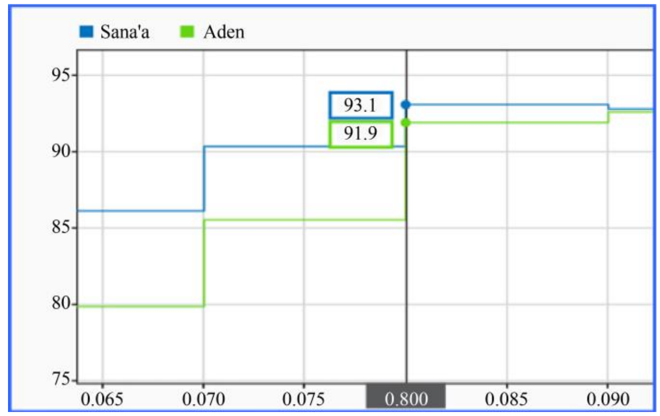

Fig. 15 Efficiency of power in Sana'a and Aden

Power outputs in both cities, under varying solar conditions, are compared in (Figure 16). The results indicate that Sana'a experiences higher power outputs than Aden, with the highest measured values of 198.2 W and 151.5 W for the load power (PL) and 224.6 W and 173.8 W for the PV output. These differences are primarily a result of the higher solar irradiance in Sana'a. The minor differences observed in the graphs are due to the fluctuations in sunlight intensity and temperature, which affect system performance.

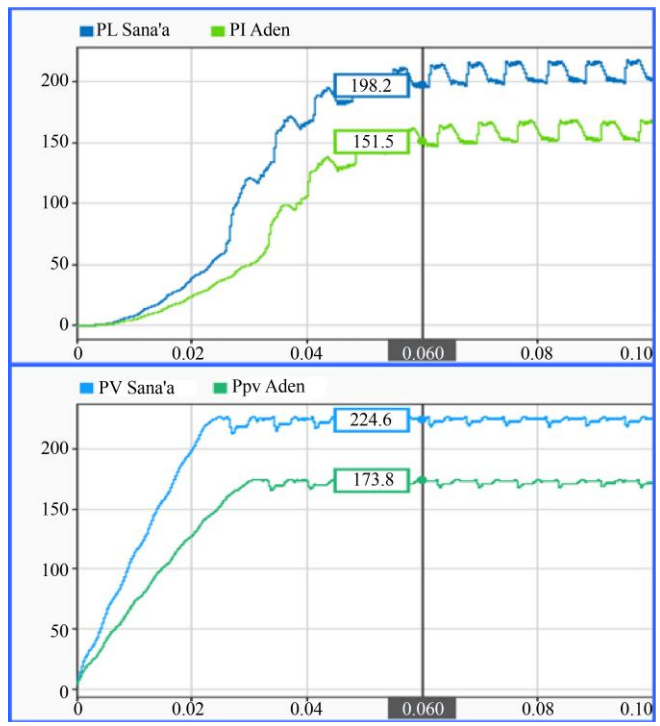

Fig. 16 Power Output Comparison of PL and PV Systems in Sana'a and Aden

8.4. Changes in Solar Irradiance and Temperature Using a Fuzzy Logic Controller

Temperature and solar irradiance variations are important to PV systems' power output. The result indicates an improved response of the Fuzzy Logic Controller (FLC) in adapting to environmental changes. The power response of the FLC is more efficient and faster than that of the Perturb and Observe (P&O) method. (Figure 17) shows a comparison of performance between the two control strategies, indicating that the FLC has a more desirable power output of 198.0 W than the P&O scheme, which achieves only 159.6 W under the same fluctuation conditions of solar radiation.

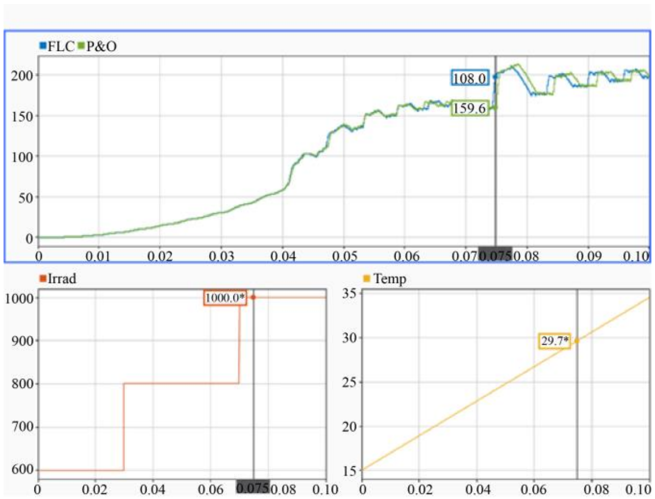

Fig. 17 Changes in Solar Irradiance and Temperature Using a Fuzzy Logic Controller

9. Dissections

The comparative investigation carried out in this research work brings to the forefront the enhanced performance of Photovoltaic (PV) systems with the Fuzzy Logic Controller (FLC) compared to the traditional Perturb & Observe (P&O) algorithm. Various reasons are responsible for these better results, which are elaborated upon in the following sections.

9.1. Adaptive Nature of FLC

One of the major reasons FLC performs better is because of its adaptive nature. Compared with the P&O method, which has fixed perturbation steps, FLC also has control actions that vary dynamically based on real-time environmental conditions. Thus, the FLC is better following abrupt solar irradiance and temperature changes, and the PV system is always or near operating at the Maximum Power Point (MPP). According to Jamshidi et al. [11], FLCs are highly appropriate for controlling nonlinear systems and, hence, highly suitable for PV systems where environmental conditions can change drastically.

9.2. Better Convergence Speed and Accuracy

FLC converged to the MPP more quickly than the P&O method. As can be seen from Figure 17, the FLC was capable of achieving 198.0 W output power under changing solar radiation conditions. In contrast, the P&O algorithm alone could only achieve 159.6 W. This convergence speed and accuracy improvement is critical to achieving high efficiency and optimal energy output, especially for regions with significantly changing climatic conditions like Yemen. FLC minimizes oscillations around the MPP and boosts its efficiency, as per Athira et al. [12].

9.3. Comparison with Contemporary Literature

Whereas several studies have commented on the deployment of advanced MPPT techniques, the literature lacks adequate information relating to their execution in specific local climatic settings, particularly in the developing world. For example, Bangert [1] and Zohuri and McDaniel [2] have alluded to machine learning and AI techniques in generic energy system scenarios, albeit briefly, without many direct addresses of their usage within PV systems operating in a scenario of great environmental uncertainty.

This study fills the gap by comprehensively assessing FLC and P&O performance in Yemeni city-specific weather, contributing considerably to renewable energy system research. The application of Yemen's special climatic problems in this work underscores the necessity of adapting MPPT approaches to environmental conditions in a local context.

The findings not only reiterate the superiority of intelligent control techniques like FLC but also provide pragmatic recommendations on how to optimize PV efficiency in dry climatic environments. This work emphasizes the necessity of adopting advanced MPPT techniques to adapt climate conditions on regional levels towards the development of more resilient and sustainable solar-powered systems.

9.4. Improved Energy Harvesting Efficiency

The simulation results show that the FLC-based MPPT technique improves the energy harvesting efficiency by 2–5% compared to the P&O method. This improvement is higher under conditions of extreme temperatures and changing solar irradiance. For instance, in Sana'a, the energy efficiency was 93.1% with FLC, compared to 91.9% in Aden with P&O, as indicated in Figure 15. These findings demonstrate the ability of FLC to minimize the adverse effect of environmental variability in optimizing the use of solar energy [12].

9.5. Robustness under Dynamic Environmental Conditions

The second most important advantage of the FLC is its stability under dynamic environmental conditions. Traditional P&O algorithms suffer from rapid environmental changes, leading to inefficiency and energy losses. The FLC, however, with its ability to adapt quickly to the variation in solar irradiance and temperature, ensures steady and reliable performance. This strength is particularly beneficial in desert climates like Yemen, where extreme temperatures and varying solar irradiance pose a grave challenge to the efficiency of PV system operation [10].

9.6. Practical Implications and Future Directions

The practical implications of these findings are tremendous. By integrating intelligent control strategies like FLC, PV systems can achieve better performance, sustainability, and resilience under harsh climatic conditions.

This research validates FLC's superiority and provides practical guidelines for optimizing PV performance in desert climates. Future research is suggested to explore hybrid MPPT approaches that combine the strengths of various techniques, including machine learning and AI-based optimization, to enhance PV system adaptability and stability [1].

10. Conclusion

The study satisfactorily explored the effects of weather on the performance and efficiency of Photovoltaic (PV) systems in the Yemeni cities of Sana'a and Aden.

The findings highlight the roles played by solar irradiance and temperature in determining PV power output, with more solar radiation leading to increased energy generation and high temperatures adversely influencing efficiency via voltage degradation.

The comparative analysis of Aden and Sana'a revealed that Sana'a possesses greater solar energy potential due to its improved solar irradiance and moderate temperatures, leading to more effective energy conversion efficiency. However, the sea climate in Aden possesses potential for passive cooling, and this can counteract temperature-related efficiency losses to some extent.

Also, the research verified the efficiency of advanced Maximum Power Point Tracking (MPPT) techniques to optimize PV performance. The MPPT based on FLC, in particular, exhibited a faster response time and improved energy harvesting than the conventional Perturb and Observe (P&O) strategy, testifying to its relevance to changing environmental conditions.

With the growth of Yemen towards augmented integration of renewable energy, technological advancement and the development of efficient solar technologies along with intelligent MPPT methods will be the key to achieving energy robustness and sustainability. Artificial intelligence-based optimization and hybrid MPPT approaches are fields that need to be addressed in the coming times for enhanced PV system adaptability and stability over climatic conditions.

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