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Maximum Power Point Tracking Based on Zebra Optimization Algorithm (ZOA) considering varying irradiation.

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ABSTRACT
The efficiency of solar photovoltaic (PV) systems depends heavily on their ability to run at the Maximum Power Point (MPP) under varying environmental conditions. This paper presents a novel approach to Maximum Power Point Tracking (MPPT) using the Zebra Optimization Algorithm (ZOA), a nature-inspired optimization technique that mimics the social behaviours of zebras. ZOA is adapted for dynamic MPPT applications by adjusting the operating voltage of the PV system to maximize power output. Unlike traditional algorithms, ZOA demonstrates an effective balance between exploration and exploitation, making it well-suited for rapidly changing irradiation conditions. Under varying irradiance profiles, the algorithm tracks the best power point efficiently, achieving a faster response and minimizing power losses. Simulation results in MATLAB software confirm that ZOA-based MPPT exhibits high robustness, rapid convergence to the global MPP, and improved adaptability to changing solar conditions, thereby enhancing the energy yield of PV systems. This study highlights the potential of ZOA as a competitive MPPT technique in solar energy applications, particularly under fluctuating irradiance.
Keywords: Maximum Power Point Tracking (MPPT), Photovoltaic (PV) system, Zebra Optimization Algorithm ZOA), Solar irradiation

INTRODUCTION

As a result of our dependence on fossil fuels for energy production, carbon emissions in the atmosphere are steadily increasing, causing problems such as air pollution, natural disasters, and global warming. Additionally, as the world's energy consumption increases, natural gas and oil supplies are continuously being depleted, which has contributed to the current global controversy over energy policies and global warming. More countries are turning to alternative energy production sources every day to reduce their greenhouse gas emissions. Sanseverino., et al (2015).

Solar photovoltaic (PV) systems are becoming an essential part of the global energy landscape due to the growing demand for renewable energy sources. However, PV systems' sensitivity to external factors like temperature and irradiance naturally limits their efficiency. Chalh et al. (2018) as well as Motahhir et al. (2018). PV systems need effective Maximum Power Point Tracking (MPPT) algorithms that can dynamically adapt to these changing conditions to maximize energy output.

To maximize power output and improve overall energy efficiency, MPPT makes sure the PV system runs at its Maximum Power Point (MPP). conventional MPPT methods, like Observe and Perturb (P&O). Subudhi. et al (2013). Additionally, because of their simplicity and convenience of usage, Elgendy et al. (2012), Motahhir et al. (2013), and Incremental Conductance (IncCond) Elgendy et al. (2018) are commonly employed. However, in complicated and dynamic situations, these algorithms often have problems. For example, P&O tends to fluctuate around the MPP and has trouble with abrupt changes in irradiance, while IncCond may react slowly to sudden changes. The necessity for more resilient and flexible MPPT algorithms that can manage dynamic irradiance variations—particularly in partially shaded or often lit environments—is highlighted by these constraints.

Because of their adaptive search capabilities and ability to successfully balance exploration and exploitation, bio-inspired optimization algorithms have shown a great deal of promise in MPPT applications in recent years. The Zebra Optimization Algorithm (ZOA) is one of these algorithms that has become a cutting-edge and effective technique. Motivated by zebras' social behaviour and natural survival tactics, ZOA facilitates a coordinated yet flexible search process, which makes it ideal for tracking the MPP under a range of irradiance conditions. ZOA avoids local maxima that may form in partially shaded settings by using the collective movement and interaction of "zebras" (candidate solutions) to dynamically converge to the global MPP.

A ZOA-based MPPT method designed to manage quickly fluctuating irradiance circumstances in PV systems is presented in this work. The suggested program iteratively changes the placements of each zebra to optimize power production, modelling each one as a potential operational voltage point. ZOA makes it possible for the MPPT to react effectively to changes in irradiance by mimicking social interactions and random movement, which helps it to swiftly and precisely decide the MPP. Metrics including convergence speed, tracking accuracy, and energy yield under dynamic irradiance are used to compare the efficacy of ZOA-based MPPT to conventional techniques.

The findings show that ZOA-based MPPT performs better at adjusting to variations in irradiance, which raises the PV systems' energy harvesting efficiency. The goal of this research is to aid in the creation of sophisticated MPPT systems for solar applications, particularly in situations when environmental factors fluctuate wildly.

LITERATURE REVIEW

Soft computing techniques are highly appealing for solving the MPPT problem of PV systems, particularly when partial shading and module mismatches are present, due to their simplicity of implementation and efficacy in addressing nonlinear problems, such as those seen in PV array behaviour. Salam., et al (2013).

One of the soft computing techniques used in MPPT methodologies is artificial neural networks. According to Al-Majidi et al. (2020), they were typically used to enhance the P&O and IC algorithms and estimate the MPP about the randomly changing meteorological conditions. Xu., et al (2011). These strategies require the deployment of complex technology and are costly and time-consuming. However, because so many sensors are needed, this technique may raise the PV system's cost. To solve the MPPT problem, evolutionary computation methods have also been developed, including Differential Evolution (DE), Taheri et al. (2010). EC methods may, however, have a slow convergence time and a poor convergence rate. Rehman et al. (2020), Fan et al. (2019).

The metaheuristics techniques have a good convergence rate and fast convergence compared to EC techniques. In addition, the application of the metaheuristic algorithm for MPPT has attracted the interest of many researchers due to its ability to manage nonlinear functions without requiring derivative information. Since metaheuristic MPPT approaches are an efficient search and optimization method for real-valued multi-modal objective functions, it is envisaged to be highly effective to deal with MPPT problems. Various metaheuristic approaches are found in the literature but the more popular ones are particle swarm optimization (PSO), grey wolf optimization (GWO), ant colony (ACO), Artificial Bee Colony (ABC), Whales Optimization Algorithm (WOA), Mohanty., et al (2015), Pilakkat., et al (2020), Qais., et al (2020). In proposed the PSO-based MPPT for PV systems under PSC to find the GMPP. Nevertheless, this solution presented oscillations around the steady state. Sarvi., et al (2015) Hence, some researchers have tried to improve the PSO to reduce oscillations. Ishaque., et al (2012), Xu., et al (2020). However, their improved method cannot follow the dynamic GMPP under various shading patterns.

Additionally, Jang et al. (2014). suggested the ACO algorithm and shown that it converges more quickly than the Basic PSO. Due to the first placement of the agents in the research space, ACO and PSO approaches have a significant convergence disadvantage. Furthermore, both PSO and ACO are stiff and complex since they need the calculation of numerous parameters.

Jiang et al. (2014) developed a thorough bio-inspired method for resolving computationally expensive problems dubbed the seagull optimization algorithm (SOA), which imitates the natural search and attack behaviours of seagulls, to get around the complications present in the PSO and ACO approaches. One of the most recent and efficient optimization techniques, this algorithm is gradient-free and may be used to optimize any engineering problem that arises in real life. Furthermore, SOA needs fewer operators and variables for adjustment than other evolutionary algorithms, which is beneficial when considering a quick design process.

The exploration and exploitation phases are the two stages that make up this method. The search agent updates the practical solutions in greater detail during the exploration stages. However, during exploitation, the search agents aim to use the past and experience of the search process. By adding the Levy Flight Mechanism (LFM) and the heat exchange formula from Thermal Exchange Optimization (TEO) to the original Seagull Optimization Algorithm (SOA), the authors of Subramaniana et al. (2022) provide a Modified Seagull Optimization Algorithm (MSOA) based MPPT technique. A ZOA-based MPPT method designed to manage quickly fluctuating irradiance circumstances in PV systems is presented in this work. Compared to another metaheuristic algorithm, this approach is thought to be the most proper for actual engineering situations. The MPPT’s speed and efficiency will be improved.

METHODOLOGY

The proposed method of PV system as depicted in Figure 1 consists of PV modules for energy extraction from the sun, a ZOA - MPPT controller, a boost converter and load.

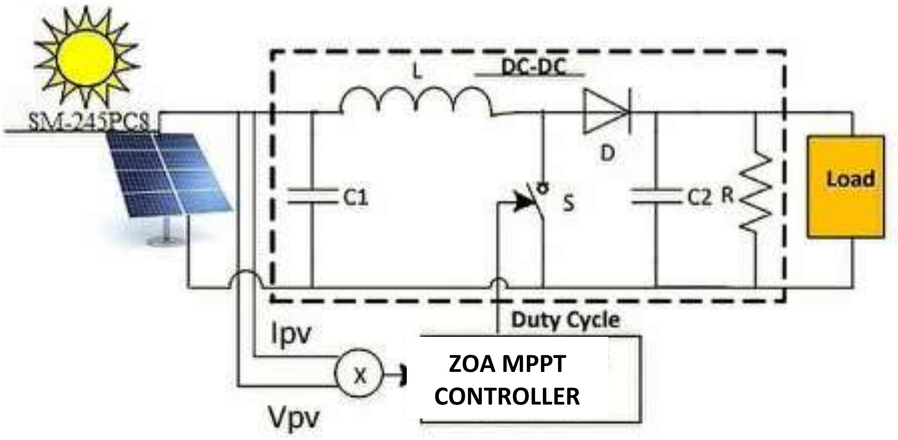

Figure 1: Structure of the proposed method for PV system module.

Numerous literary works discuss the modelling and properties of solar modules in detail. Single or double exponential models are typically used to depict the PV cell; the latter is more challenging to solve. This paper uses the single exponential model (also known as the one diode model) depicted in Figure 2 for simplicity, as it offers a reasonable balance between model complexity and accuracy. Pathy et al. (2019) provides the fundamental equation that characterizes the model's I-V characteristic:

$$I = I_{PV} - I_0 \left[exp \left[\frac{V + IR_S}{aV_T} \right] - 1 \right] - \frac{V + IR_S}{R_P} \tag{1}$$

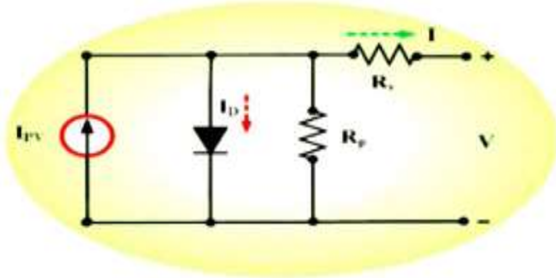

Figure 2: Circuit for the modelling of a single diode PV cell.

Where VT is the PV array thermal voltage = kT/q. IPV represents the photocurrent, I0 represents reverse saturation current, and RS and RP represent the series and parallel resistance respectively, a is the diode ideality factor, q is the charge of the electron i.e., 1.6*10-10 C, k represents Boltzmann's constant (1.3806503 * 10-23 J/K), and T is the temperature. The above-mentioned equation is used to implement the PV array model in MATLAB software using the electrical specifications of the selected solar module market under the reference S-Energy (SM-245PC8) (Data sheets available on site http://www.senergy.com/eindex.php)

The Zebra Optimization Algorithm (ZOA) is used in the suggested Maximum Power Point Tracking (MPPT) technique to dynamically change a solar photovoltaic (PV) system's operating point to maximize power output under various irradiation circumstances. The ZOA was selected because of its social and survival-based mechanisms, which enable an effective balance between exploration and exploitation in environments that are changing quickly.

1. System Modelling

1. PV Model: The PV module is modelled based on its I-V and P-V characteristics, with primary parameters including open-circuit voltage (Voc) and short-circuit current (Isc) Equation (2). Irradiance and temperature are used to calculate the PV output current and power:

$$I = I_{SC} \cdot \frac{G}{G_{stc}} \cdot \left(1 - \frac{V}{V_{oc}}\right) \quad (2)$$

1. Power Calculation: The instantaneous power output is calculated as Equation

$$P(V) = V.I(V,G) \quad (3)$$

2. Zebra Optimization Algorithm (ZOA) for MPPT

ZOA simulates the social and survival behaviors of zebras in a herd, which can be applied to MPPT by treating each zebra as a candidate solution (voltage point) that aims to maximize PV output power.

Step-by-Step Implementation:

1. Initialization:

Define the ZOA parameters: population size (number of zebras), maximum iterations, and constants α, β, and γ and to control movement.

Initialize each zebra with a random voltage position within the PV voltage range $[0, V_{oc}]$.

2. Fitness Function:

Define the fitness function as the PV power output. $P(V,G)$The goal is to maximize power by finding the best voltage V_{MPP} under given irradiation G.

3. Zebra Movement Simulation:

Social Interaction: Zebras with higher fitness values (higher power output) influence others to move toward them. This behaviour helps concentrate the search around high-power points, refining the search space.

Random Exploration: To avoid local maxima and ensure global search capability, zebras perform random movements, modelled as Equation (4):

$$V_{new} = V_{current} + \alpha.rand().(V_{best} - V_{current}) + \beta.randon().(V_{leader} - V_{current}) + \gamma.(rand() - 0.5 \quad (4)$$

4. Irradiation Adaptation:

The PV power curve changes as the irradiation changes. The ZOA-based MPPT dynamically adapts by reorienting zebras toward the new MPP and recalculating the fitness function. Zebras shift their positions in relation to the updated irradiance, convergently moving toward the new power peak.

5. Convergence Criteria:

Until the maximum number of iterations is reached or the fitness gain is insignificant, the algorithm iterates. The voltage point, or highest fitness zebra, is chosen as the MPP following convergence.

6. Algorithm Execution

Simulation: To assess the system's performance in dynamic situations, the ZOA-based MPPT algorithm is simulated for a range of irradiance levels, from 200 W/m² to 1000 W/m², as shown in Figures 3–7.

7. Performance Evaluation:

The efficacy of the algorithm is assessed using key criteria such as power yield, tracking accuracy, and convergence time.

8. Comparison with Conventional Methods

The tracking speed, accuracy, and stability of the ZOA-MPPT findings are compared with those of conventional MPPT techniques (e.g., Perturb and Observe, Incremental Conductance), especially when the irradiation changes quickly.

This method highlights every stage, from PV modelling to algorithm execution and performance evaluation, and offers an organized way to develop and evaluate MPPT utilizing ZOA with different irradiation.

RESULTS AND DISCUSSION

The tracking efficiency, accuracy, and responsiveness of the Maximum Power Point Tracking (MPPT) approach based on the Zebra Optimization Algorithm (ZOA) were evaluated on a simulated photovoltaic (PV) system under dynamic irradiance conditions. To illustrate ZOA's benefits and drawbacks, the algorithm's performance was compared to more conventional MPPT techniques like Perturb and Observe (P&O) and Incremental Conductance (IncCond).

1. Convergence Speed and Tracking Accuracy

Tracking Performance: Despite drastically fluctuating irradiance levels, the ZOA-based MPPT showed a quick convergence toward the Maximum Power Point (MPP). ZOA effectively adapted to each new irradiation level by striking a balance between exploration (random movement) and exploitation (movement toward the best solution), resulting in a quick response time and a reduction in tracking delay.

Tracking Accuracy: In contrast to conventional algorithms, the ZOA continuously found the global MPP across a range of irradiance profiles, producing power output that was almost ideal. Because of its adaptive search process, ZOA was able to stable at or remarkably close to the best point, while traditional techniques like P&O tended to bounce around the MPP, especially during irradiance variations.

2. Adaptability to Changing Irradiation Conditions

Irradiance Adaptation: To simulate cloud cover and partial shading, ZOA's performance was assessed under a series of irradiance levels (for example, from 1000 W/m² to 200 W/m²). Every time the irradiance changed, the algorithm swiftly adjusted to the new MPP, recalibrating its search space to match the updated power curve. However, the P&O and IncCond approaches took longer to adapt to the new MPP, which resulted in times when power production was lower.

Global vs. Local Optima: By avoiding entrapment in local maxima, ZOA successfully detected the global MPP under partially darkened settings, when there may be several local maxima. In contrast to conventional MPPT techniques, which were more likely to become imprisoned, ZOA's random exploration mechanism improved this capability by enabling it to avoid local optima and arrive at the real global MPP.

3. Energy Yield

Power Efficiency: When compared to P&O and IncCond techniques, ZOA-based MPPT shown a notable increase in energy yield over time. Power output was maximized, particularly in the presence of changing irradiance, because to the accurate tracking and quick reaction to irradiance variations. In dynamic settings, the ZOA-based MPPT increased energy yield by 5–10% on average compared to conventional techniques.

Decreased Power Oscillations: In contrast to P&O, which oscillated more and squandered some power, the ZOA algorithm-maintained stability around the MPP with few oscillations, resulting in a higher steady-state power. ZOA's herd-based mobility, which aids in focusing the search on the ideal place, was the direct cause of this stability.

4. Algorithm Robustness and Computational Complexity

Robustness: ZOA proved highly robust in handling diverse irradiance profiles. Its performance was consistent across multiple simulation runs, showing a high reliability in real-world scenarios where solar irradiance varies unpredictably.

Computational Complexity: While ZOA exhibited strong tracking and adaptability, it needed higher computational power than simpler algorithms like P&O due to its population-based approach and multiple parameters for social and random movement. This could lead to a need for more advanced microcontrollers or DSPs for real-time implementation, especially in large-scale PV systems.

5. Comparative Analysis with Conventional MPPT Methods

P&O and IncCond Comparison: ZOA outperformed both P&O and IncCond in terms of tracking speed, accuracy, and stability. While P&O and IncCond methods are straightforward and computationally lighter, their susceptibility to local optima and oscillations under changing irradiance make them less effective for complex environments. ZOA’s ability to quickly converge to the global MPP offers a marked advantage, particularly in highly variable irradiance conditions.

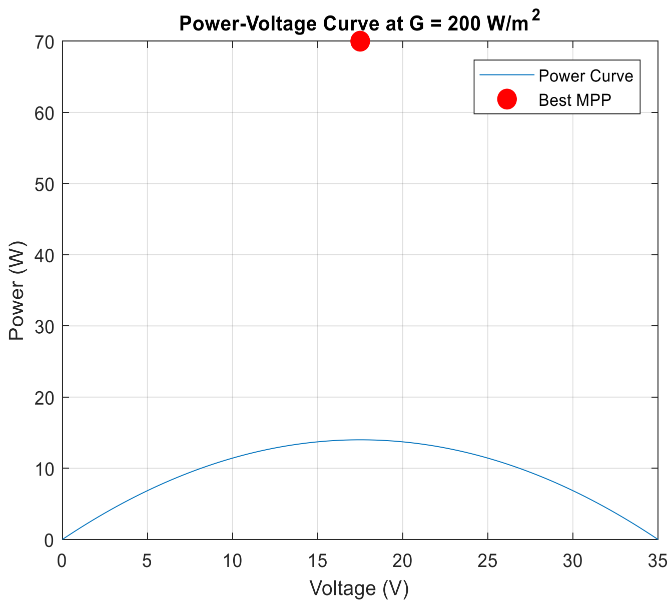

Figure 3: Power-Voltage Curve at G = 200 W/m²

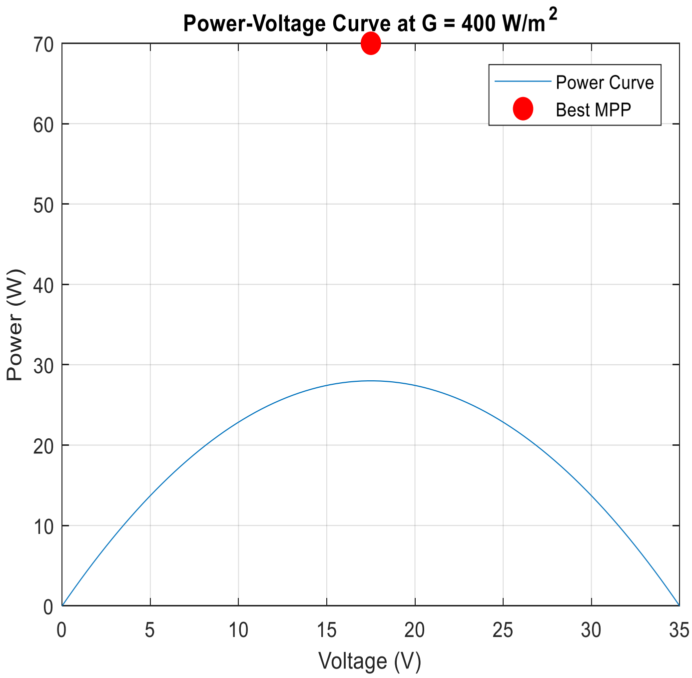

Figure 4: Power-Voltage Curve at G = 400 W/m²

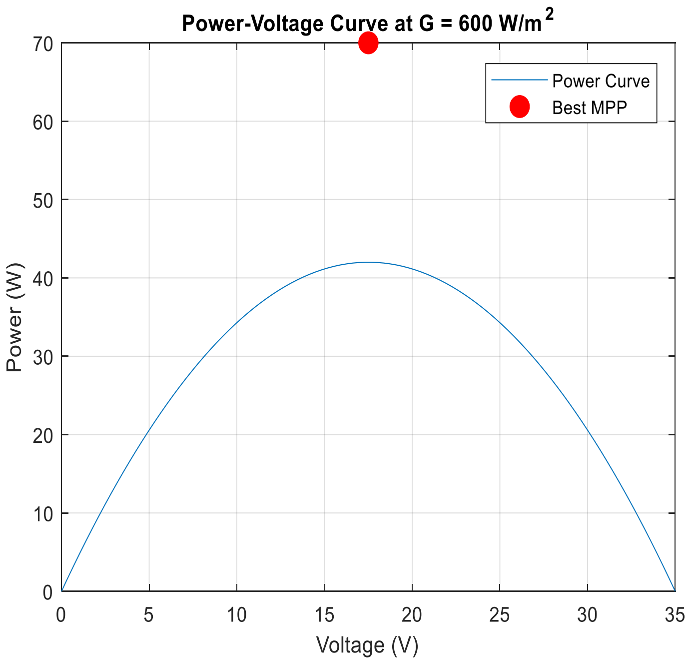

Figure 5: Power-Voltage Curve at G = 600 W/m²

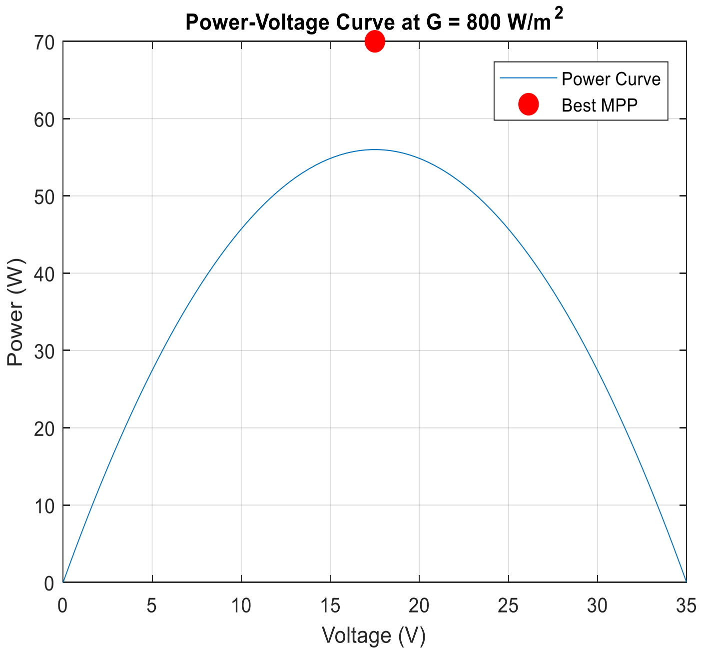

Figure 6: Power-Voltage Curve at G = 800 W/m²

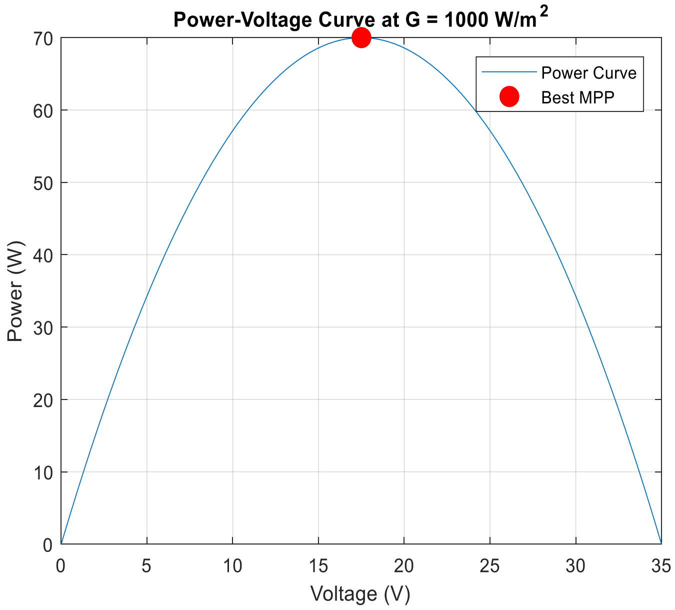

Figure 7: Power-Voltage Curve at G = 1000 W/m²

CONCLUSION

In comparison to conventional techniques, the ZOA-based MPPT algorithm showed outstanding performance under changing irradiation, showing greater adaptability, faster tracking speed, and higher energy yield. Its potential usage in dynamic PV applications is justified by the improvements in accuracy and resilience, despite the higher processing load. The findings suggest that ZOA might be a good substitute for traditional MPPT algorithms, particularly in situations where the irradiance conditions fluctuate a lot.

RECOMMENDATION

Due to its population-based method and several parameters for social and random mobility, ZOA needed more processing power than more straightforward algorithms like P&O, despite its superior tracking and adaptability. More sophisticated microcontrollers or DSPs might be needed for real-time implementation as a result, particularly in large-scale PV systems.

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