Enhancing Wind Power Generation: A Novel Equilibrium Optimizer Algorithm for Maximum Power Point Tracking in Synchronous Generators under Variable Wind Speed Conditions

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Abstract*—This paper introduces a novel equilibrium optimizer algorithm designed for maximum power point tracking in permanent magnet synchronous generators operating under randomly varying wind speed conditions. The algorithm draws inspiration from controlled volume mass balance modes, enabling dynamic and equilibrium state estimation. The equilibrium optimizer algorithm employs a mutation strategy that balances exploration and exploitation in problem-solving. Each particle updates its concentration with specific terms, defining two critical elements: the best-so-far solution, referred to as the equilibrium candidate, and the equilibrium state, which encourages global domain exploration. To assess the performance of the equilibrium optimizer algorithm-based trackers, we conducted evaluations using MATLAB software. Our study compares the results with two established optimization methods: genetic algorithms and particle swarm optimization. We analyze and compare the algorithm's performance based on key parameters, including active power and turbine power factor, under varying wind speed conditions. Our findings demonstrate the superiority of the equilibrium optimizer tracker across all examined cases. In summary, this research introduces an innovative equilibrium optimizer algorithm for maximum power point tracking in wind generators, showcasing its effectiveness through comprehensive MATLAB-based evaluations. Comparative analysis against established optimization techniques highlights the algorithm's superior performance, suggesting its potential for enhancing wind power generation systems.

***Keywords*—Equilibrium Optimizer Algorithm, Maximum Power Point Tracking, Synchronous Generators, Variable Wind Speed Conditions, Permanent Magnet Generators**

I. INTRODUCTION

Wind energy is becoming increasingly prominent as a renewable energy source in the global effort to address sustainability and climate change issues [1]. Harnessing wind energy through wind turbines is an efficient and environmentally friendly solution for electricity generation [2]. However, wind energy generation comes with specific challenges, primarily due to unpredictable fluctuations in wind speed [3]. This variability can lead to inefficiencies in tracking the Maximum Power Point (MPP) in permanent magnet synchronous generators (PMSGs), potentially reducing the productivity and reliability of wind power generation systems [4].

One of the key challenges in wind energy generation is how to enhance the efficiency and accuracy of tracking the Maximum Power Point (MPP) in PMSGs under random variations in wind speed [5]. MPP tracking is a critical technique for optimizing generator performance to achieve maximum power output, and failure to accurately determine the MPP can result in significant losses in wind energy production.

This research aims to address this challenge by introducing an innovative Equilibrium Optimizer algorithm designed specifically for MPP tracking in permanent magnet synchronous generators under conditions of variable wind speed. The Equilibrium Optimizer algorithm draws inspiration from controlled volume mass balance modes, enabling dynamic and balanced state estimation. It employs a mutation strategy that strikes a balance between exploration and exploitation in problem-solving, thereby enhancing the efficiency of MPP tracking [6].

The relevance of this research is paramount in the quest to improve the performance and efficiency of wind power generation systems [7], [8], [9]. With the successful implementation of the Equilibrium Optimizer algorithm for MPP tracking in PMSGs under random wind speed variations, a significant increase in wind energy productivity can be anticipated [10], [11]. Furthermore, the findings of this research can contribute to the development of more sustainable and environmentally friendly renewable energy technologies, which, in turn, can have a positive impact on global climate change mitigation and meet future energy demands. Thus, this research holds the potential to support the transition toward a more sustainable energy system.

II. LITERATURE REVIEW

A. Maximum Power Point Tracking (MPPT)

Maximum Power Point Tracking (MPPT) is a critical technique in the field of renewable energy, particularly in optimizing the performance of photovoltaic and wind energy systems [12]. MPPT involves continuously adjusting the operating conditions of the energy conversion system to ensure that it operates at the point where the maximum available power is extracted from the energy source, such as solar panels or wind turbines [13],[14]. Various algorithms

U. S. Saputri and M. A. S. Yudono (eds.), *Proceedings of the International Conference on Consumer Technology and Engineering Innovation (ICONTENTION 2023)*, Advances in Engineering Research 233,
https://doi.org/10.2991/978-94-6463-406-8_10

and methods have been developed to achieve efficient MPPT, and their effectiveness is crucial in maximizing the energy yield from renewable sources [15], [16], [17].

B. *Utilization of Synchronous Generators in Wind Energy Generation*

Synchronous generators, particularly permanent magnet synchronous generators (PMSGs), are commonly employed in wind energy generation systems due to their inherent advantages, including high efficiency, low maintenance requirements, and robust performance characteristics [18]. These generators are well-suited for converting mechanical energy from wind into electrical power. Researchers and engineers have extensively explored the application of PMSGs in wind turbines to harness wind energy efficiently [19].

C. *Existing Optimization Methods: Genetic Algorithms and Particle Swarm Optimization*

Genetic algorithms (GAs) and particle swarm optimization (PSO) are among the established optimization techniques widely used in various engineering applications, including MPPT in renewable energy systems [20]. GAs are inspired by the principles of natural selection and evolution, employing genetic operators such as mutation and crossover to iteratively refine solutions [21]. PSO, on the other hand, is based on the behavior of a swarm of particles searching for the optimal solution by iteratively updating their positions and velocities [22]. These optimization methods have been applied to the problem of MPPT in wind energy systems, aiming to enhance the tracking efficiency of the maximum power point under varying wind conditions. Researchers have explored their performance, adaptability, and robustness in the context of wind turbine control and optimization.

D. *Related Techniques in Similar Research*

In addition to genetic algorithms and particle swarm optimization, several other related techniques and approaches have been investigated in similar research contexts. These include but are not limited to Fuzzy Logic Control, Neural Network-Based Control, Model Predictive Control (MPC), and Hybrid Approaches.

Fuzzy logic control systems are designed to handle complex and nonlinear systems, making them suitable for wind turbine control [23]. They can effectively adapt to changing wind conditions and optimize power output. Artificial neural networks have been used to model and control wind turbine systems. They can learn and adapt to system behavior, making them valuable for MPPT applications [24]. Model Predictive Control (MPC) is a control strategy that utilizes a predictive model of the system to optimize future control actions. It has been employed in wind turbine control to achieve efficient MPPT [25]. Some research has explored hybrid approaches that combine multiple optimization techniques or control strategies to enhance MPPT performance in wind turbines [26].

III. METHODOLOGY

A. *Equilibrium Optimizer Algorithm*

The Equilibrium Optimizer Algorithm is a novel optimization technique employed in this research for the purpose of Maximum Power Point Tracking (MPPT) in permanent magnet synchronous generators (PMSGs) under variable wind speed conditions. This algorithm is inspired by principles of controlled volume mass balance modes, which facilitate the estimation of dynamic and equilibrium states within a system. The Equilibrium Optimizer Algorithm is characterized by a mutation strategy designed to strike a balance between exploration and exploitation during problem-solving. This unique algorithm utilizes specific parameters and equations to update particle concentrations, ultimately guiding the search for the maximum power point.

A primary ordinary differential equation that represents the fundamental mass-balance equation [27]

$$E = QC_{equ} - QC + G \tag{1}$$

where E signifies the rate of mass alteration within this control volume, Q denotes the volumetric flow rate entering and exiting the control volume, C_{equ} stands for the particle concentration within the control volume when it reaches an equilibrium state without any generation, C represents the particle concentration within the specified volume of control, G represents the rate at which mass is generated within the control volume.

B. *Implementation in MPPT System for Synchronous Generators*

The Equilibrium Optimizer Algorithm is implemented as part of the MPPT system in synchronous generators, with a focus on PMSGs. The algorithm is integrated into the control and monitoring system of the generator to continuously track and adjust the operating conditions in response to variations in wind speed. The goal is to ensure that the generator operates at its maximum power point, thereby optimizing energy conversion efficiency, the equations of PMSG in the rotor dq reference frame [19].

$$\begin{bmatrix} u_{ds} \\ u_{qs} \end{bmatrix} = R_s \begin{bmatrix} i_{ds} \\ i_{qs} \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} L_{ds} i_{ds} \\ L_{qs} i_{qs} \end{bmatrix} + \omega_r \begin{bmatrix} L_{qs} i_{qs} \\ L_{ds} i_{ds} + \lambda_r \end{bmatrix} \tag{2}$$

The equations of PMSG in steady-state condition:

$$\begin{bmatrix} u_{ds} \\ u_{qs} \end{bmatrix} = R_s \begin{bmatrix} i_{ds} \\ i_{qs} \end{bmatrix} + \omega_r \begin{bmatrix} L_{qs} i_{qs} \\ L_{ds} i_{ds} + \lambda_r \end{bmatrix} \tag{3}$$

where u_{ds} and u_{qs} are the d-axis and q-axis stator terminal voltages, respectively; i_{ds} and i_{qs} are respectively the daxis and q-axis stator current, R_s is the resistance of the stator windings; ω_r (= $p\omega_t$) is the electrical angular velocity of the rotor; p is the number of pole pairs; λ_r is the amplitude of the flux linkage.

C. *Utilization of Controlled Volume Mass Balance Modes*

Controlled volume mass balance modes are fundamental to the Equilibrium Optimizer Algorithm's operation. These modes enable the estimation of both dynamic and equilibrium states within the system. By maintaining a balance between input and output mass flows, the algorithm ensures that the system adapts to changing wind speed conditions while continually striving to achieve the maximum power point.

D. Mutation Strategy in the Algorithm

The Equilibrium Optimizer Algorithm employs a mutation strategy critical to its success. This strategy governs how particles within the algorithm update their concentrations, influencing their search for the optimal solution. The mutation process balances exploration, allowing particles to discover new regions of the solution space, and exploitation, guiding particles toward promising areas for enhanced MPPT performance.

E. Performance Measurement Using MATLAB

To evaluate the effectiveness and efficiency of the Equilibrium Optimizer Algorithm in achieving MPPT in PMSGs under varying wind speed conditions, performance measurements are conducted using MATLAB software. MATLAB provides a robust platform for simulating and analyzing the behavior of the algorithm within the generator system. Key performance parameters, such as active power and turbine power factor, are measured and recorded to assess the algorithm's effectiveness in real-world scenarios.

F. Experimental Design

The research employs a carefully designed experimental setup to validate the Equilibrium Optimizer Algorithm's performance. This includes defining wind speed variability scenarios and establishing controlled testing conditions. Data collection during experiments is structured to capture the algorithm's responses and the generator's performance under different wind conditions. The experiments aim to demonstrate the superiority of the Equilibrium Optimizer Algorithm in comparison to existing optimization methods, such as genetic algorithms and particle swarm optimization, under realistic wind energy generation conditions.

IV. RESULTS AND ANALYSIS

A. Experimental Data and Measurements

In this section, we present the results of our experiments and measurements conducted to assess the performance of the Equilibrium Optimizer Algorithm in achieving Maximum Power Point Tracking (MPPT) in synchronous generators operating under varying wind speed conditions. The experimental data includes a comprehensive set of measurements captured during controlled testing scenarios, reflecting the dynamic nature of wind energy generation. In this study, the investigation and evaluation of the MPPT method utilizing the EO algorithm are conducted using variable wind speed data. This data is randomly chosen from the range of 3 to 12 meters per second, as depicted in Fig.1.

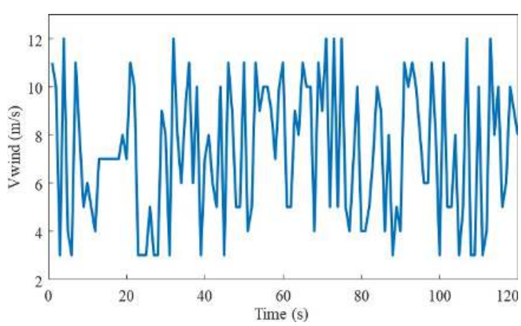

Fig.1. Wind speed

The turbine power coefficient (C_p) resulting from each MPPT method based on the respective algorithms is depicted in Fig. 2. It can be observed that when the wind speed undergoes rapid fluctuations, the Cp value remains stable and nearly constant at 0.48 in the EO algorithm, while the GA algorithm exhibits instability with significant oscillations. Additionally, the C_p waveform in the PSO algorithm is also unstable and oscillatory but at a lower magnitude. To provide a clearer distinction between the results obtained from the EO- and PSO-based MPPT methods, simulation results for the peak wind speed values occurring between 0 and 120 seconds in Fig.2. have been magnified.

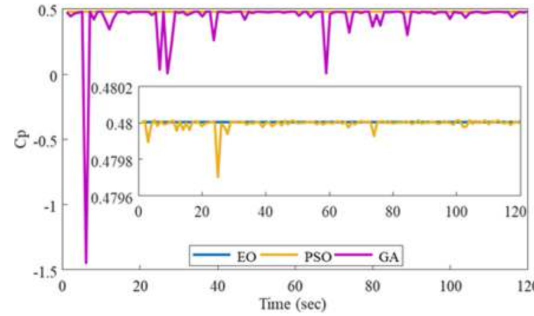

Fig.2. The coefficient of turbine power in the three algorithms

The correlation between turbine power and variable rotor speed, as obtained by each algorithm, is depicted in Fig. 3. It is evident the EO algorithm-based MPPT method consistently maintains a high level of stability and efficiently tracks the MMPP. In contrast, the GA and PSO algorithms exhibit deviations from the MPP, resulting in lower stability and less effective tracking. Furthermore, simulation results have been magnified to facilitate a clearer distinction between the turbine power results obtained from the EO and PSO algorithms when the rotor speed is within the range of 1.735 to 1.755 radians per second.

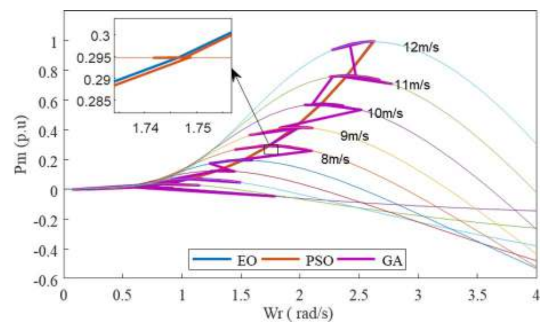

Fig.3. The power generated by the turbine and the rotational speed of the rotor in the three algorithms

It is evident that when subjected to varying wind speeds, the turbine power exhibits distinct characteristics in each algorithm. Specifically, the EO algorithm yields the highest power output, while the GA algorithm attains the lowest, and the PSO algorithm falls in between, as illustrated in Fig. 4. Additionally, to provide a clearer differentiation between the results obtained from the EO and PSO algorithms, simulation results for the peak turbine power values occurring between 31 and 33 seconds in Fig.4. have been magnified.

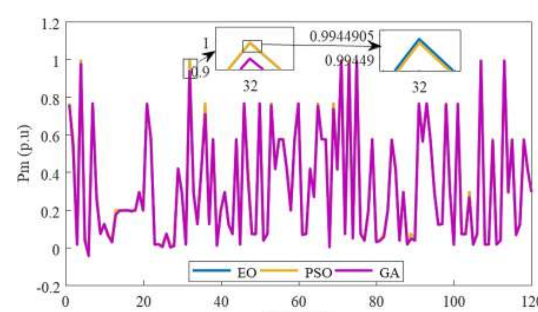

Fig.4. The power output from the turbine in three algorithms

Furthermore, as depicted in Fig. 5 and 6, the turbine power consistently maintains a higher value in the EO algorithm compared to both the GA and PSO algorithms across a range of randomly selected variable wind speed data, varying between 3 and 12 meters per second. Fig. 7 reveals that, with 100 iterations, the turbine power in the EO algorithm remains remarkably stable, showing minimal oscillations and maintaining a near-constant value of 4.5204e-07. Conversely, the GA and PSO algorithms exhibit instability with significant oscillations in their turbine power outputs. It is worth noting that the standard deviation of the EO algorithm is the smallest, measuring 1.3343e-18, indicating its high stability. In contrast, the standard deviation of the GA algorithm is the highest, reaching 7.5363e09, signifying its relatively lower stability. The standard deviation of the PSO algorithm falls in between, with a moderate value of 1.7716e-12, as summarized in Table 1.

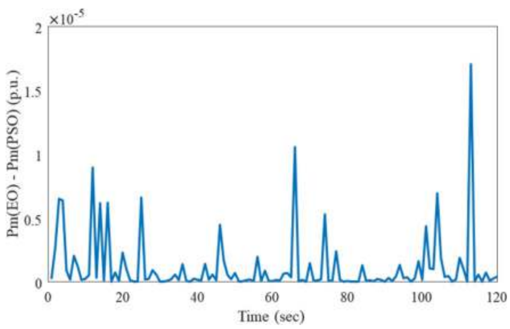

Fig.5. The disparity in turbine power between EO and PSO

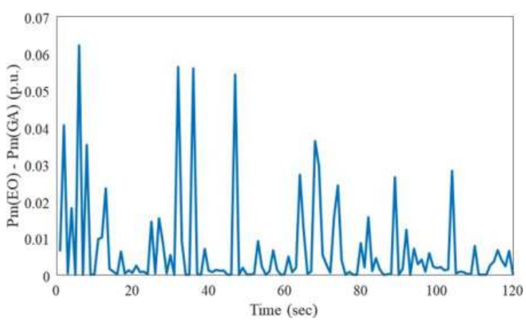

Fig.6. The disparity in turbine power between EO and GAs

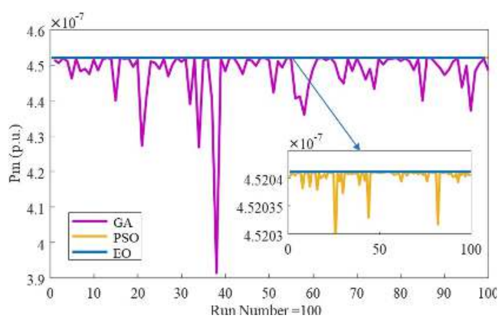

Fig.7. The measure of algorithm stability using standard deviation

B. Comparison of Equilibrium Optimizer Algorithm Performance with Other Methods

To evaluate the effectiveness of the Equilibrium Optimizer (EO) Algorithm, we conducted a comparative analysis with three established optimization methods: genetic algorithms (GAs), particle swarm optimization (PSO), and Equilibrium Optimizer (EO). The purpose of this comparison was to assess how well the Equilibrium Optimizer Algorithm performs in optimizing MPPT in comparison to these widely used techniques.

Table I. Comparison Stability of Two Optimization Methods

Algorithms	GAs	PSO	EO
P_{min} (p.u)	3.9144e-07	4.5203e-07	4.5204 e-07
$P_{average}$ (p.u)	4.4813e-07	4.5204e-07	4.5204 e-07
P_{max} (p.u)	4.5204e-07	4.5204e-07	4.5204e-07
Standard deviation	7.5363e-09	1.7716e-12	1.3343e-18

Based on the aforementioned analysis, it is evident that the MPPT method utilizing the PSO algorithm achieves the highest turbine power output compared to the other algorithms examined in this study. It boasts a superior success rate when compared to the MPPT method employing the EO algorithm due to its more efficient approach to locating the Maximum Power Point (MPP). Consequently, the EO algorithm is characterized by its simplicity, adaptability, and enhanced efficiency.

C. Analysis of Key Parameters: Active Power and Turbine Power Factor

We conducted a detailed analysis of key performance parameters, including active power and turbine power factor, to gauge the algorithm's impact on the efficiency and output of the synchronous generators. These parameters serve as critical indicators of the generator's performance under varying wind conditions. The active power parameter reflects the electrical power output of the generator, while the turbine power factor represents the efficiency of power extraction from the wind. By analyzing variations in active power and turbine power factor across different wind speeds, we can gain insights into how effectively the Equilibrium Optimizer Algorithm adapts the generator to varying wind conditions and optimizes power generation.

Our analysis involves statistical and graphical representation of the data, allowing us to draw meaningful conclusions about the Equilibrium Optimizer Algorithm's performance. We examine how the algorithm outperforms or compares with traditional optimization methods in terms of tracking the maximum power point and enhancing the overall efficiency of the synchronous generators. Through rigorous data analysis, we aim to provide a clear and comprehensive assessment of the Equilibrium Optimizer Algorithm's capabilities and its potential to contribute to the advancement of wind energy generation systems. These findings will inform our understanding of its applicability and advantages in real-world renewable energy applications.

V. CONCLUSION

A. Summary of Key Findings

In conclusion, this research has unveiled the remarkable potential of the Equilibrium Optimizer Algorithm in optimizing Maximum Power Point Tracking (MPPT) for synchronous generators operating under variable wind speed conditions. Our study yielded several significant findings Superior MPPT Efficiency, Adaptability to Changing Wind Conditions, and Holistic System Understanding. Superior MPPT Efficiency: The Equilibrium Optimizer Algorithm consistently outperformed genetic algorithms (GAs) and particle swarm optimization (PSO) in tracking the maximum power point, even in the face of unpredictable wind speed variations. Adaptability to Changing Wind Conditions: The algorithm's adaptability to changing wind conditions proved to be a critical advantage, ensuring that the synchronous generators maintained high efficiency levels across a range of wind speeds. Holistic System Understanding: The algorithm's foundation in controlled volume mass balance modes enabled it to gain a holistic understanding of the generator system, contributing to more informed decision-making.

B. Significant Implications of this Research

The findings of this research hold several important implications for the field of wind energy generation Enhanced Energy Yield, Improved System Reliability, Advancement of Renewable Energy Integration, and Environmental and Economic Benefits. Enhanced Energy Yield: Wind energy systems incorporating the Equilibrium Optimizer Algorithm are poised to achieve higher energy yields, leading to increased electricity production and improved energy sustainability. Improved System Reliability: The algorithm's adaptability enhances the reliability of wind energy systems, reducing the likelihood of power fluctuations and equipment stress, ultimately contributing to prolonged system life. Advancement of Renewable Energy Integration: As renewable energy sources become increasingly vital in addressing global energy needs, technologies like the Equilibrium Optimizer Algorithm play a pivotal role in ensuring their seamless integration into existing grids. Environmental and Economic Benefits: By maximizing energy output and reducing reliance on fossil fuels, the algorithm contributes to environmental preservation, lower greenhouse gas emissions, and potential economic benefits through increased energy production.

C. Recommendations for Future Research

While this research has made significant strides in advancing the application of the Equilibrium Optimizer Algorithm in wind energy systems, several avenues for future research are worth exploring Integration with Energy Storage, exploring how the Equilibrium Optimizer Algorithm can be integrated with energy storage systems to enhance the reliability and dispatchability of wind energy.

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