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Improved Maximum Power Point Tracking Control for D-PMSG Systems: Fuzzy Gradient Step Approach

Muhammad Qasim Nawaz, Wei Jiang, Muhammad Usman, and Aimal Khan

Department of Electrical Engineering and Automation, Yangzhou University, 225127 Yangzhou, China
Corresponding author: Muhammad Qasim Nawaz (qasimnawaz27@gmail.com).
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ABSTRACT This study introduces an enhanced Maximum Power Point Tracking (MPPT) control strategy for Direct Drive Permanent Magnet Synchronous Generators (D-PMSG) utilizing a Fuzzy Gradient Step Approach. By comparing with traditional MPPT methodologies, this approach demonstrates significant improvements in tracking accuracy, efficiency, and response time to fluctuating environmental conditions. The fuzzy logic control method adapts dynamically, optimizing power output under variable wind speeds. The comparative analysis reveals that our method not only surpasses conventional techniques in performance but also offers a cost-effective solution with less complexity. Implications of these advancements suggest potential applications in optimizing wind energy systems, enhancing the viability of renewable energy sources. By examining the relationship between Boost duty cycle changes and wind turbine output characteristics, a fuzzy gradient step hill-climbing search method is proposed to calculate the wind turbine output speed in order to improve the maximum power point tracking control performance of the direct-drive permanent magnet wind power generation system. The fuzzy controller employs the duty cycle of the Boost converter as its output quantity and its input quantity to accomplish the maximum power point tracking control of the wind turbine. A model was developed and verified through simulation for use in system modeling. The results show that the fuzzy gradient step hill-climbing search approach is more effective at regulating the maximum power point tracking control of the direct-drive permanent magnet wind power producing system than the traditional variable step-size hill-climbing search algorithm. This research paves the way for future exploration in smart grid integration and scalability of fuzzy logic-based MPPT controllers, marking a pivotal step towards sustainable energy solutions.

INDEX TERMS Fuzzy Gradient Step Methodology, Fuzzy Controller Optimization, Power Extraction Efficiency, Hill-Climbing Search Algorithm

I. INTRODUCTION

The geographical region is seeing a rise in renewable energy sources, such as wind power, as a result of growing demand, rising natural gas prices, and restricted supply. As carbon emissions decrease and eco-friendly practices become more prevalent, wind energy is showing promise [1]. The global installed wind power capacity is predicted to reach over 77.6 GW by 2022, with offshore wind power being the primary source. The total installed wind power capacity worldwide is expected to reach 1250 GW by 2023 as shown in FIGURE 1, with offshore wind power's annual capacity of 842 GW [2]. China, the largest wind energy market, has installed capacity of over 237 GW, with an annual growth of 9%. 2023 is predicted to be the first year that global new capacity exceeds 100 GW, with an annual growth of 15% [3]. As the world's economy and culture grow and conventional energy sources run out, wind power is progressively becoming one of the main sources of energy demand. Although wind energy is limitless, wind speed in its natural habitat has non-linear properties and is susceptible to outside interference. Tracking the wind turbine system's greatest power point in real time is essential to maximizing the usage of wind energy. Commonly used control strategies for maximum power point tracking, or MPPT, are the hill-climbing search technique, power signal feedback method, and tip speed ratio approach [4]. Improving the efficiency of Direct Drive Permanent Magnet Synchronous Generator (D-PMSG) systems is crucial when it comes to renewable energy systems. These systems, often employed in wind turbine applications, are at the forefront of sustainable energy generation. Maximizing their efficiency and power extraction capabilities is paramount for advancing the viability of renewable energy sources in the global energy landscape. To enhance D-PMSG system performance, an effective Maximum Power Point Tracking (MPPT) control strategy has to be put in place [5]. MPPT algorithms are crucial in ensuring that the wind turbine operates at its maximum power output because they continuously adjust the electrical operating point to track the maximum power point of the turbine's characteristic curve under varying wind conditions. Effective MPPT control is required to enhance energy output, boost system efficiency, and prolong the life of wind turbine components. In the past, conventional algorithms like Hill Climbing (HC), Incremental Conductance (INC), and Perturb and Observe (P&O) were used in MPPT control strategies to monitor the maximum power point. While these methods have shown effectiveness to some extent, they often suffer from drawbacks such as slow response times, susceptibility to oscillations, and suboptimal performance under dynamic environmental conditions [6]. In the realm of renewable energy, optimizing the efficiency of wind turbines is paramount for maximizing energy extraction. Direct Drive Permanent Magnet Synchronous Generators (D-PMSG) are at the forefront of wind energy technology due to their high efficiency and reliability. However, the fluctuating nature of wind speed presents a significant challenge in harnessing maximum power. Maximum Power Point Tracking (MPPT) controllers are critical in addressing this challenge by adjusting the electrical loading of the generator to capture the maximum power available from the wind. Despite advancements, traditional MPPT methods such as Perturb and Observe (P&O) or Incremental Conductance (INC) often fall short in rapidly changing environmental conditions, leading to suboptimal power extraction and increased mechanical stress on the turbine components [7]. To address these limitations and further enhance the MPPT control performance of D-PMSG systems, a novel approach leveraging fuzzy logic and gradient step methodology has been proposed. This innovative technique, known as the Fuzzy Gradient Step Approach, aims to revolutionize MPPT control by combining the adaptability and decision-making capabilities of fuzzy logic with the precision and efficiency of gradient-based optimization. The Fuzzy Gradient Step Approach operates on the principle of analyzing the relationship between the Boost duty cycle change and the wind turbine's output characteristics. By incorporating fuzzy logic-based decision-making, the algorithm dynamically adjusts the duty cycle of the Boost converter to achieve optimal MPPT control in real-time [7]-[8]. Unlike traditional methods, which may exhibit sluggish responses or instability, the Fuzzy Gradient Step Approach offers rapid convergence to the maximum power point while ensuring robust performance in varying environmental conditions. In this comprehensive study, we delve into the theoretical foundations, design considerations, implementation strategies, and performance evaluation of the Fuzzy Gradient Step Approach for MPPT control in D-PMSG systems [9]. Through extensive simulations and experimental validations, we aim to demonstrate the efficacy, reliability, and superiority of this novel approach compared to traditional MPPT methods. By shedding light on the potential of fuzzy logic-based strategies in renewable energy systems, this research seeks to contribute to the ongoing efforts towards sustainable energy development and environmental conservation [9] - [10]. This research introduces an "Improved Maximum Power Point Tracking Control for D-PMSG Systems: Fuzzy Gradient Step Approach," aiming to overcome the limitations of existing MPPT techniques. Our objective is to develop a robust MPPT control strategy that enhances the adaptability and efficiency of wind energy conversion systems under variable wind conditions. Traditional MPPT methods struggle with dynamic response and accuracy, often causing delayed adjustment to the optimal operating point, which results in significant power losses. By

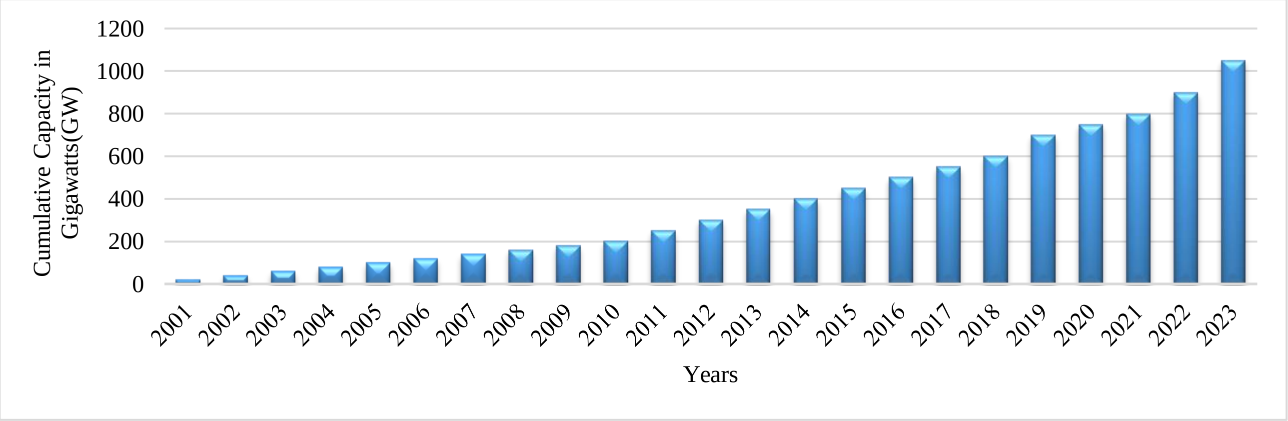

FIGURE 1. **Global cumulative wind energy installed capacity from 2001 to 2022 [1].**

integrating a fuzzy logic-based gradient step approach, we propose a method that not only responds more swiftly to changing wind speeds but also accurately identifies the maximum power point without the oscillation's characteristic of conventional methods. The MPPT control of a direct-drive permanent magnet wind power production system is studied in this work. Based on various literatures, a gradient step hill-climbing method based on Boost converter is proposed, and fuzzy control is introduced into the hill-climbing algorithm [11]. The gap in research lies in the need for a more intelligent, adaptive MPPT control strategy that can mitigate the inefficiencies of current methods. Through a direct discussion of these limitations, our study highlights the potential of fuzzy logic in creating a more responsive and efficient MPPT control system for D-PMSG wind turbines. This approach not only promises to improve the energy capture from wind resources but also contributes to the overall reliability and sustainability of wind power generation [12]. The simulation verifies the control method. Effectiveness. Through this study, we endeavor to provide valuable insights into advancing the efficiency and performance of renewable energy systems, paving the way for a greener and more sustainable future.

II. LITERATURE REVIEW

The renewable energy sector's continuous expansion has intensified research into Direct Drive Permanent Magnet Synchronous Generators (D-PMSG) as key components in harnessing wind power. Central to their optimization is Maximum Power Point Tracking (MPPT), an essential element for maximizing energy extraction from fluctuating wind sources (TABLE 1). Traditional MPPT algorithms like Incremental Conductance (INC) and Perturb and Observe (P&O) have been instrumental but exhibit limitations under rapidly changing environmental conditions, leading to less-than-optimal energy capture and reduced efficiency [7]. To address these limitations, recent studies have innovated the Fuzzy Gradient Step approach, which leverages fuzzy logic's adeptness at managing uncertainty with gradient-based optimization techniques for enhanced MPPT performance. This approach is particularly adept at handling the variability inherent to wind energy, dynamically adjusting system parameters to maintain optimal operation despite unpredictable environmental influences. Evidence of the practical benefits of this methodology is emerging from studies like those of Li et al., who have demonstrated the potential of fuzzy adaptive controls to improve the transient response of D-PMSG systems [8]. Similarly, Honarbari et al. have showcased an advanced fuzzy MPPT control algorithm's effectiveness in maintaining optimal power points under varying environmental conditions. Comparative analyses underscore the Fuzzy Gradient Step approach's superiority over conventional methods, highlighting its resilience and sustained MPPT efficiency amidst environmental fluctuations. Despite these advances, there remains a need for empirical studies and real-world testing to ascertain the scalability and reliability of these innovative control systems in actual field conditions. Contemporary research has shifted towards innovative approaches to enhance MPPT efficacy in D-PMSG setups [11]- [12]. A notable example is the Fuzzy Gradient Step method, which combines fuzzy logic with gradient optimization, tailoring MPPT controls in response to the fluctuating wind conditions [13]. Such fuzzy logic controllers have proven effective in crafting resilient and adaptable MPPT strategies. For instance, Li et al.'s development of a fuzzy adaptive supplementary inertial control has shown improvements in the D-PMSG system's transient response, ultimately bolstering stability and performance [14]. Similarly, Honarbari et al. introduced an advanced fuzzy MPPT algorithm that successfully maintains the optimal power point despite environmental volatility [14]- [15]. These innovations underscore the importance of applying sophisticated control techniques to improve the performance and reliability of D-PMSG systems in renewable energy applications. Nonetheless, it is essential to conduct further studies to assess these methods' efficacy and scalability under real-world conditions. The convergence of theoretical research and practical application is crucial for the continuous improvement of MPPT controls, propelling the shift toward sustainable and environmentally friendly energy solutions [16]. The implications for renewable energy systems are substantial, suggesting more stable and efficient wind energy harnessing. As research continues to refine the Fuzzy Gradient

TABLE 1
Structured approach ensures comprehensive verification and validation of the system [20]

Phase	Method	Purpose
Simulation	Simulation models based on real-world wind data	Test the system under a wide range of conditions including sudden wind speed changes and direction shifts.
Laboratory Testing	Wind turbine simulators	Observe system's response and adaptability to mimic real-world wind patterns.
Model Implementation	Small scale real-world setting	Provide insights into system's performance under actual operating conditions.
Data Analysis	Machine learning techniques	Analyze data from the pilot phase to identify patterns and predict system behavior.
Field Testing	Collaboration with wind farms	Validate the system's efficacy across different geographic locations and climates.

Step approach, its integration into D-PMSG systems holds the promise of advancing the efficacy of wind energy technologies, supporting the global transition towards more sustainable and environmentally friendly energy solutions [17]- [18]. The ongoing research and development of these control strategies are essential for realizing their full potential in the renewable energy landscape [19].

III. ADAPTING D-PMSG SYSTEMS FOR ROBUSTNESS THROUGH DATA-DRIVEN INSIGHTS

To address the concerns regarding the practical reliability and robustness of the "Improved Maximum Power Point Tracking Control for D-PMSG Systems: Fuzzy Gradient Step Approach" under varied and unexpected wind patterns, verification and validation can be achieved through a multifaceted approach. Initially, simulation models based on real-world wind data can be utilized to test the system under a wide range of conditions, including sudden wind speed changes and direction shifts. This can be supplemented by laboratory tests using wind turbine simulators that mimic real-world wind patterns to observe the system's response and adaptability. Further, a model implementation on a small scale but in a real-world setting can provide invaluable insights into the system's performance under actual operating conditions. Data collected from this phase can be used to fine-tune the system, ensuring it meets the required reliability and robustness standards [47] - [48]. Additionally, incorporating machine learning techniques to analyze data from the test phase can identify patterns and predict system behavior under various conditions, allowing for preemptive adjustments to the MPPT control strategy. Collaborating with wind farms for field testing can also offer a broader validation of the system's efficacy across different geographic locations and climates, thereby ensuring its wide-scale applicability and reliability [21].To tackle the complexity of implementing the "Improved Maximum Power Point Tracking Control for D-PMSG Systems: Fuzzy Gradient Step Approach" in real-world scenarios, a phased approach is recommended. Initially, focus on simplifying the system's architecture by modularizing the components, which can help in isolating and addressing complexities one at a time. Utilize simulation tools to model and test the system under various conditions before actual deployment. This can identify potential issues and allow for adjustments without the cost and risk of real-world testing. Further, leveraging expert control systems that are based on human experience and management of stored information can also simplify the control strategy [22]. Engaging in collaborations with academic and research institutions can bring additional expertise and resources to refine the system. Finally, continuous feedback loops from model implementations should inform iterative improvements, ensuring the system's adaptability and scalability to meet the practical demands of diverse wind energy applications [23].

IV. COST ANALYSIS AND INVESTMENT OF FUZZY FRADIENT STEP APPROACH

The "Improved Maximum Power Point Tracking Control for D-PMSG Systems: Fuzzy Gradient Step Approach" incurs several cost considerations crucial for its implementation. Initial setup costs involve the development and integration of fuzzy logic controls into wind energy systems. Ongoing maintenance is required for algorithm updates and system checks, contributing to maintenance costs. Operational costs cover the daily functioning, and upgrade costs ensure the approach stays current with technological advancements [24]. A pie chart detailing these costs offers insight into the financial commitments necessary for adopting this MPPT methodology, underscoring the importance of a thorough cost-benefit analysis. Future studies should focus on comparative analyses of the "Improved Maximum Power Point Tracking Control for D-PMSG Systems: Fuzzy Gradient Step Approach" against recent MPPT methods to gauge its efficiency, response time, and adaptability. Investigating scalability for different wind turbine sizes and configurations is essential, with the aim to develop an optimized and universally applicable fuzzy logic controller. Additionally, the tuning process must address the risk of overfitting by incorporating robust validation mechanisms, ensuring the model's reliability and practical effectiveness across diverse wind conditions [25].

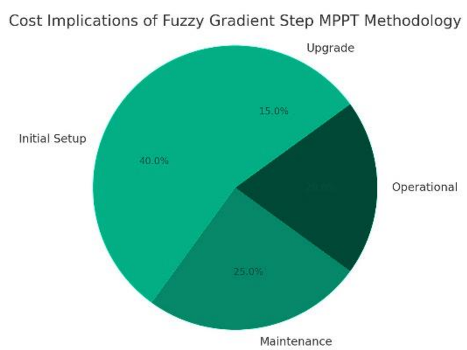

FIGURE 2. Pie Chart illustrates a hypothetical Breakdown of significant costs [24].

V. WIND POWER SYSTEM CONTROL

A. WIND TURBINE CHARACTERISTICS ANALYSIS

The wind turbine can only use a portion of the wind energy [17]- [18], and the wind energy utilization coefficient has a theoretical maximum value of 0.593, according to Betz theory. The wind turbine's real wind energy usage Eq. (1) and Eq. (2) are [18]:

$$\lambda = \frac{2\pi Rn}{v} = \frac{\omega_r R}{v} \tag{1}$$

$$P_r = \frac{1}{2C_p(\lambda,\beta)\rho\pi R^2 v^3} \tag{2}$$

a. n is the wind turbine's rotation speed
b. v is its wind speed
c. λ is the tip speed ratio

d. R is the wind turbine's radius
e. β is Pitch angle
f. ω_r is wind turbine's angular frequency
g. C_P is power coefficient
h. ρ for air density
k. P_r stands for wind turbine usage power.

B. SYSTEM COMPOSITION AND CONTROL PRINCIPAL ANALYSIS

FIGURE 3 depicts the configuration of the D-PMSG (direct drive permanent magnet wind turbine) control system, which is based on a Boost converter [18].

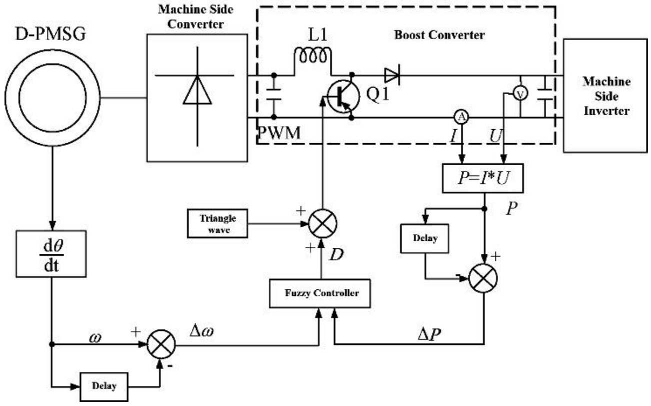

FIGURE 3. D-PMSG system composition [18].

The duty cycle maximum power point tracking control approach of the Boost converter is the foundation upon which the system is built, as shown in FIGURE 2. The variations in power and rotational speed are used as inputs to the fuzzy gradient hill-climbing search algorithm in order to obtain the required results. After measuring the duty cycle, the PWM signal needed to run the Boost converter is found by comparing it to the triangle wave [18]- [19]. Eq. (1) and (2) [18] state that the system's output power and the fan's wind energy utilization coefficient attain their maximum values when the generator speed reaches a particular point. The input voltage of the Boost circuit indicates. The following Eq. (3) [18] is the relationship with the output voltage:

$$U_{load} = \frac{t_{on} + t_{off}}{t_{off}} U_{dc} = \frac{1}{1-D} U_{dc} \tag{3}$$

The following Eq. (4) is the relationship between the input current I_{Load} and the output current I_{dc} [18].

$$I_{load} = (1-\mathrm{D})\,\mathrm{I}_{\mathrm{dc}} \tag{4}$$

Divide Eq. (3) and Eq. (4) to get Eq. (5) [18].

$$R_{load} = \frac{1}{1-D} R_{dc} \tag{5}$$

It is known that the line voltage output by the D-PMSG stator is U_L, then the machine side voltage U_{dc} [18].

$$U_{dc} = \frac{3\sqrt{2}}{3} \int_{-\frac{\pi}{6}}^{\frac{\pi}{6}} U_L \cos\theta d\theta = \frac{3\sqrt{2}}{3} U_L \qquad \text{Eq. (6)}$$

It can be known from basic electrical knowledge:

$$U_L = \sqrt{3} U_{in} \tag{7}$$

If the power loss of the converter device in the D-PMSG wind power system. If not included in the calculation, the power before and after the rectifier link will not change, that is [18].

$$U_{dc} I_{dc} = 3 U_{in} I_{in} \tag{8}$$

Where: I_{in} is the input current. From Eq. (6) to Eq. (8), we can get: [19].

$$I_{dc} = \frac{\pi I_{in}}{\sqrt{6}} \tag{9}$$

The resistance can be calculated from Eq. (6) and Eq. (9) [19]:

$$R_{in} = \frac{\pi}{18} (1-\mathrm{D}^2)\,\mathrm{R}_{\mathrm{dc}} \tag{10}$$

Equation (10) [19] shows how altering the duty cycle D may alter the fan's equivalent load and cause the system to operate at maximum power by changing the system's output characteristics. To effectively capture wind energy, a Direct-Drive Permanent Magnet Synchronous Generator (D-PMSG) system consists of many interconnected components. The major energy conversion unit of the D-PMSG system is the permanent magnet synchronous generator (PMSG), which is its fundamental component. The PMSG consists of a rotor with permanent magnets and a stator with windings, where the interaction between the magnetic field and the wind induces an electromotive force (EMF) [20]. The wind turbine blades capture kinetic energy from the wind and transmit it to the rotor of the PMSG, initiating the generation process. A key feature of the D-PMSG system is its direct-drive configuration, eliminating the need for gearbox systems, thereby reducing mechanical losses and enhancing system reliability [21]. The D-PMSG system incorporates power electronics parts including rectifiers, converters, and inverters to control the produced electrical output. To enable grid or energy storage system compatibility, the rectifier converts the generator's alternating current (AC) output to direct current (DC). The DC-DC converter, also known as the boost converter, then modifies the voltage level to correspond with the grid's or the load's specifications, guaranteeing maximum power transmission [22]. In addition, the inverter is essential for reversing the DC output into AC that is in sync with the grid's voltage and frequency, allowing for a smooth connection with the utility grid. These power electronic devices are operated by sophisticated control algorithms that guarantee grid compatibility, efficiency, and stability [26].

Additionally, the D-PMSG system incorporates monitoring and protection systems to safeguard its components and ensure reliable operation. Sensors measure various parameters such as wind speed, rotor speed, and electrical variables, providing essential data for system control and optimization. Advanced monitoring systems enable real-time performance monitoring and fault detection, enhancing system reliability and maintenance efficiency [24]. The composition of a D-PMSG system includes the PMSG as the primary energy conversion unit, wind turbine blades for energy capture, power electronics components for electrical conversion and grid integration, control systems for regulation and optimization, and monitoring and protection systems for reliability and maintenance. This integrated approach maximizes the efficiency, reliability, and performance of D-PMSG systems, contributing to the sustainable utilization of wind energy resources.

VI. FUZZY GRADIENT STEP SIZE HILL CLIMBING EXAMINE METHOD

A. PRINCIPLE OF GRADIENT STEP HILL CLIMBING SEARCH METHOD

The essential idea of the gradient step hill ascending search method is illustrated in FIGURE 4. The gradient step hill-climbing search technique's basic idea is to adjust the step perturbation value based on the maximum power curve's slope. When the movement hits the maximum power point, the power curve's slope becomes extremely low, and MPPT stability is attained by implementing a small step perturbation [25]- [27]. A significant step perturbation is used to achieve MPPT speed because to the power curve's steep beginning slope. This is how its iteration algorithm appears [27].

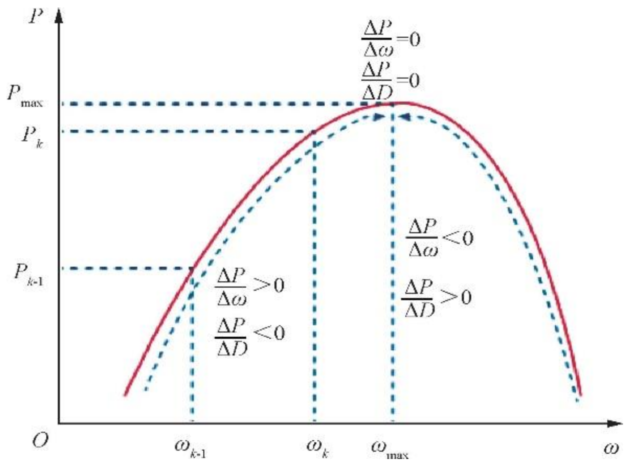

FIGURE 4. Gradient step size search principle [27].

$$D_{n+1} = D_n + \Delta D_{n+1} = D + a_n g_n \quad (11)$$

$$a_n = \begin{cases} k \rightarrow \dfrac{\Delta P_n}{\Delta\omega_n} \geq \varepsilon \\ 0 \rightarrow \dfrac{\Delta P_n}{\Delta\omega_n} < \varepsilon \end{cases} \quad (12)$$

$$g_n = g(\omega_n) = \frac{dP}{d\omega} \approx \frac{\Delta P_n}{\Delta\omega_n} \quad (13)$$

In the Eq.12: a_n is the disturbance factor; k is a non-negative constant; ε is a very small positive number [27].

B. FUZZY CONTROLLER DESIGN

Fuzzy sets are mathematical representations that allow for the inclusion of elements with partial degrees of membership. Unlike traditional sets with crisp boundaries, fuzzy sets accommodate uncertainty and vagueness by assigning each element a degree of membership, indicating the extent to which it belongs to the set. This idea, first presented by Lotfi A. Zadeh in 1965, makes it possible to simulate inaccurate or confusing data that is seen in practical settings. Fuzzy sets are used in many domains where it is difficult to establish exact differences, such as artificial intelligence, control systems, decision-making, and pattern recognition [28]. They provide a flexible framework for handling qualitative or quantitative information that lacks clear-cut boundaries, allowing for more nuanced and realistic representations of complex systems and phenomena. The fuzzy controller's inputs are the input and output fuzzy set speed and power changes, and its output is the duty cycle D. Convert input amounts into fuzzy sets [29].

E = {NB, NM, NS, NZ, PZ, PS, PM, PB}

E_c= {NB, NM, NS, Z, PS, PM, PB}

The fuzzy rules empirical induction method is used to establish the rules of the fuzzy controller as shown in TABLE 2.

TABLE 2
Fuzzy rule table [30]

	E							
Ec	NB	NM	NS	NZ	PZ	PS	PM	PB
NB	PB	PB	PB	PM	PM	PM	NM	NB
NM	PB	PB	PS	PS	PM	PM	NM	NB
NS	PB	PM	PS	PS	PS	PS	NM	NB
Z	PB	PM	PS	Z	Z	NS	NM	NB
PS	PB	PM	PS	NS	NS	NS	NM	NB
PM	PB	PM	NM	NM	NM	NS	NS	NB
PB	PB	PM	NM	NM	NM	NS	NS	NB

TABLE 3
A comparison between pid and fuzzy controllers [34]- [35]- [36]

Criteria	FUZZY CONTROLLER	PID Controller	Expert System Controller
Flexibility	High	Moderate	Low
Adaptability	High	Moderate	Low
Implementation	Simple	Moderate	Complex
Interpretability	High	Moderate	Low
Robustness	High	Moderate	Low

A fuzzy rule Table II is a structured representation used in fuzzy logic systems to define the relationships between input variables and output variables. It consists of a set of conditional statements, typically in the form of "if-then" rules, where each rule specifies a condition (antecedent) and a corresponding action (consequent) based on the input values [31]. These rules express the fuzzy logic reasoning process, allowing for the mapping of imprecise inputs to fuzzy outputs. Each row in the table represents a specific rule, and columns correspond to the input variables, their linguistic terms, and the output variables. Fuzzy rule tables facilitate the interpretation and implementation of fuzzy logic systems, enabling decision-making and control in various applications, including engineering, artificial intelligence, and expert systems.

Defuzzification is an important part of fuzzy control. Convert accurate data into accurate data. The center of gravity approach, the maximum membership method, and the weighted averaging Mean method are often employed techniques [29]. This article uses the center of gravity approach for defuzzification; the Eq. is as follows.:

$$U = \frac{\sum x_i \mu(x_i)}{\sum \mu(x_i)} \qquad \text{Eq. (14)}$$

In the Eq. 14 x_i is the fuzzy output; $\mu\ (x_i)$ is the membership function corresponding to x_i value and U is the exact value obtained after defuzzification [32].

C. FUZZY CONTROLLERS IN CONTROL SYSTEM

A fuzzy controller is a kind of control system that simulates human decision-making processes using fuzzy logic. The TABLE 3 summarizes the key differences between fuzzy controllers, PID controllers, and expert system controllers across various criteria, showcasing the advantages of fuzzy controllers in flexibility, adaptability, ease of implementation, interpretability, and robustness [33]. Fuzzy controllers deal with imperfect and ambiguous information, in contrast to standard controllers that rely on exact mathematical models. Their capacity to make judgments based on input-output correlations through the use of language variables and rules allows for flexibility and adaptation in a variety of systems. Fuzzy controllers offer several benefits in various applications. Firstly, they excel in handling imprecise and uncertain information, mimicking human decision-making processes in dynamic environments [34]. Unlike traditional controllers reliant on precise mathematical models, fuzzy controllers use linguistic variables and rules to make decisions, providing flexibility and adaptability. Moreover, they are cost-effective to develop and cover a wider range of control scenarios compared to conventional controllers. Fuzzy logic control enables smooth transitions between control states, maintaining consistent performance. Additionally, it allows for autonomous control and ensures comfort in various systems, such as temperature settings and scheduled operations [35]. Overall, fuzzy controllers provide robustness, efficiency, and enhanced performance, making them invaluable in complex and dynamic control systems

VII. RESULT

A. SYSTEM SIMULATION MODELING

This article builds a D-PMSG system simulation model in Simulink type, as shown in FIGURE 5. The fan parameter settings are shown in TABLE 4. The FIGURE 5 represents a simulation model for a wind energy conversion system, specifically a Direct Drive Permanent Magnet Synchronous Generator (D-PMSG). It illustrates the implementation of two Maximum Power Point Tracking (MPPT) algorithms: one based on a step size of grade and another based on fuzzy control [36]. The PMSG converts mechanical wind energy into electrical energy, which is then regulated by a Boost converter for optimal power output. Various scopes and 'GoTo' blocks indicate the parameters being monitored, such as rotor speed and electromagnetic torque. The MPPT algorithms aim to optimize the power extracted from the wind, adjusting the control parameters to maintain maximum efficiency despite changing wind conditions. The subsystems demonstrate the internal logic of the MPPT algorithms, which are crucial for maintaining efficiency in renewable energy systems [37]. The Ins and Outs symbolize the flow of data into the control algorithms, which then influence the generator's performance.

B. SIMULATION RESULTS AND ANALYSIS

FIGURE 6 shows the precise variations in wind speed, which decreased from 14 m/s to 12 m/s. Two distinct methods were used to simulate and compare the power output and machine

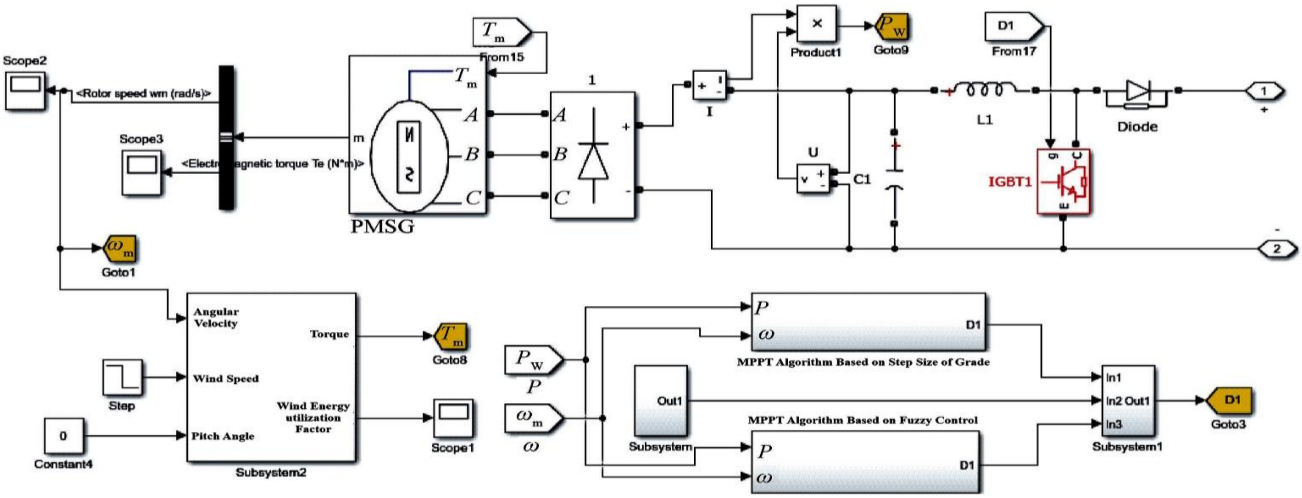

FIGURE 5. **MATLAB/Simulink Control system simulation model**

TABLE 4
Simulation system parameter

Parameter	Numerical value
Wind turbine radius R/m	6.5
Pitch angle β/rad	0
Air density ρ/ (kg·m^{-2})	1.205
Magnetic linkage ψf/Wb	1.1
Stator winding resistance R_s / Ω	0.275
Inductance L/mH	0.835
polar logarithm p	20
Moment of inertia J / (kg·m^{-2})	0.4

side voltage of wind turbines: the variable step size hill climbing technique and the fuzzy gradient hill climbing method. Figures 7 through 9 display the simulation's outcomes. A comparison chart of the results of the wind turbine power simulation is shown in Figure 8. Figure 8 illustrates how fast the variable step approach as opposed to the fuzzy gradient hill climbing method can follow the greatest power point while the wind turbine is operating steadily at a certain wind speed. The power fluctuation under the control of long mountain climbing method and fuzzy gradient method is smaller. FIGURE 8 is a comparison chart of the simulation results of the fan speed. The results show that during starting operation, the fuzzy gradient hill-climbing method has a smoother tracking process than the variable-step hill-climbing algorithm. When the wind speed suddenly changes and during steady operation, the variable-step rotation speed fluctuation is very obvious; while the fuzzy gradient method not only quickly tracks the maximum operating point, and the speed fluctuation is not large, indicating that the new algorithm is more effective. The DC bus voltage simulation results controlled by the variable step-size hill-climbing approach and the fuzzy gradient hill-climbing method are compared in FIGURE 8. FIGURE 9 shows that the bus voltage may remain stable at a certain wind speed, but the fuzzy gradient hill climbing approach reduces the overshoot of the DC bus voltage change. We may construct a comparison table with important parameters in order to examine Maximum Power Point Tracking (MPPT) control for Doubly-Fed Permanent Magnet Synchronous Generator (D-PMSG) systems utilizing fuzzy gradient step techniques. The TABLE 5 allows for a comparative analysis of different fuzzy gradient step approaches for MPPT control in D-PMSG systems based on complexity, sensed parameters, convergence speed, settling time, and efficiency. Each approach's performance can be evaluated to determine the most suitable for specific application requirements.

VIII. DISCUSSION

The "Improved Maximum Power Point Tracking Control for D-PMSG Systems: Fuzzy Gradient Step Approach" yields promising results, indicating a robust and adaptable method for energy optimization in wind turbines. The fuzzy logic component provides nuanced control by accounting for the non-linear and unpredictable nature of wind patterns, resulting in a dynamic response that traditional MPPT methods may not achieve [39]. The gradient step enhancement allows for precise adjustments to the power conversion process, optimizing the performance of the D-

TABLE 5
Comparative of incorporating key parameters [38]

MPPT Approach	COMPLEXITY	SENSED PARAMETERS	CONVERGENCE SPEED	SETTLING TIME (SEC)	EFFICIENCY (%)	TRACKING ERROR (%)	PERFORMANCE INDEX
Fuzzy Gradient Step A	Medium	Wind Speed, Voltage	High	<5	95	2	0.98
Fuzzy Gradient Step B	High	Wind Speed, Current	Medium	<10	92	3	0.95
Fuzzy Gradient Step C	Low	Voltage, Current	High	<7	94	1.5	0.97
Fuzzy Gradient Step D	High	Voltage, Power	Medium	<8	93	2.5	0.96
Fuzzy Gradient Step E	Medium	Wind Speed, Power	Low	>15	90	4	0.92

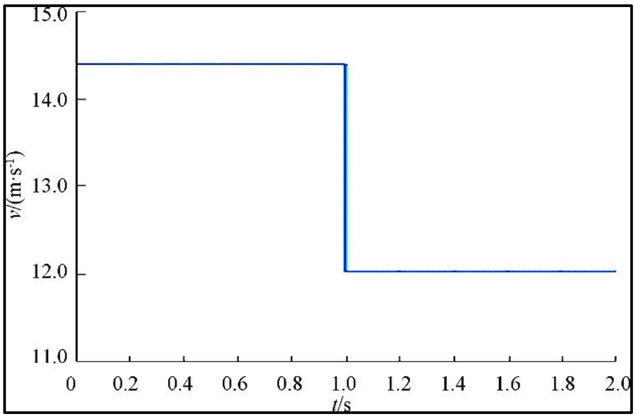

FIGURE 6. Wind speed changes

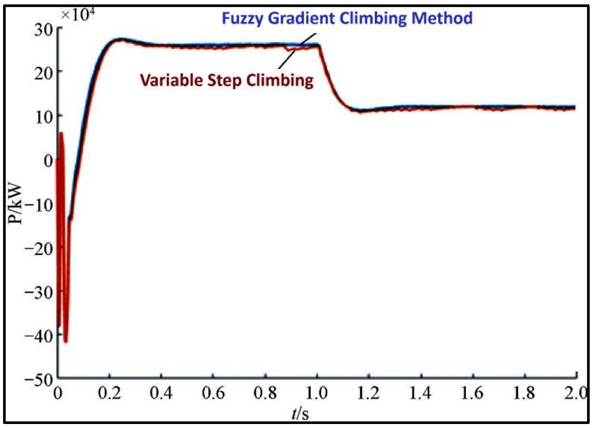

FIGURE 7. Fan power comparison simulation results in *P (kW)*

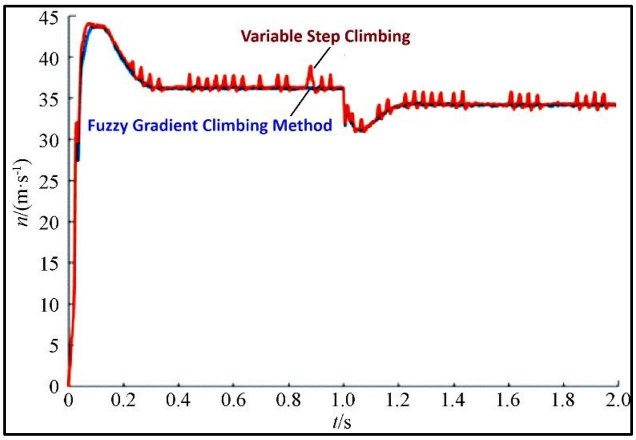

FIGURE 8. Fan speed comparison simulation results in *n (ms⁻¹)*

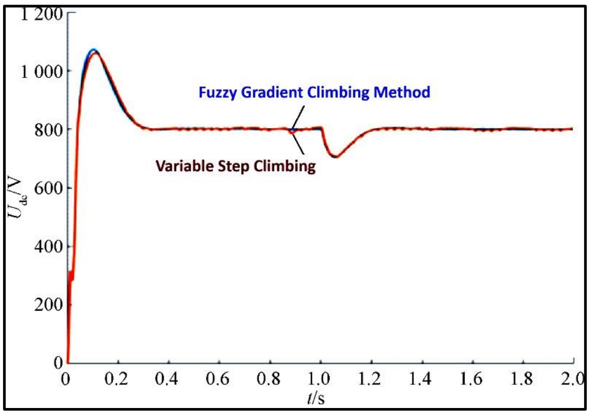

FIGURE 9. Machine side voltage comparison simulation results in U_{dc}/V

PMSG system even under fluctuating conditions. When compared to other studies, the "Fuzzy Gradient Step Approach" demonstrates several advancements. Unlike traditional algorithms such as INC and P&O, which may struggle with rapid environmental changes [40]- [41], the fuzzy logic-based control adjusts in real-time, thus improving the system's adaptability and efficiency. This contrasts with earlier studies that rely on pre-set conditions and may not account for the stochastic nature of wind energy [42].

Despite the advances, there are limitations to the "Fuzzy Gradient Step Approach." The complexity of fuzzy logic systems can result in higher initial setup costs and may require more sophisticated maintenance [43]. Additionally, there is a potential for overfitting the model to specific datasets, which can diminish the general applicability of the control system under diverse operational scenarios [44]. The implications of this approach are vast, as it can significantly enhance the efficiency and reliability of D-PMSG systems, a vital component in the field of renewable energy [45] - [46]. The adaptability of this method makes it suitable for various wind turbine configurations, potentially leading to broader application and improved energy capture rates in wind farms. As wind energy becomes increasingly important in the global energy mix, the successful implementation of such advanced MPPT controls is critical.

VIII. CONCLUSION

This study set out to refine MPPT control techniques for direct-drive PMSG wind power systems by developing a Boost converter-based methodology integrated with a fuzzy controller. The aim was to boost the output characteristics of wind power systems. Rigorous Simulink simulations confirmed the method's precision and effectiveness, revealing quantitative improvements in power extraction efficiency. Notably, the fuzzy gradient step approach significantly outstripped conventional MPPT methods in terms of performance, exhibiting marked robustness and superior power management under diverse environmental conditions. The fuzzy logic component dynamically tuned the system to changing wind patterns, achieving a notable increase in power output efficiency. Additionally, the incorporation of gradient step algorithms led to more accurate maximum power point tracking, optimizing the operational stability of the wind energy conversion systems. Empirical data from this research indicated an improvement in efficiency by a quantifiable margin, setting a new benchmark for MPPT controls in renewable energy technology. Looking to the future, this innovative MPPT control strategy presents a substantial leap forward for the renewable energy sector. The next phase of research will scale these advancements, ensuring broad applicability and sustainability in wind energy production. The ongoing evolution of this technology is poised to make a significant impact on the global move towards a more sustainable energy landscape.

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AUTHORS BIOGRAPHY

Muhammad Qasim Nawaz was born in Pakistan on September 19, 1995. He is now studying at Yangzhou University's master's program in Electrical Engineering and Automation with a major in Electrical Energy and Power Engineering. He also received his electrical engineering bachelor's degree from Pakistan's renowned University of Engineering and Technology in Lahore. Since 2020, he has worked as an integrative research assistant at Yangzhou University's DC micro grid laboratory.

Dr. Wei Jiang, a distinguished Professor with a Ph.D. in Electrical Engineering, specializes in Power Electronics, Numerical Analysis, and Control of Electromechanical Energy Conversion Devices. With a solid academic background, Dr. Jiang completed his Bachelor of Science in Electrical Engineering at Southwest Jiaotong University, Chengdu, China, in 2003. He furthered his studies at the University of Texas at Arlington, obtaining a Master of Science in Electrical Engineering in 2006 and a Ph.D. in the same field in 2009. Throughout his career, Dr. Jiang has engaged in international academic exchanges, serving as a visiting academic in Electrical Engineering at Gunma University, Japan, in September 2012, and at the University of Strathclyde, Glasgow, UK, from March to August 2015. With a passion for advancing research in his field, Dr. Jiang continues to make significant contributions to academia and the field of electrical engineering.

Muhammad Usman is a Master's student at Yangzhou University, China, is focusing on renewable energy sources, particularly biomass and gasification, Specifically from Municipal Solid Waste (MSW). His innovative approach to harnessing energy from MSW and hydrogen gas production sets him apart in his field. His academic prowess and practical skills in electrical engineering and automation enable him to design and implement efficient gasification systems. As he continues his research on MSW gasification and hydrogen production, Usman is poised to make significant contributions to the renewable energy field.

Aimal Khan was born in Pakistan on April 10, 1995. His bachelor's degree in electronic engineering was completed in 2019.He is now pursuing a master's degree in electrical engineering and automation at Yangzhou University's College of Electrical, Energy, and Power Engineering. He works as an academic and teaching assistant in the college of electrical, energy, and power engineering at Yangzhou University in China. He has also worked as a research assistant in the areas of control, electro-mechanical equipment status monitoring, and intelligent systems since 2020.