Review on Fuzzy Logic-Based Offshore Wind Farm HVDC Control

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Abstract: *To fulfill rising energy needs while lowering carbon emissions, the integration of offshore wind farms into the electrical grid has become more and more important. Grid stability, however, may face difficulties due to the inherent fluctuation of wind generation. As a promising solution to these problems, this research gives a thorough analysis of fuzzy logic-based offshore wind farm HVDC control. The paper investigates the concepts, benefits, and applications of fuzzy logic control in the context of high-voltage direct current (HVDC) systems for offshore wind farms. The review talks about how fuzzy logic-based control could improve grid frequency management, stability, and power quality. It also emphasizes the requirement for adaptive control techniques to take account of shifting wind conditions. As a result of a combination of case studies and previous research, this review offers valuable insights into the current state of the field and identifies future research directions.*

Keywords: *Offshore wind farm, HVDC control, Fuzzy Logic, Frequency regulation, Grid stability, Renewable energy integration.*

1. INTRODUCTION

The production of wind energy is regarded as the leading renewable energy source because of its reliability, stability, and efficient power generation. In comparison to onshore wind farms, the wind speed in offshore wind farms (OWFs) is potentially higher and more stable, which contributes to increased power generation. There are also few restrictions on the implementation of OWFs compared to onshore wind farms. It is anticipated that the generation of wind energy using OWFs can be nearly 54 GW in the United States. The technical complexities associated with the implementation of offshore platforms and the process of transferring power from OWF to onshore power grids needs significant attention [1]. However, electric power systems worldwide have experienced a significant transformation, which has been predominantly characterized by an increased penetration of power electronic converter interfaced technologies [2]. Among these new technologies are wind and photovoltaic generation, various storage technologies, flexible AC transmission systems (FACTS), High Voltage Direct Current (HVDC), lines, and power electronic interfaced loads. With significant integration of converter interfaced generation technologies (CIGs), loads, and transmission devices, the dynamic response of power systems has progressively become more dependent on (complex) fast-response power electronic devices, thus, altering the power system dynamic behavior.

Concept of Wind Turbine

A great range of configurations has resulted from the field of wind turbine designs' tremendous evolution over the duration of its growth. However, more recent technological developments have brought about a level of standardization that has propelled three-bladed horizontal axis turbines to the top of the industry. Because of the great efficiency and effectiveness of this particular design in capturing wind energy, it has gained considerable adoption. It has actually taken over as the standard option in the industry, being adopted almost entirely by both energy enthusiasts and manufacturers of wind turbines.

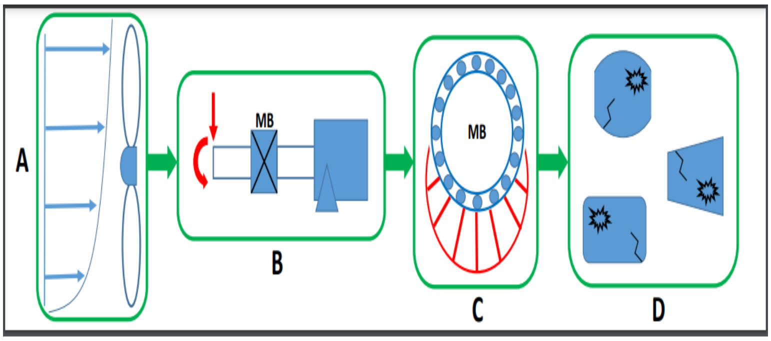

Figure 1.3: Flowchart Illustrating Loading Relationships Leading to Main-Bearing Damage and Failure [3]

Because of the rising need for clean, renewable energy sources, offshore wind farm integration into the world energy landscape has experienced impressive growth in recent years. The strength of strong, dependable winds over vast coastal oceans may be harnessed by offshore wind farms, which provide significant potential for the production of clean electricity. To maximize the effectiveness, stability, and reliability of power generation and transmission, though, complex control systems are needed to fully realize this potential. To manage the complex and dynamic nature of offshore wind farms, particularly when connected through High Voltage Direct Current (HVDC) systems, fuzzy logic-based control strategies have emerged as a cutting-edge solution in this context.

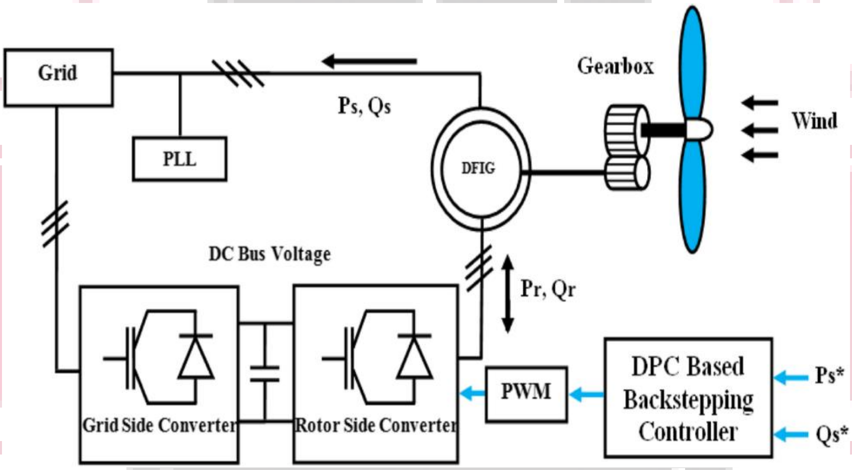

Figure 1.4: DFIG-Based Wind Energy Conversion System Structure [4]

A Wind Energy Conversion System (WECS) is an essential framework for reliably and precisely controlling the efficient capture of electrical energy from wind resources. The three primary categories of this system's architecture are electrical, mechanical, and control systems, each of which is essential to the effective operation of wind turbines. WECS integrates a variety of crucial parts into its electrical system, such as generators that convert wind energy into electrical power, grid-side and generator-side converters that make energy transmission easier, step-up transformers for voltage optimization, harmonic filters for power quality assurance, and distribution systems that are seamlessly integrated into the three-phase grid. The nacelle, which houses the turbine's essential mechanical parts, stands out as a key component in this category on the mechanical front. The mechanical and electrical components of energy conversion are both intimately knit together with the control systems. According to [5], these devices are essential for maximizing turbine performance, assuring safety, and preserving grid compatibility. The two main categories of wind generation—offshore and onshore—each with their own distinctive qualities and difficulties—must be distinguished when looking at the wider technology spectrum of wind turbines.

2. Offshore Wind Generation

In the search for clean and sustainable energy sources, offshore wind power marks a new frontier. Offshore wind farms, in contrast to conventional onshore wind farms, strategically place their wind turbines on water, usually near the coast or farther out at sea. This location benefits from the regular and strong winds that blow over open waters, offering a number of benefits. Higher energy yields and improved reliability are possible thanks to offshore wind farms' access to stronger and more reliable wind resources. In areas with high population densities, they are also a desirable option because they are frequently less intrusive on the landscape and encounter less land-use problems. However, because of the harsh sea climate and the requirement for specialized equipment along with vessels, the installation and maintenance of offshore wind turbines present special engineering and logistical issues.

The emphasis on wind energy has changed significantly during the past ten years, shifting from onshore to offshore regions, especially in Europe. The advantages provided by the open sea, where wind speeds are noticeably stronger and more steady, frequently exceeding 10 meters per second at heights of 50 meters above sea level, have been the driving force behind this transformation. Offshore wind energy has a lot of potential because of its greater resource potential, which tends to increase with distance from the coast and produces significantly higher energy yields [6]. A different set of design factors must be taken into account when using wind energy at sea as opposed to on land. The average capacity of wind farms climbed dramatically to 485 MW in 2013, which is a remarkable 78% growth from the previous year, while the average turbine size remained largely unchanged from the previous year at 4 megawatts (MW). It's important to note that the average turbine capacity fell to 3.7 MW in 2014, a 7.5% fall from 2013, partly as a result of the rising use of Siemens' 3.6 MW wind turbine technology [6].

4. EMERGING TRENDS – RELATED WORK

Offshore wind farms (OWFs) have drawn interest because of the abundance of wind energy they can produce and their growing distance from the coast, according to Yang, B., et al. 2022 [7]. Three power transmission systems are suggested for connecting these huge OWFs to onshore grids: high voltage alternating current (HVAC), high voltage direct current (HVDC), and low-frequency alternating current (LFAC). This paper includes five HVDC topologies and offers a thorough analysis of these technologies. The fault ride-through technologies are also discussed, and eight indications are used to evaluate the seven grid connection choices. The report presents six potential research directions for integrating big OWFs and summarizes eight major findings.

According to Dongyeong Lee et al., [8] Offshore wind energy has become a promising and preeminent renewable energy source as the world's focus on reaching carbon neutrality has grown. Grid stability is challenged by the inherent fluctuation and uncertainty of renewable energy sources. Wind generators must cooperate in frequency regulation to solve this problem. Large offshore wind farms that are linked by high-voltage direct current (HVDC) systems have an independent offshore frequency from the onshore grid. The frequency fluctuations induced by wind generation under typical conditions are addressed in this work by introducing a sustainable control strategy. The management of extreme wind fluctuations is made possible by deploying communication-free frequency regulation through offshore wind farm HVDC systems. By employing only local data and this creative approach, offshore wind power may regulate onshore frequency using local measures alone, without the need for communication infrastructure. Analysis of the frequency response and control stability trajectory was done to evaluate the system's performance and control stability. To guarantee efficient control in a variety of wind situations, an adaptive gain mechanism is also suggested. According to the results of the simulation, this autonomous frequency smoothing control is effective at regulating frequency and is well suited for big offshore wind farms that use HVDC technology. Last but not least, this suggested frequency smoothing control has the potential to improve carbon neutrality in power systems with low inertia and low frequency regulation reserves.

According to Desalegn B et al., [9] continuous advancement of supporting technologies and research pertaining to wind farm systems is required to maintain the wind power industry's competitiveness. Wind farm technologies, which include different turbine generating systems and power transmission arrangements, have a significant impact on the efficiency of wind energy production. Furthermore, in order to fulfill the increasingly complex demands for electricity generation, contemporary wind farms must use reliable power control algorithms. In order to reshape the wind power industry, this study explores the existing situation, potential future effects, and wind farm control measures. Wind energy harvesting technology built on the Doubly Fed Induction Generator (DFIG) has reached maturity and shown a solid track record in recent experiences. The fundamental reason for its incompatibility with high-voltage power transmission networks is that it is not scaleable for large-scale power production. In contrast, technology based on Permanent Magnet Synchronous Generators (PMSG) is significantly improving to achieve maximum efficiency, enabling larger-scale power generation. But there is still a need for the expensive and large building of electricity transmission infrastructure. The cost and design of high-voltage power transmission lines should be optimized in the wake of upcoming technical developments in the wind farm sector.

Parallel to this, more and more studies are integrating power optimization-based control models to smoothly incorporate these wind farm technologies, hence improving electricity production dependability while assuring system safety. But additional investigation is anticipated in the future to carry out thorough analyses of the effectiveness of various control models under comparable environmental circumstances.

The rising use of renewable energy sources and power electronics in the power system causes the inertia of the grid to decrease continuously as the amount of wind power in the electrical grid continues to increase, according to Li Q et al., [10]. The stability of the system's frequency can be greatly impacted by this loss of inertia. System stability and frequency regulation are greatly influenced by the inertia of the system. This research offers a revolutionary fuzzy logic-based virtual inertial control method to overcome this problem. This technology has been created expressly to let wind turbines take an active role in controlling grid frequency. In this method, a fuzzy logic controller that adjusts the frequency adjustment coefficient adaptively depending on power tracking is developed. Power tracking curve optimization is done in real-time using fuzzy logic rules. A real-time simulation platform with hardware-in-the-loop capabilities is built to verify the efficacy of this technology in supporting system frequency and boosting the frequency response of the power grid. The study makes a case for the technology's practical advantages in preserving system frequency stability and enhancing the grid's capability to react to frequency changes through the use of this platform.

The growing integration of renewable energy sources into power systems necessitates novel functionalities from renewable generation plants, according to Jesús Castro Martínez et al. [11]. System operators are particularly concerned about maintaining system stability, as renewable generators tend to act as consistent power sources. As a result, grid-following generators are being required to take on additional roles to enhance their contribution to system stability, essentially transforming into grid-supporting generators. However, the application of grid-supporting control can still pose challenges to system stability, especially with a high penetration of renewables. This has led to the emergence of grid-forming control strategies to ensure reliable operation. This paper presents an innovative grid-forming control approach tailored for doubly-fed induction generators (DFIGs), enabling them to function akin to authentic voltage sources. The proposed grid-forming control hinges on orienting the rotor flux to a reference axis derived from the emulation of the synchronous generator's swing equation. Achieving this rotor flux orientation is managed by a flux controller, which concurrently regulates the flux magnitude. This flux orientation, in turn, facilitates control over the DFIG's torque, while the regulation of flux magnitude permits the management of reactive power or terminal voltage. To assess its grid-forming capability, the proposed control system has been thoroughly validated via real-time simulations with hardware in the loop. Furthermore, a small signal analysis has been carried out to evaluate system stability.

According to Aboozar Mohammad Nezhad et al. [12], for a grid-connected doubly fed induction generator (DFIG), a unique control method is presented in this work. The durability of this method is demonstrated in the presence of measurement noise and parametric uncertainty. The rotor side converter (RSC) controllers and the grid side converter (GSC) controllers are the two main categories that the doubly fed induction generator (DFIG) controllers fall under. The parameters of a DFIG may differ from the values that were provided due to operational differences. In order to address this, a robust H vector control (VC) is used, utilizing the complex sensitivity technique, to manage this parametric uncertainty. Instead of proportional-integral (PI) controllers, a robust controller that has been built has been employed in the RSC controller's development, which was done utilizing the vector control method. Obtaining the measured currents for use in the control equations is one of the steps in vector control. System control will be compromised by noise-polluted currents. Therefore, it is advised that a Kalman filter be used to address this issue. After then, thorough simulations run in a variety of scenarios are used to examine the effectiveness of the suggested strategy. The outcomes show that the proposed controller performs effectively and is robust to model and measurement uncertainty.

Benbouhenni, H., & Bizon, N. [13] introduces a novel method for controlling the flux and torque of a single-rotor wind turbine (SRWT) driven by an asynchronous generator (AG), known as "third-order sliding mode controller-based direct flux and torque control" (DFTC-TOSMC). This innovative method provides an alternative to well-known techniques like direct flux and torque control (DFTC) or direct torque control (DTC) combined with an integral proportional regulator (DFTC-PI), which have gained popularity in asynchronous generators due to their efficiency gains over conventional DFTC switching techniques. However, a significant drawback of these approaches is the substantial magnetic flux and torque ripples introduced by the classical PI regulator. To overcome these limitations, this research focuses on enhancing the strategy by eliminating these PI regulators. The proposed strategy employs a TOSMC method as a replacement, maintaining the same inputs as the removed regulators. Numerical simulations were conducted using MATLAB software to evaluate the effectiveness of the designed strategy in comparison to the traditional approach. The results obtained from these simulations provide insights into the improved performance of the proposed strategy relative to the conventional one.

In 2016, Turkey ranked first in Europe and the world for the increase of wind power capacity thanks to the country's wind energy market's considerable growth. Turkish offshore wind farms are not yet in operation, despite the country's vast onshore and offshore wind potential. Using multi-criteria site selection, energy output estimation, and economic feasibility analyses, Umit Cali et al. [14] conducts a complete techno-economic analysis of potential offshore wind farm projects in three feasible locations. The outcomes show that the economic sustainability of these projects depends on certain circumstances, with radial electrical design emerging as the most economical choice. The Bandirma project is not as economically viable as the offshore wind farm near Bozcaada, which offers a more appealing investment prospect. The offshore wind market in Turkey will be shaped by these findings, which provide insightful advice for investors and regulators.

5. CURRENT CHALLENGES

Offshore wind farms are becoming more and more important in satisfying electricity demands while lowering carbon emissions as the globe continues to move toward renewable energy sources [15]. Offshore Wind Farm with Fuzzy Logic In order to overcome the particular difficulties involved in capturing wind energy from offshore locations, HVDC Control has emerged as a potential technique. The use and improvement of this technology, however, still face a number of serious obstacles:

Offshore wind conditions are extremely variable and difficult to anticipate with accuracy due to their unpredictable wind patterns. Fuzzy logic-based control systems must respond quickly to these shifting wind patterns to ensure effective energy production and grid stability.

Grid Integration and Compatibility: Using high-voltage direct current (HVDC) technologies, in particular, requires complex control methodologies to integrate offshore wind farms with onshore electricity networks. Continuous research and development are needed to ensure seamless interoperability and efficient power transmission.

Fuzzy logic-based control systems are adaptable, but improving these techniques so they can adjust to changing load conditions, wind conditions, and grid requirements is a continuous problem. Maximizing energy capture and grid stability requires the creation of more complex adaptive algorithms.

Hardware and Infrastructure: Constructing and maintaining HVDC infrastructure and offshore wind farms requires significant capital investment. It is logistically and technically difficult to manage and optimize the hardware parts, which include power converters and offshore substations.

Considering the growing reliance on digital control systems, it is crucial to ensure their cybersecurity and dependability. A key problem is safeguarding against cyber threats and making sure that operations continue in challenging offshore conditions.

Environmental Impact: Offshore wind farms must take into account their possible effects on maritime ecosystems and species as well as other environmental factors. The development of renewable energy must be balanced with environmental sustainability, which is a difficult task.

Regulation and Policy Frameworks: Each country and region has a different regulatory environment for the construction of offshore wind farms. Making clear and advantageous policy frameworks that encourage the expansion of offshore wind energy is still a difficult task.

Offshore wind farms need routine maintenance, but getting to them can be difficult because of their distant locations. Creating techniques for upkeep that are affordable and enhancing accessibility are essential for long-term sustainability.

It is essential to do ongoing research and work in conjunction with stakeholders, including researchers, engineers, policymakers, and business leaders, to address the current difficulties. Although Fuzzy Logic-Based Offshore Wind Farm HVDC Control has a lot of potential, it must constantly change and adapt to overcome these challenges and continue to support the development of a sustainable energy future.

6. CONCLUSION

The significance of Fuzzy Logic-Based Offshore Wind Farm HVDC Control as a promising and flexible strategy for resolving the difficulties involved in integrating offshore wind power into the electrical grid is highlighted by this review. This work has demonstrated the potential of fuzzy logic control to improve power quality, frequency regulation, and grid stability by thoroughly examining its principles and applications. In addition, the assessment emphasized how crucial it is to use adaptive control techniques to account for wind power's changing output. The conclusions drawn from this analysis strongly suggest that fuzzy logic-based control systems have the potential to play a crucial part in the further growth and success of offshore wind energy. To ensure the dependable and effective operation of offshore wind farms, research efforts should focus the improvement and optimization of these control systems as the renewable energy landscape continues to change. In order to advance the integration of offshore wind generation while maintaining grid stability and dependability, this assessment is an invaluable resource for researchers, engineers, and policymakers alike.

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