Optimizing Offshore Wind Farm Power Flow Via Fuzzy Logic-Based Control Strategy for HVDC Transmission

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Abstract: *Power system stability has been a persistent challenge in electrical engineering since the early 1920s. The integration of power electronic converter technologies, including wind and solar generation, energy storage, FACTS devices, HVDC lines, and power electronic loads, has significantly transformed power systems. This evolution has emphasized the need for a deeper understanding of transient voltage stability, which lacks a universally accepted definition and practical criteria. Additionally, identifying dominant instability modes in complex scenarios remains challenging. India's wind energy sector has achieved substantial growth but faces a recent slowdown, necessitating a comprehensive examination of contributing factors. This study focuses on modeling offshore wind energy systems with DC transmission, incorporating Unified Power Flow Controllers (UPFCs) and fuzzy logic control to enhance power output, using MATLAB/SIMULINK for simulation. The results highlight the potential benefits of these technologies for offshore wind energy systems connected to HVDC networks.*

Keywords: *Power System Stability, FACTS Devices, HVDC Lines, Power Electronic Loads, India, Wind Energy Sector, Growth Slowdown, Regulatory Factors, Economic Factors, Unified Power Flow Controllers (UPFCs), Fuzzy Logic Control, MATLAB/SIMULINK Simulation.*

I. INTRODUCTION

Power system engineers have struggled for a long time with the complexity of the issue of power system stability. In 1920, the stability of electricity systems was acknowledged as a significant issue. The first field tests on the stability of a practical power system were undertaken in 1925, and the results of the first laboratory studies on tiny systems were reported in 1924. Early stability issues were related to distant hydroelectric producing units feeding into urban load centers via long-distance transmission. However, there has been a considerable change in the way electric power networks operate all over the world, which is mostly attributable to the increased use of technologies that are power electronic converter interfaced [1]. These innovative technologies include high voltage direct current (HVDC) lines, power electronic interfaced loads, flexible ac transmission systems (FACTS), and photovoltaic and wind energy generating. The dynamic reaction of power systems has steadily become more dependent on (complex) fast-response power electronic devices as a result of the significant integration of converter interfaced generation technologies (CIGs), loads, and transmission devices, changing the dynamic behavior of the power system.

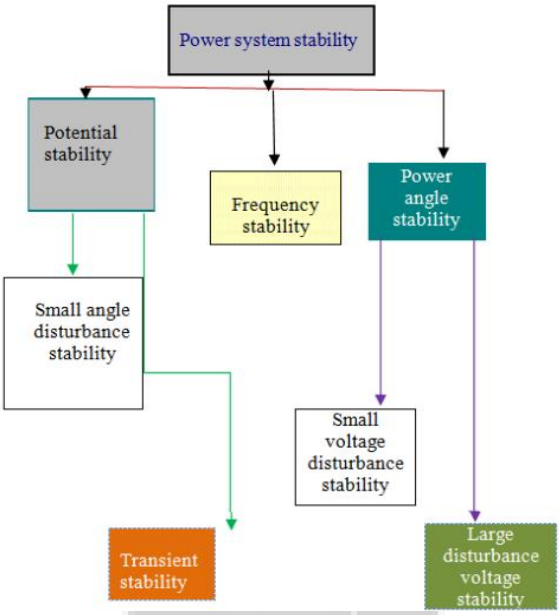

Figure 1 Types of Stability

The research on static voltage stability is reasonably advanced due to the earlier commencement of the study and the ease of the mathematical model. Despite the fact that transient voltage stability research has made significant strides recently, compared to mature power angle stability, people still do not have a fully developed understanding of transient voltage stability. Voltage stability has not yet been defined uniformly or explicitly both domestically and overseas. There is no transient voltage stability criterion that takes engineering practicalities and theory into careful consideration. A straightforward and efficient strategy for identifying the dominant instability mode in complicated instability scenarios involving transient voltage and power angle is still lacking [3]. Higher standards will be set for the study of the mechanisms underlying transient voltage stability in order to solve the aforementioned concerns. Large disturbances are a part of transient stability, and for a generator near the disturbance source, they often happen in less than a second. Switching on and off system components (transmission lines, transformers, generator load, etc.) as well as applying and clearing faults are all examples of unexpected major disturbances. A system is deemed temporarily stable if it is discovered that its machine fundamentally stays in synchronism with the first and second. Some mechanical characteristics of the machines in the system are involved with transient stability analysis. The machines must alter their rotors' relative angles in response to each disturbance in order to line up with the requirements for power transfer. Both mechanical and electrical elements are present in this difficulty. The steady-state limit is usually lower than the transient stability limit, highlighting the crucial importance of this limit. Depending on the nature, location, and magnitude of the disturbance, the transient stability limit may not be reached [4].

India's wind energy sector has achieved a commendable milestone with a cumulative installed capacity of around 39 GW as of March 2021. This underscores the country's steadfast commitment to harnessing renewable energy resources [5].

However, an area of concern emerges when analyzing the year-over-year cumulative capacity additions, revealing a concerning trend of sluggish growth. This deceleration in wind energy expansion prompts a reevaluation of the underlying factors contributing to this pattern [6].

Numerous studies conducted in the past have provided comprehensive insights into various aspects of India's wind energy landscape. These studies have delved into the technological advancements, market trends, challenges, and opportunities inherent in the sector [5, 6].

Despite this wealth of information, the observed deceleration in the growth rate of wind capacity demands a more comprehensive review. The current landscape prompts an in-depth exploration into the intricate factors underlying the declining wind growth. Such an investigation will shed light on the regulatory, economic, technological, and environmental influences that may be impacting the growth trajectory of wind energy in India.

WECS are primarily divided into two groups, standalone and grid-connected, according on the type of application. It is a replacement choice for power users in areas where expanding the electrical grid would be too expensive for independent WECS. Due to the fluctuating load demand with respect to time and the output power of the turbine with the variation of wind speed, standalone WECS is employed in integration with other forms of power generation [7]. As a safe and dependable renewable energy source, offshore wind energy is gaining popularity on a global scale. Turbine fatigue is decreased by the stronger, more consistent, and less turbulent offshore winds compared to onshore settings. Furthermore, there are less restrictions on offshore wind farms in terms of noise, visual impact, community opposition, and physical space. Offshore wind turbines have an edge over onshore ones since a sizable section of the world's population lives near the coast. Future energy markets will need them because they don't produce dangerous waste or air pollution. Offshore wind farms are anchored using monopile or jacket structures in shallow waters, with many extant farms adopting the monopile design. However, as demonstrated by Denmark's offshore wind turbines, this strategy is constrained by geological considerations and water depth.

II. LITERATURE REVIEW

G. Shi et al., (2016) [7] A suggested approach for collecting offshore wind energy is a DC wind farm (DCWF) using series-connected DC wind turbines (DCWT). Detailed descriptions are provided of the coupling behavior of series-connected DCWTs. First, a quantitative analysis is done to determine the primary effect elements of any potential wind energy curtailment during the wind turbine voltage limitation period. In order to increase the DCWT's ability to harvest wind energy, a decoupling control method is suggested under voltage limiting conditions. Without communication, this control technique can be implemented in the local DCWT controller. The efficiency of the suggested control technique has been evaluated using dynamic simulation cases under various operating conditions. It has been discovered that the proposed control method could be a wind energy curtailment solution, which will considerably enhance the performance of the series-connected DC wind turbines between the time scale above seconds and below minutes.

According to **Lakshmanan, P. (2022) [8],** the power curtailment losses, one of the biggest problems with DC series-parallel gathering systems, are examined in this work. The MVDC (medium-voltage DC) converters within the wind turbine exhibit voltage fluctuations due to varying wind speeds among the interconnected turbines, leading to both over- and under-voltage scenarios. This study focuses on a redundancy-driven upper-voltage limit to address power curtailment losses attributed to the upper-voltage thresholds of MVDC converters in wind turbines. Through a comparative analysis of a 200 MW DC series-parallel connected wind farm, incorporating the redundancy-driven upper-voltage limit, the study offers a comprehensive quantitative assessment of annual energy curtailment losses.

Bala, J. P. S., et al., (2014) [9] introduces the innovative notion of platformless DC connections for offshore wind turbines. Initially, the document outlines various wind turbine drivetrain configurations capable of generating sufficiently high DC voltage. Subsequently, it delves into the design considerations for electrical systems tailored to the platformless DC setups. The study proceeds to scrutinize the potential economic advantages linked to the direct DC connections of offshore wind turbines, revealing substantial CapEX reductions of around 20-25% compared to traditional AC collection and transmission solutions. Furthermore, the paper briefly examines control strategies for both the wind farm and the DC connection system. In summation, the paper underscores the potential of platformless DC connections to provide cost-effectiveness, heightened efficiency, and improved grid support. As a result, this approach holds promise for medium and large-scale offshore wind installations across multiple scenarios.

In order to improve the performance of doubly-fed induction generators (DFIGs) under unbalanced grid voltage situations, **Kerrouche et al. (2018) [10]** carried out a comparative evaluation of methods for enhancing the low-voltage ride-through (LVRT) capabilities of DFIGs. They proposed a cost-effective software-based LVRT solution for DFIGs coupled to wind turbines based on an original control strategy. Lyapunov-based resilient control (RC) theory and dual-sequence decomposition methods are used in this control strategy. This method effectively prevents oscillations in the interchange of active and reactive power between the generator and the grid when there is an imbalanced grid voltage, and it also makes sure that the grid current injection is symmetrical and sinusoidal. They used a 1.5 MW DFIG-based wind turbine system in their simulation, which was done using MATLAB®/Simulink®. The findings confirmed the viability and efficiency of the dual control scheme in maintaining stable performance during grid-connected operation under unbalanced voltage supply conditions. The proposed approach outperformed conventional vector control methods based on a single control scheme

Mahieddine, H., et al., (2019) [11] seeks to investigate the efficiency of the electrical segment within a wind generation system. The setup involves the utilization of two back-to-back PWM voltage-fed inverters that are interconnected between the stator and rotor. A two-way power transmission is made possible by this setup. On the grid side, the second inverter performs two functions: it powers the DFIG rotor both actively and passively, acting as an active power filter to reduce harmonics coming from nonlinear loads. Nevertheless, switching frequency harmonics in the stator current, particularly during diode bridge transitions, might present serious difficulties. In order to solve this problem, a small passive LC filter is used to efficiently filter out high-frequency shaft voltage and grid current from a DFIG that is run by a voltage-source pulse-width-modulation rotor inverter under Space Vector Modulation (SVM) control. The study explores the underlying control theory of this setup and provides information on how the controller is put into practice. It also describes the standards for design. a simulation test outcomes showcase the outstanding static and dynamic performance of this proposed system, underscoring its effectiveness in managing harmonic distortion and ensuring efficient power transfer.

According to **Simon, L., & Swarup, K. S. (2016) [12],** the transient and fault current behaviors of the conventional grid alter as a result of the addition of renewable energy sources to power systems. Grid disturbances, including unexpected changes in load or faults, cause changes in system behavior and may jeopardize the efficiency of traditional safety and control measures. The dynamics of short-circuit currents within the system grow complex because the operational state of a Doubly-Fed Induction Generator (DFIG) is affected by grid features and control tactics. This paper develops an analytical formulation for the three-phase fault current and examines the short-circuit properties of DFIG. Fault current responses are developed with and without crowbar resistance by taking the fault severity in terms of voltage drop. The paper also examines power swings that happen when faults are cleared within the system. Transient simulation analyses are performed using PSCAD/EMTDC, with DFIG integration into a WSCC system. Multiple case studies are conducted to examine the relationship between fault location, power swings, and fault current contributions.

III. OBJECTIVES

The objectives of the study include:

- Integrating the system with long-distance DC transmission and grid connection for improved reliability and efficiency.
- Developing a controller using Unified Power Flow Controller (UPFC) to enhance power output in the wind energy system, contributing to the DC transmission.
- Implementing fuzzy logic rules for power enhancement control within the DC wind turbine system.
- Creating a MATLAB SIMULINK model for offshore wind energy systems using DC transmission. This involves comparing models with and without a power flow controller, integrating AI-based control techniques.

IV. METHODOLOGY

The model is created within the MATLAB/SIMULINK environment. This environment employs a high-level matrix/array language that incorporates control flow statements, functions, data structures, input/output, and object-oriented programming functionalities. Its notable characteristics encompass:

- Elevated-level language suited for scientific and engineering computations
- Desktop setting designed for iterative exploration, design, and problem-solving
- Graphics for visualizing data and tools for custom plot creation
- Applications for tasks like curve fitting, data classification, signal analysis, control system tuning, and more
- Add-on toolboxes catering to a broad spectrum of engineering and scientific applications
- Instruments for constructing applications featuring tailored user interfaces
- Options for royalty-free deployment, enabling the sharing of MATLAB programs with end users

The model comes with a dual voltage source inverter technology that increases system dependability by using solar or wind resources depending on their availability for load supply.

A. Modeling of Wind Energy System

The wind turbine model featuring a PMSG has been established to address the incomplete harnessing of wind energy. The various constituents of the wind turbine are represented by the subsequent equations. The expression for the generated aerodynamic power output of the wind turbine is as follows:

$$P_{Turbine} = \frac{1}{2}\rho A C_p(\lambda,\beta) v^3 \tag{1}$$

In this context, ρ signifies air density (usually 1.225 kg/m3), A represents the rotor blade swept area (in m2), C_p denotes the power conversion coefficient, and v stands for wind speed (in m/s).The tip-speed ratio is defined as:

$$\lambda = \frac{\omega_m R}{v} \tag{2}$$

In this equation, ω_m and R symbolize the rotor's angular velocity (in rad/sec) and radius (in m), respectively. The mechanical torque output of the wind turbine is denoted as $m\ T$.

$$T_m = \frac{1}{2}\rho A C_p(\lambda,\beta) v^3 \frac{1}{\omega_m} \tag{3}$$

The power coefficient exhibits non-linear behavior for both the tip-speed ratio (λ) and blade pitch ang le (β) expressed in degrees, leading to the following expression for power output:

$$P_{Turbine} = \frac{1}{2}\rho A C_{p_{max}} v^3 \tag{4}$$

B. Working of UPFC

The UPFC comprises two GTO-based voltage source converters (shunt and series) connected back to back through a shared DC link, as depicted in Figure 3.1. The primary purpose of the series converter is to generate an AC voltage Vc with adjustable magnitude and phase angle. In order to introduce this modified voltage to the transmission line, a series-connected transformer design is used. These changes in real and reactive power levels at the AC terminals of the transmission line are caused by the voltage injection, which occurs at the fundamental frequency.

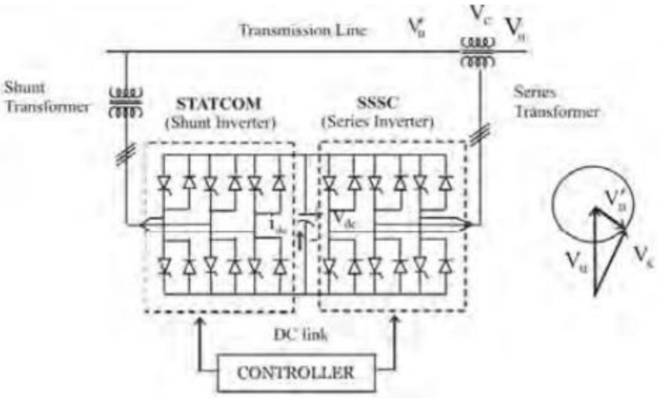

Figure 2 Fundamental Circuit Layout of the Unified Power Flow Controller

Through the provision of sufficient real power at the DC terminals, the shunt converter manages real power or controls DC voltage across the capacitor. Reactive power (either generating or absorbing) is also adjusted to control voltage at the shunt connection point.

C. Fuzzy based UPFC

Fuzzy logic operates on the principle of making decisions based on assumptions, utilizing sets to define possible output states. Each linguistic variable corresponds to a set, describing potential output conditions. Within these sets, input states and their degrees of change contribute to determining the output. "The core concept parallels an If-else statement, like If A AND B Then Z. Envision a scenario where the system's output fits within a set X, housing a generic value x from X. Let's consider a specific subset A of X, where its members range from 0 to 1. This set A is a fuzzy set, and fA(x) at x signifies x's membership strength in A. Output depends on x's membership degree in the set, shaped by assumptions about input-output relations and their rate of change. Each Fuzzy Logic block has two inputs and one output, utilizing error and its rate for control. Transmission line parameters share similar membership functions, replacing conventional control with fuzzy control utilizing error and its change as inputs. Each input and output variable is allocated seven fuzzy levels: Where, negative big is depicted by NB, negative medium by NM, negative small by NS, zero by Z, positive small by PS, positive medium by PM, and positive big by PB. The rules, are based on optimizing control output for high and low error. The membership functions for input and output variables are illustrated.

Table 1 Fuzzy Rule Table for UPFC

error/coe	**NM**	**NS**	**Z**	**PS**	**PM**	**NB**
NM	NH	NM	NL	NL	Z	NH
NS	NH	NL	NH	Z	PS	NH
Z	NH	PS	NL	PM	NM	Z
PS	NL	Z	PS	PM	PB	NM
PM	PB	PS	PM	PB	Z	NL
NB	NH	NH	NH	NM	NL	NH
PH	PL	PM	PH	PH	PH	Z

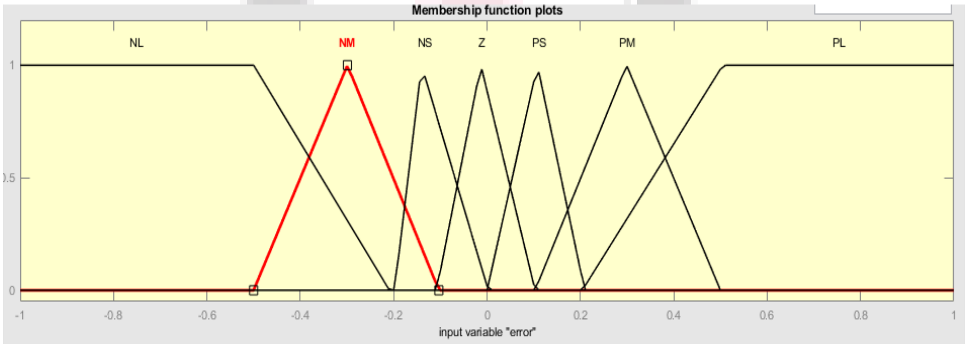

Figure 3 Input Variable (error) Normalized Membership Function

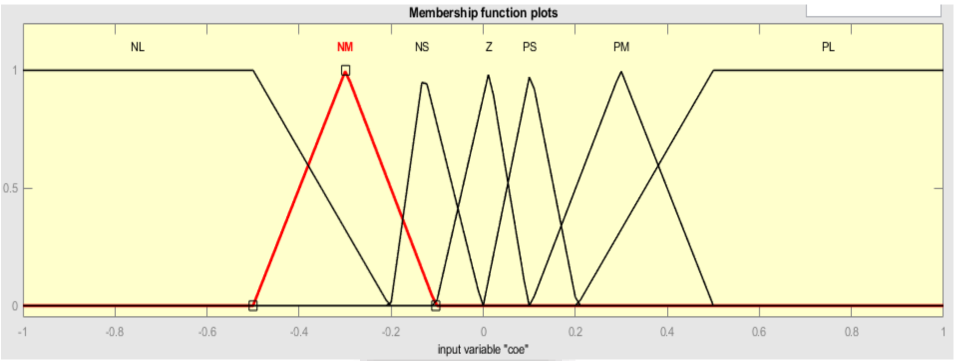

Figure 4 Input Variable (coe) Normalized Membership Function

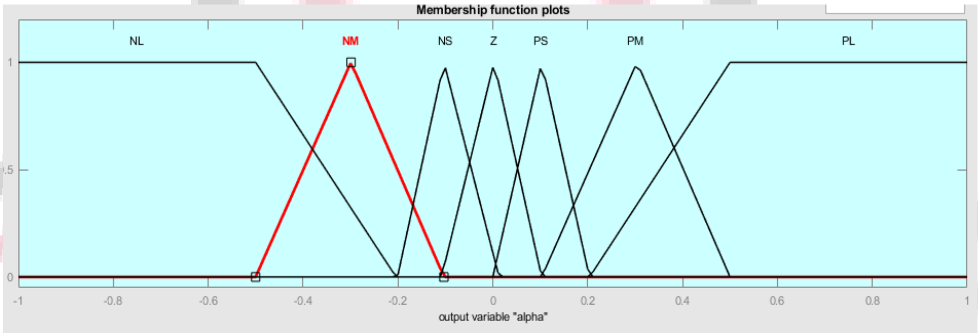

Figure 5 Output Variable Normalized Membership Function

A simulation is conducted using a consistent renewable energy generation that surpasses the load demand. The outcomes of both situations are then compared.

V. SIMULATION AND RESULT ANALYSIS

Simulation is a method that replicates real-world scenarios to explore research advantages. It aids users and researchers in evaluating designs and algorithms, ensuring efficiency and quality. Conducting simulations prior to system construction is crucial for cost-effective changes and design optimization. Simulation offers numerous benefits, enabling experiments with abundant data in various abstraction levels. Simulators create virtual environments for verification and performance assessment, providing insights into system worth.

HVDC-based power transmission systems are integral in future power networks, especially offshore grids. HVDC network behavior hinges on control strategies due to electronic interfaces at each station. To assess a proposed control strategy, a 5MW DCWT average model is implemented in MATLAB/SIMULINK.

A. Implementation Details

For the Unified Power Flow Controller (UPFC) in a group of offshore Wind Power Plants (WPPs) connected to a single High Voltage Direct Current (HVDC) connection, a coordinated control technique using fuzzy logic is deployed and evaluated in this study. The goal is to retain control over the voltage in the offshore AC grid while efficiently managing the flow of active and reactive power between the HVDC converter and the WPP cluster. The results of two particular scenarios are then described in the chapter:

Scenario 1: Integration of Offshore Wind Energy System with the Grid, Uncontrolled

Scenario 2: Integration of Offshore Wind Energy System with the Grid, Employing Fuzzy-Based Power Enhancement Controller

In this case, each Directly Coupled Wind Turbine (DCWT) experiences wind speeds that are marked by random fluctuations, with an average wind speed of 12 m/s. The vast range of speed variations in the simulation, which range from 0 to 12 m/s, mimics the constantly changing characteristics of wind conditions. The output of the wind system, which is then produced in a three-phase form, is then transmitted over a large area using the Direct Current (DC) transmission system. This set up emphasizes how important it is to account for the wind's inherent variability and effectively transmit the captured energy throughout the system.

B. Modelled offshore Wind Energy System

The permanent magnet synchronous machine (PMSG) used in the wind energy system precisely replicates the process of transforming wind-induced mechanical torque into dynamic three-phase electrical power. Through its output, it enables for wind speed modification between 0 and 12 m/s. The shown DC output from the wind energy system is the result of rectification, which converts the electrical output from the three-phase system into DC.

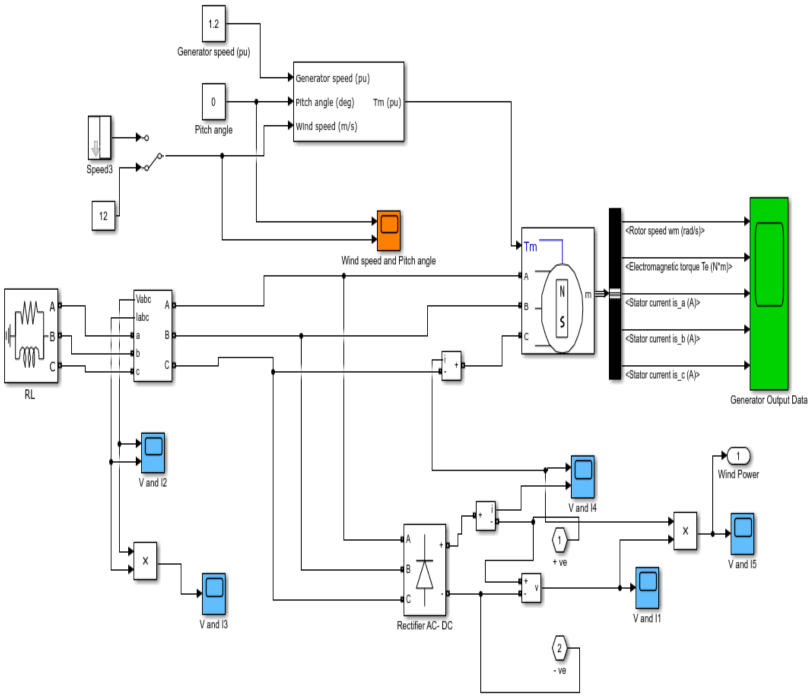

Figure 6 Modeling the Wind Energy System using MATLAB/SIMULINK

The wind energy system under study utilizes detailed parameters from the provided table, essential for defining component behavior and ensuring simulation accuracy. These parameters enable capturing system dynamics and interactions, facilitating comprehensive exploration of its behavior across diverse conditions. This approach deepens our understanding of responses to inputs and external factors, aiding insightful analysis and informed decisions for operational enhancements.

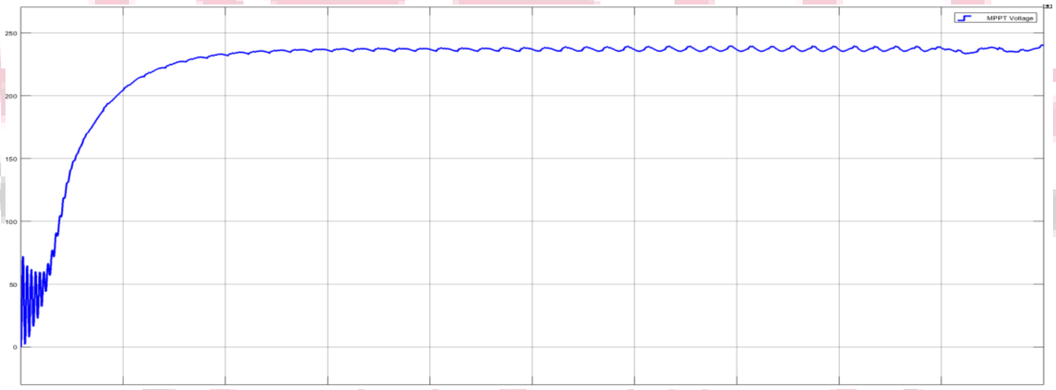

Figure 7 DC Output from the Wind Energy System after Rectification

The wind energy system's output is roughly 200 volts DC after the rectification process. This DC output is then sent into an inverter, which converts it into a three-phase AC output. The alternating current (AC) output is subsequently directed into the high-capacity direct current (DC) transmission grid covering long distances.

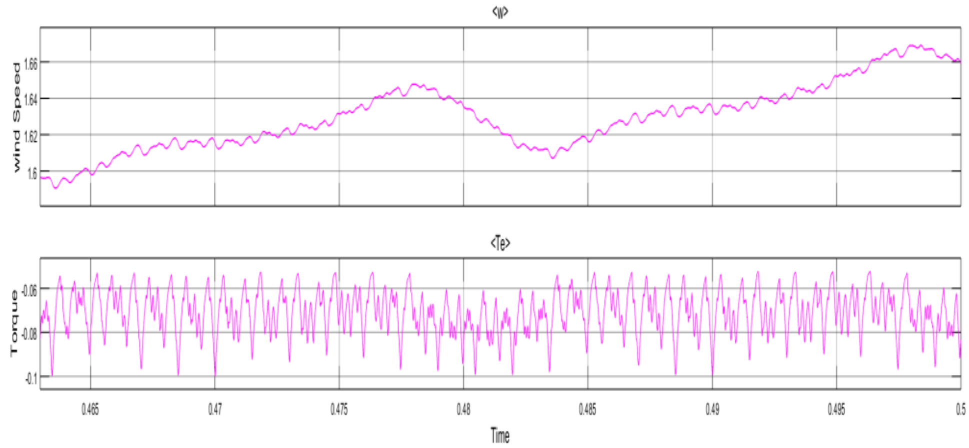

Figure 8 Wind Velocity and Its Corresponding Turbine Torque Output

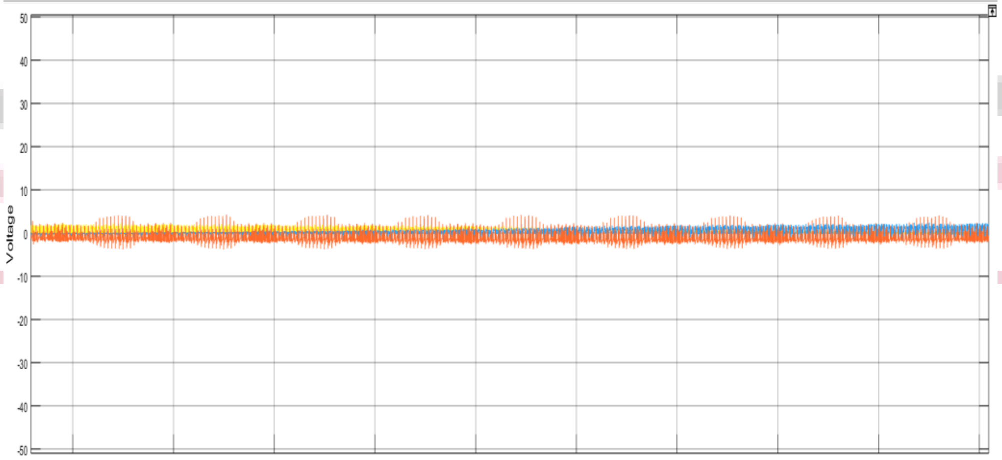

Figure 9 Voltage Generation from DC Wind Turbine (Per Unit)

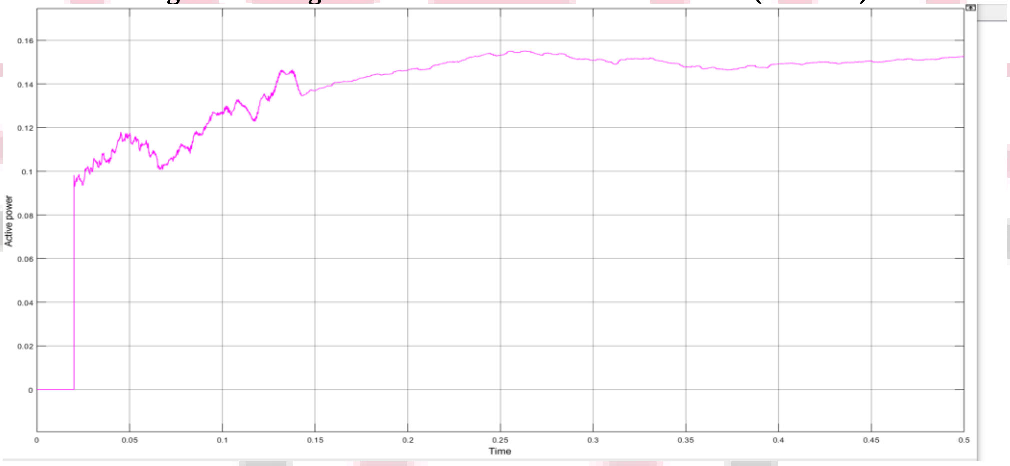

Figure 10 Active Power Generation from DC Wind Turbine (Per Unit)

The graph depicts the DC wind turbine's active power output in units. The power output per unit is about 0.5.

C. Scenario 1: Integration of Offshore Wind Energy System with the Grid, Uncontrolled

The inverter is crucial to the conversion of the DC output captured from the wind energy system because it uses a complex control mechanism. A strong three-phase AC output is produced as a result of this complex transformation. The inverter's procedure enriches the AC power, which is then effectively directed toward a long-distance DC transmission line to enable efficient power distribution over great distances. High-voltage AC transmission is more expensive than DC transmission. However, the difficulty lies in the requirement of two converter stations for HVDC transmission. Converting AC power to DC is the first step in starting the transmission process. When the DC electricity reaches the proper tie-in point, it is then converted back into AC and made useful by the grid. This two-way conversion procedure demands the usage of two power converter stations within the model, which are in charge of converting AC to DC and vice versa at the site of the load.

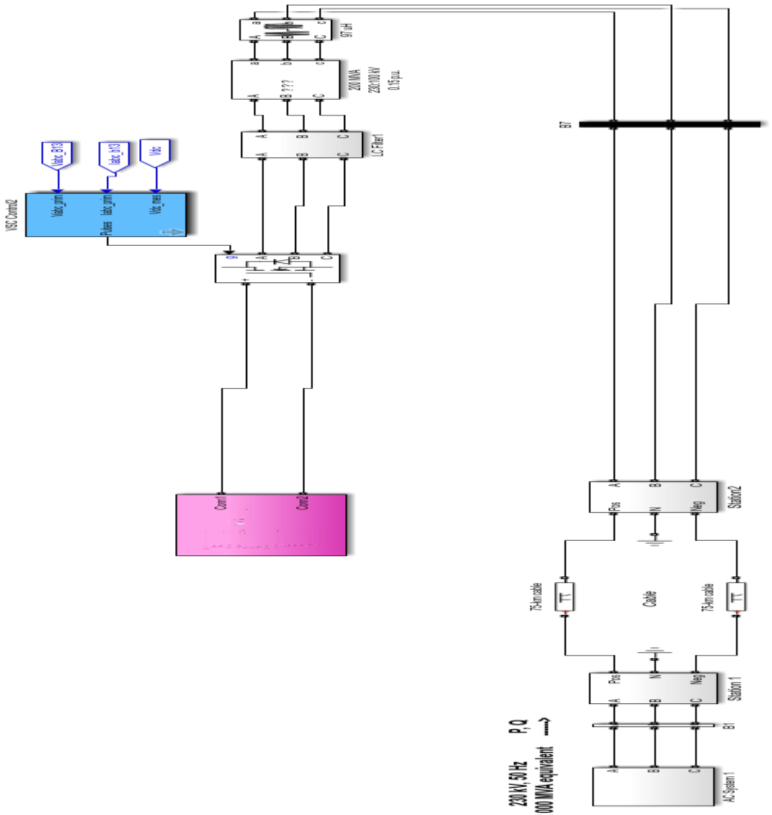

Figure 11 Integration of Offshore Wind Energy System with the Grid in the Absence of Power Controller

Any type of power enhancement device or controller in this system has no effect on the AC side waveform. In the generating station, the AC electricity is produced. Initially, this needs to be converted to DC. With the aid of a rectifier, the conversion is completed. Through the overhead lines, the DC electricity will be transmitted. This DC must be transformed into AC at the user end. At the receiving end, an inverter is positioned for that reason. The figures below display the energy system's output in terms of voltage, current, and power.

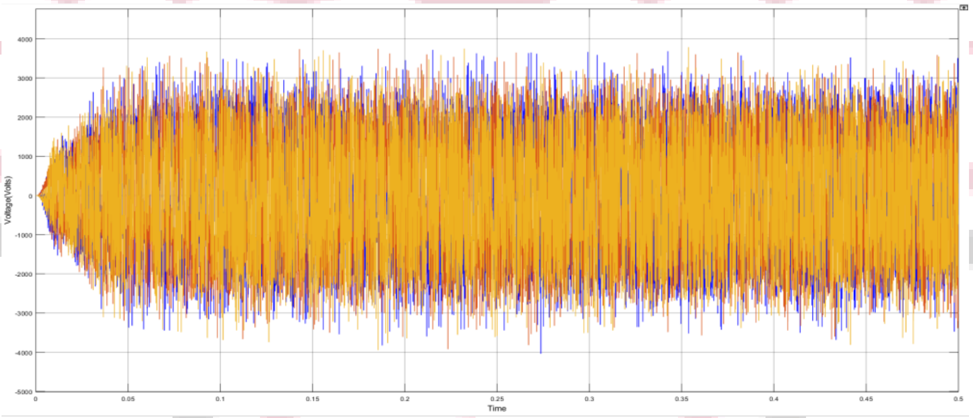

Figure 12 Voltage Output of the System without using Power Controller

The voltage output in this wind energy system is roughly 2.5 KV when there are no power controller devices connected. This voltage output is a result of multiple DC wind turbines being integrated into a system and having their voltage output measured.

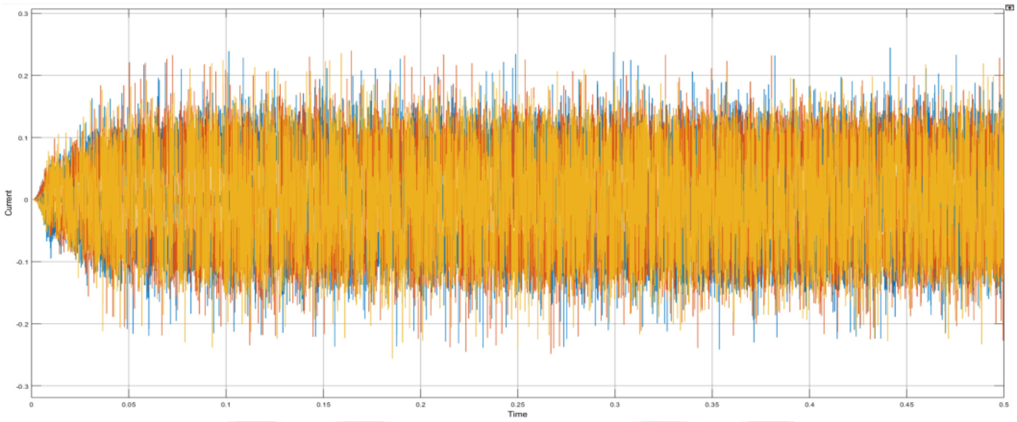

Figure 13 System's Current Output in the Absence of Power Controller

In Figure 4.8, the current output of the DC wind turbine is shown precisely at the juncture where the inverter converts DC power to AC power. This current, operating at a frequency of 50 hertz, can be harnessed to drive various types of loads.

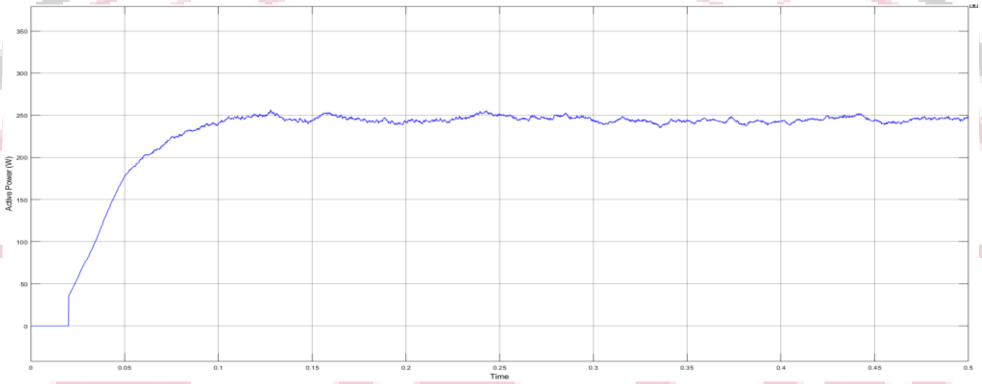

Figure 14 System's Active Power Output in the Absence of Power Controller

The power that actually dissipates within the circuit is known as the active power. The active power output from the wind turbine in this wind energy system, in which we are not utilising any form of power controller, is shown in Figure 4.9. This power will subsequently be sent to long-distance DC transmission. A 250W output is found to be the approximate.

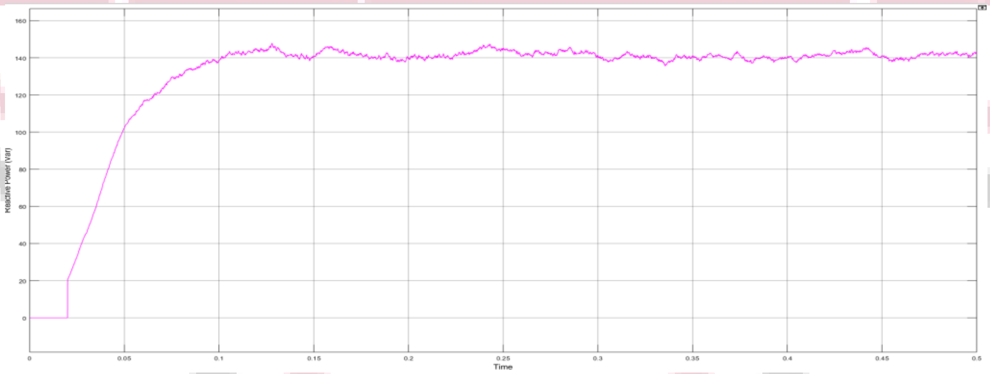

Figure 15 System's Reactive Power Output in the Absence of Power Controller

Between the circuit's source and load, reactive power flows. Reactive power management is crucial for the stability and dependability of the electrical power supply. It was discovered that the DCWT system's reactive power output was about 140Var.

D. Scenario 2: Integration of Offshore Wind Energy System with the Grid, Employing Fuzzy-Based Power Enhancement Controller

In this context, the Directly Coupled Wind Turbine (DCWT) system is interconnected with the offshore energy system's DC transmission network. A power controller, guided by fuzzy logic algorithms, is seamlessly incorporated within the setup. The subsequent enhancements in active and reactive power outputs are discussed in detail, highlighting the controller's robustness in enhancing the performance of DCWT-based wind energy systems.

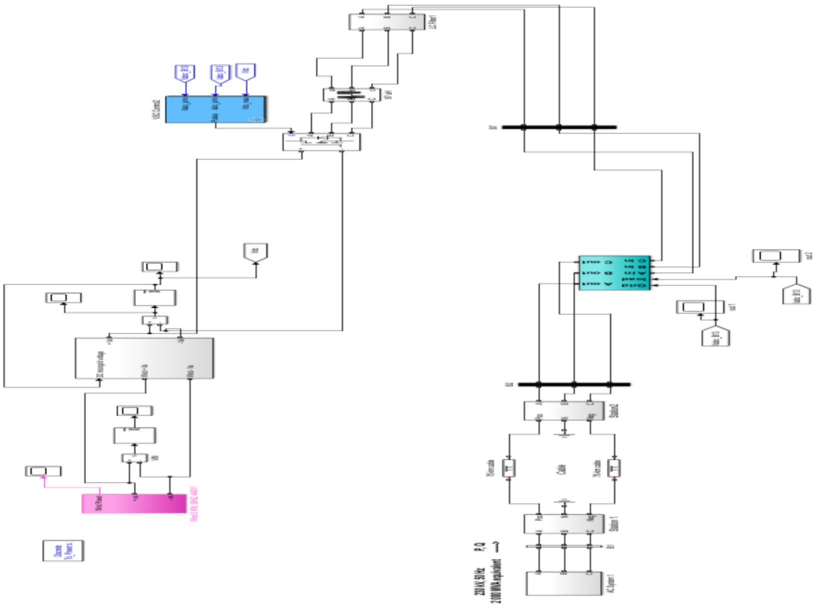

Figure 16 Integration of Offshore Wind Energy System with Grid Empowered by Fuzzy-Based Power Enhancement Controller

The Direct-Driven Wind Turbine (DCWT) system's performance is anticipated to be greatly improved with the addition of fuzzy logic control. In order to process analog inputs, fuzzy logic, a novel mathematical framework, uses linguistic variables that can represent a continuum of values between 0 and 1. Fuzzy logic allows for inaccurate information in contrast to binary logic, which can only handle true or false by employing terms like "low," "medium," and "high" with corresponding degrees of membership. This makes it possible to represent intricate relationships that conventional approaches find difficult to handle. Fuzzy logic control is useful for the DCWT system because it may be adjusted to the uncertainties that are typical of wind energy. It uses linguistic variables and fuzzy rules to take into account variables like wind speed, blade angle, and generator speed, enabling real-time complex decisions. The ability to adjust is essential in dynamic wind energy systems affected by rapid environmental changes. Overall, integrating fuzzy logic enhances the DCWT system's decision-making, offering flexibility and robustness. By embracing linguistic variables and fuzzy logic principles, the control system optimizes performance by managing uncertainties and capturing complex relationships fundamental to efficient wind turbine functioning. This contrasts with classical or digital logic systems.

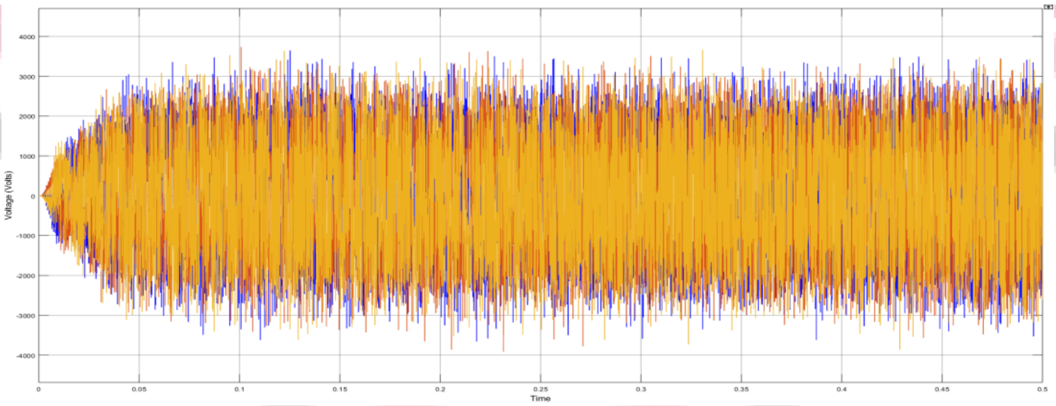

Figure 17 System's Voltage Output Empowered by Fuzzy-Based Power Enhancement Controller

An integration of a power controller controlled by fuzzy logic rules introduces a significant impact within the context of the Wind energy system. An estimate of 2.5 KV, arising from a system configuration that includes many DC wind turbines, is the voltage output that is produced as a result. Each of these turbines is essential in influencing the overall operational dynamics of the system by making a significant contribution to the collective voltage output.

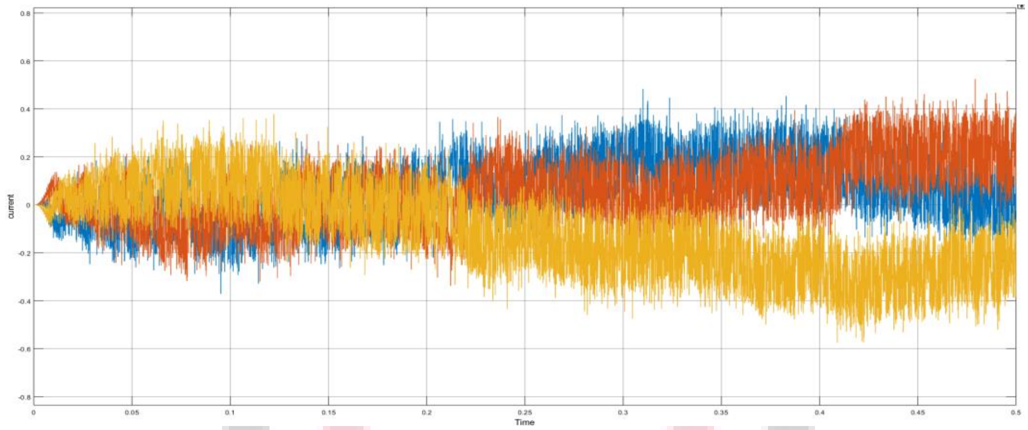

Figure 18 System's Current Output Optimized by Fuzzy-Based Power Enhancement Controller

The DC wind turbine's current output as it is precisely measured at the location where a power converter converts DC power to AC power. Notably, this representation incorporates a technique for power enhancement that is controlled by fuzzy-based rules. The generated current operates at a frequency of 50 hertz, suitable for driving a variety of loads at this stage.

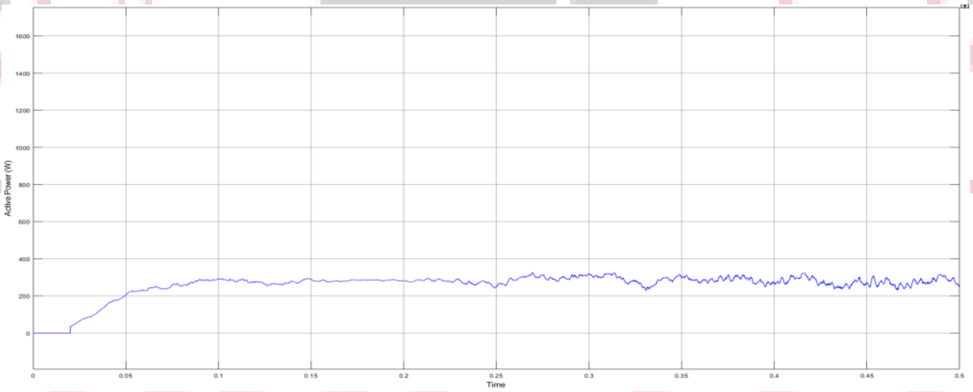

Figure 19 System's Active Power Output Optimized by Fuzzy-Based Power Enhancement Controller

Illustrates the system's active power output, which is enhanced by the inclusion of a power enhancement controller powered by fuzzy logic. The data shows a notable gain in power generation, reaching about 300 Watts, which is a major improvement over the performance of the prior model. This result highlights how well the fuzzy-based power enhancement controller increases the active power output of the system.

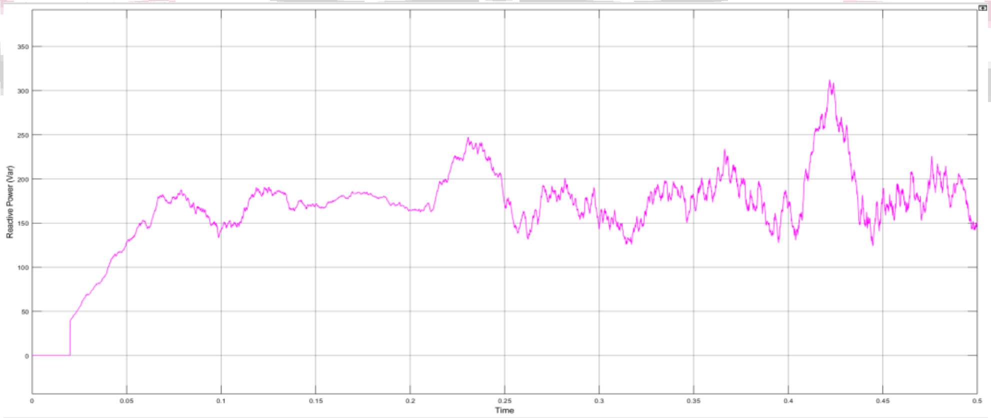

Figure 20 System's Reactive Power Output Enhanced by Fuzzy-Based Power Enhancement Controller

An essential component that flows inside electrical circuits and maintains stability and dependability is reactive power. To maintain proper voltage levels and electromagnetic fields in power systems, it works in conjunction with real power, which completes useful tasks. To prevent voltage problems, these powers must be balanced. Additionally, especially in industrial settings, reactive power protects equipment by avoiding overheating and failure. Its job is essential to ensuring the reliable and effective operation of the power system in the face of rising electrical demand and potential disruptions. The system's reactive power output, achieved through the use of a fuzzy-based power controller for the DCWT system with a power enhancement device, was measured to be around 150Var.

E. Validation

This section discusses the comparative analysis between a system without a power controller and a wind energy system equipped with a UPFC-based power flow controller. The primary emphasis lies in elevating both active and reactive power outputs by utilizing fuzzy-based control techniques.

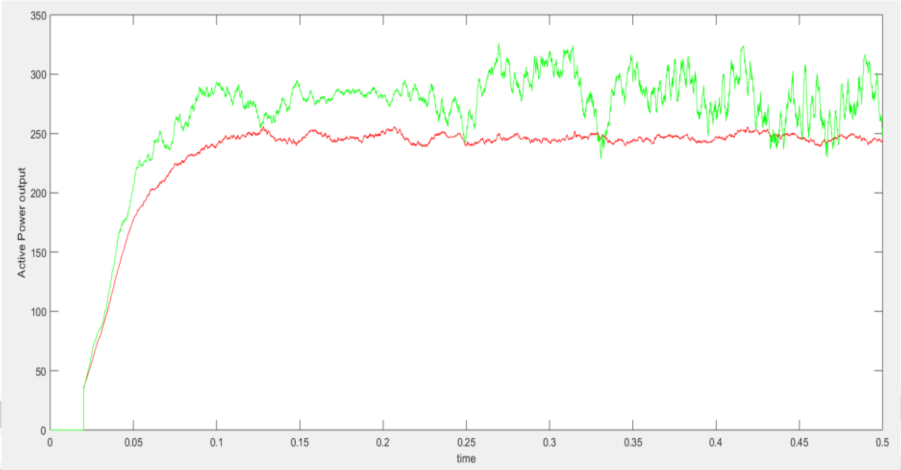

Figure 21 Comparative Assessment of Active Power Flow Control

A comparison is presented between the active power outputs of two distinct systems. The red curve shows power output without a power controller, while the green curve displays power output with a Fuzzy Logic-based controller. The intelligent control significantly improves active power. The system without control generates about 250 W, whereas the fuzzy-based controlled wind energy system achieves around 300 W.

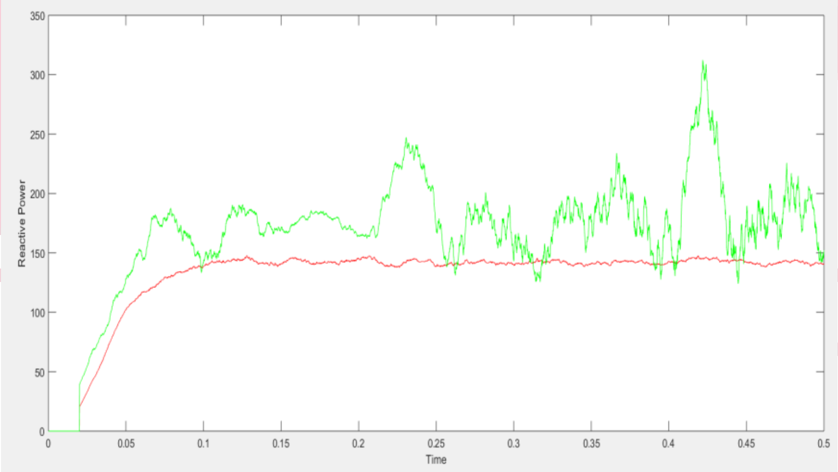

Figure 22 Comparative Assessment of Reactive Power Flow Control

A thorough analysis, comparing the reactive power outputs of two different systems. The second system has a power enhancement controller that is controlled by fuzzy logic, whereas the first system has no controller at all. The measurements show a noticeable increase in power production, notably from a value of 140 Var to a rough estimate of 150 Var. This increased power output further highlights the benefits of using the Fuzzy Logic-based power improvement controller and may be significant for applications needing load compensation.

VI. CONCLUSION

Power system stability, particularly transient voltage stability, is a critical concern in modern power systems due to the integration of power electronic technologies. India's wind energy sector has achieved significant capacity, but a slowdown in growth necessitates a detailed analysis of contributing factors. This study's focus on modeling offshore wind energy systems with UPFC and fuzzy logic control in MATLAB/SIMULINK demonstrates the potential for improving power output and system performance. Further research into transient voltage stability mechanisms is essential to address evolving power system challenges effectively and to facilitate sustainable growth in renewable energy sources like wind power.

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