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Wind Power Grid: An Analysis of Wind Farms' Energy Systems, Electrical Power, and Capacity

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Abstract: Wind power technology has emerged as a crucial aspect of renewable energy in recent years, addressing the increasing demand for energy. Extensive research is being conducted in various areas related to wind power, such as wind speed prediction, system stability, and wind generator system modeling. The uncertainties and correlations of wind farms are considered, employing the three-point estimation technique with the Cornish Fisher expansion. The criterion of transient stability is arises as a linear blend of the given node, and new types of critical lines are developed. The method is applied under different levels of wind power penetration and varying degrees of correlations. Correlations have a significant impact on the stability of transition results, particularly in high-penetration renewable energy systems. With the increasing utilization of wind farm energy, stability issues have arisen due to the lack of power inertia and the occurrence of power blackouts. These issues can adversely affect power quality, leading to harmonics and resonances caused by the interaction of power converters with the system. To address these concerns, voltage and transient stabilities are given significant attention to improve the quality of wind power. Wind Turbine Generators (WTGs) equipped with Doubly-Fed Induction Generators (DFIG) and variable speeds are widely preferred in most wind farms due to their advantages. Recent studies focus on analyzing the dynamics of wind energy using DFIGs, specifically investigating issues related to transient faults in wind turbines. Various fault scenarios, such as loss of excitation and transient faults in synchronous generators, are analyzed to assess their impact on transient stability.Advanced techniques are employed to evaluate the benefits and limitations of existing approaches, considering the power grid's compliance with the Electricity Distribution Code (EDC) and the Grid Code (GC). This comprehensive study encompasses different techniques and reviews multiple models that enhance the stability of power systems by analyzing and assessing their effects on wind power system stability. The effectiveness of the proposed methods is verified through rigorous analysis and evaluation.

Keywords: *evaluation, effectiveness, Electricity Distribution Code (EDC), Grid Code (GC), investigating*

1. Introduction

The demand for renewable energy sources, including wind energy, has significantly increased in response to the alarming climate changes triggered by global warming. Wind energy has witnessed remarkable growth in terms of capacity and technology adoption. Over the past three decades, wind power generation has undergone substantial changes as its capacity has expanded, leading to a significant increase in global power generation [1]. These changes encompass not only advancements in electrical and mechanical technologies but also the utilization of various advanced control techniques that prioritize power system integration requirements.

The integration of wind farms into traditional power systems presents distinct dynamic characteristics that impact the overall system response [2]. Consequently, modern power systems have incorporated new features to accommodate the integration of wind farms. Understanding the impacts of large-scale renewable energy integration, particularly wind energy, is crucial for confirming the security besides stability of power systems. Owing to

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the uncontrollable nature of wind as an energy source, it can give rise to voltage and transient stability issues [3]. The increased penetration of wind energy sources aims to reduce the inertia of the power system by combining them with conventional power sources. However, this integration can have adverse effects on transient stability within the power system.

When studying wind farm modeling techniques, both analytical analysis and numerical simulation are crucial technical tools for ensuring power system reliability. The analytical investigation or mathematical simulation must develop a model that accurately represents the dynamic system under consideration. These techniques need to strike a balance between precision and simplification [4]. On one hand, the model should capture the dynamic phenomena and relevant characteristics of interest to the researchers. On the other hand, a simplified model enables efficient analytical analysis or numerical calculation [5]. It is important to note that the dynamic phenomena and stability types being considered can exhibit distinct characteristics and different magnitudes of disturbances and time scales [6]. Therefore, the wind farm models employed in various research studies should be tailored to meet the specific requirements of system stability analysis. Figure 1 illustrates the classification of stability in a conventional power system [7]. In both conventional power systems with and without wind power, different types of stability phenomena can be observed. The stability classification also takes into account the magnitude and time scale of the disturbances. With the increased integration of wind power, modern power systems are facing new stability challenges [8] that were not previously encountered, such as sub-synchronous control interaction (SSCI) and harmonic stability.

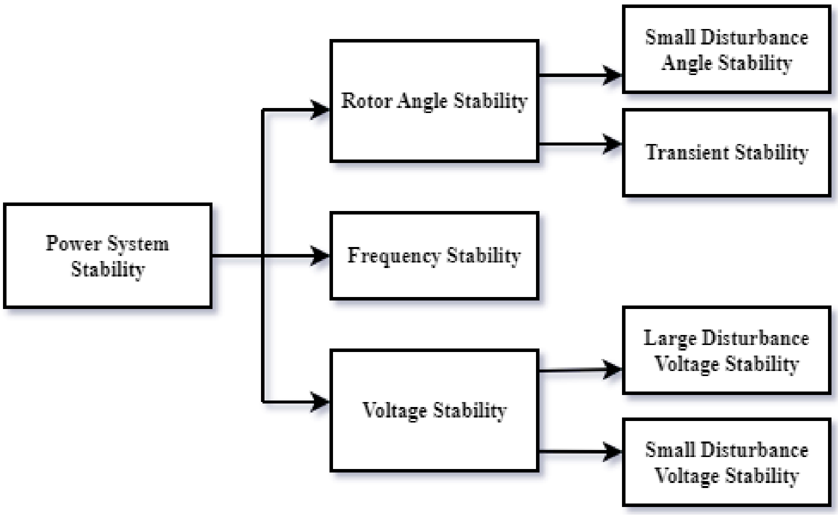


Fig 1: Sorting Stability of Power System

Undoubtedly, the absence of an established characterization or classification for potential stability issues in the present power system is becoming increasingly significant. According to [7], the development of such a classification is crucial for facilitating and enhancing the modeling and analysis of system stability in scientific endeavors. While a comprehensive version of stability classification [9] and definition is yet to be formulated, it is evident that the modern power system may encounter diverse types of stability challenges. The studies conducted on system stability offer valuable insights into the applications and requirements for wind farm modeling, addressing the need for tailored approaches to tackle these issues effectively.

Transient stability analysis refers to the assessment of a power system's ability to maintain stability and security during significant disturbances, such as short circuits or sudden failures of large generation units. Specifically, it focuses on the concept of transient stability, also known as large signal rotor angle stability, which is fundamental for ensuring stable power system operation. Figure visually presents a classification of techniques employed for transient stability analysis, encompassing both traditional methods and approaches rooted in machine learning [10]. However, this review will concentrate solely on various machine learning (ML) techniques applied in transient stability analysis, as they are integral to the broader range of applications utilizing AI (artificial intelligence) in recent power systems.

The intricacy of addressing transient stability is amplified by the presence of numerous components in power electronics, AC/DC devices, and renewable energy sources (RESs). Consequently, conducting real-time simulations involving transient energy functions or time-domain analysis becomes increasingly challenging. To overcome these difficulties, machine learning approaches are gaining popularity as they leverage data-oriented paradigms to tackle transient stability issues effectively.

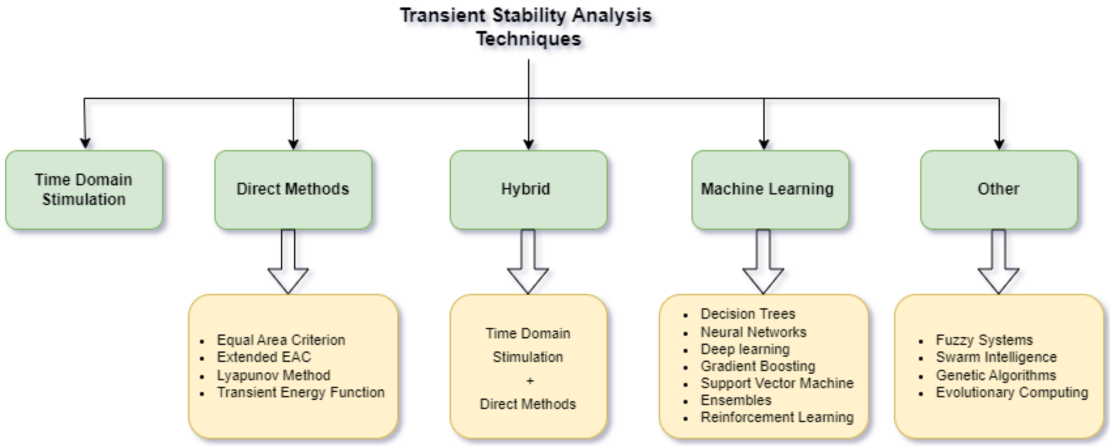


Fig 2: Techniques of Transient Stability Analysis [11]

Wind Energy Conversion Systems (WECS) based on Doubly-Fed Induction Generators (DFIG) hold great promise as a technically and economically viable solution among various renewable energy resources [12]. Extensive research efforts have been dedicated to investigating the performance of these systems under different disturbances [13]. In this regard, a local control scheme has been developed specifically for grid-connected wind turbines, aiming to restore transient stability in the system. Additionally, several research papers have proposed techniques to enhance overall system performance by designing Wind-Assisted Compressed Air Energy Storage (WAC) systems or combining local DFIG power systems [14].

It is worth noting that wind farms, when connected to the grid, generally do not actively contribute to damping power system oscillations[14] [15]. This highlights the need for effective power control techniques for renewable resources, which traditionally have been designed to mimic the excitation control of synchronous generators. However, these models often rely on linearized forms based on numerous power system network parameters [16], some of which may be unrealistic. Consequently, when it comes to transient stability analysis, these models fail to provide accurate and meaningful outcomes [17].

Transient stability analysis, in general, requires the numerical solution of several nonlinear differential equations. An approach commonly employed in this field involves direct simulations of transient dynamics following a disturbance [18]. In the absence of knowledge about the post-fault trajectory, direct methods rely on energy or Lyapunov functions [19] to ensure system convergence to stable equilibrium points. These techniques have proven effective in conventional power systems.

Despite the progress made in transient stability analysis, there is ongoing research to develop more advanced and comprehensive methodologies [20] that consider the unique characteristics of wind energy conversion systems. The aim is to accurately capture the transient behavior of these systems and improve their integration and performance within the power grid.

2. Literature Review

Transient stability refers to the ability of a power system to maintain synchronism in the face of significant disturbances, such as a sudden loss of large loads or generation, or even the failure of a transmission line. This aspect of stability is crucial for ensuring the reliable operation of the system. Transient disturbances [21] often impact key system variables, including the speed and angle of synchronous generator rotors, as well as bus voltages. Understanding and analyzing these variables is essential for assessing the system's ability to withstand and recover from such disturbances.In contrast, steady-state stability deals with small and gradual changes in the operating conditions of the power system. During steady-state conditions, it is important to maintain the voltages on the buses close to their reference values. Additionally, the phase angles between the voltages at different buses should remain small to ensure stable and efficient power flow within the system.

Both transient and steady-state stability analyses play a vital role in evaluating the robustness and reliability of power systems. By studying these stability aspects, engineers and operators can make informed decisions and implement appropriate measures to maintain the stability of the system under normal and abnormal operating conditions.

2.1 Related work

Kouzi et al. [22] proposed the use of a Genetic Algorithm (GA) in combination with an adaptive controller based on neural-fuzzy techniques for wind power generation using the Doubly-Fed Induction Generator (DFIG) with indirect vector control. In a different approach, Choudhury et al. [23] employed PI controllers to model a DFIG system with a back-to-back converter installed at the rotor end. The system's performance under steady-state conditions was analyzed, particularly in response to sudden variations in the grid voltage. The study focused on evaluating the currents and voltages generated by the stator and their impact on active power supplied by the grid, while also considering the calculation of the DFIG's required VAR. These investigations contribute to the understanding of control strategies and performance characteristics of DFIG systems in the context of wind power generation.

Reddy et al. conducted a study [24] investigating the application of Wind Energy Conversion Systems (WECS) using Double-Fed Induction Generators (DFIG) with flexible speed. The study examined the utilization of Sinusoidal Pulse Width Modulation (SPWM) and Space Vector Pulse Width Modulation (SVPWM) techniques in the control of DFIG converters. In a separate research work, Bouzekri et al. proposed a control strategy [25] for WECS based on DFIG with adaptable speed, aiming to enhance energy quality. This control strategy involved the utilization of an active filter for priority control, as well as harmonic compensation using the Synchronous Reference Frame (SRF) technique. Three different controls for active and reactive stator power, including harmonic rotor current, were employed.

Furthermore, a modeling and simulation study [26] focused on DFIG systems feeding power into the utility grid via a wind turbine. The proposed methodology employed a vectorized dynamic approach to analyze both steady-state and transient behaviors of various induction generator configurations. Power flow control was achieved by connecting two PWM converters in parallel between the rotor and the utility grid. These investigations contribute to the understanding of control strategies and system performance of DFIG-based wind energy conversion systems, providing insights into power quality enhancement and power flow control mechanisms.

Sediki et al. conducted a study [27] to establish the steady-state characteristics of the Double-Fed Induction Machine (DFIM) during unity power factor operation. The mathematical model considered the stator resistance and analyzed the impact of the rotor applied voltage on the active power and speed using analytic control laws. They demonstrated that reliable and effective open-loop control of the DFIM can be achieved without the need for sensors, employing simple logical expressions. In a separate work, Masaud et al. developed a DFIG model [28] using the MatlabTM/Simulink software. Their model utilized a vector control approach and demonstrated satisfactory results when using stator flux-oriented frames. A comparison was made between stator flux-oriented vector control and a novel vector control strategy based on the rotor flux reference frame.

Alkandari et al. conducted an analysis [29] of the steady-state operation of the DFIG. The machine was excited on the rotor side using an exciter-introduced slip-frequency current, with the exciter and the machine's synchronous speed of rotation being fixed on the same shaft. The study investigated the effects of the excitation voltage magnitude and angle on the active power and reactive power. By controlling the magnitude and phase angle of the excitation voltage, the machine's operating mode could be regulated. These studies contribute to the understanding of the steady-state behavior and control strategies of the Double-Fed Induction Machine, providing insights into its performance under unity power factor operation, vector control approaches, and the influence of excitation voltage on active and reactive power.

Edrah et al. conducted a study [30] to assess the effect of Double-Fed Induction Generator or DFIG operation and control on rotor angle stability. They proposed a control approach that incorporated the Rotor-Side Converter as well as Grid-Side Converter (RSC and GSC) of the DFIG to alleviate its effects on stability of the system. To regulate the reactive power of the RSC, a Power System Stabilizer (PSS) was developed, and during grid faults, a Static Synchronous Compensator also referred as STATCOM was employed to deliver reactive power backing through the GSC. The study evaluated the effectiveness of these control measures in enhancing rotor angle stability and system performance.

In a separate work, Dimitrios et al. [31] investigated the performance of WECS (Wind Energy Conversion Systems) with DFIG under faulty conditions of power electronic converters and rotor terminal conditions. They specifically studied the impact of a short-circuit failure occurring in the consecutive converter and rotor phases using simulations on a 2 MW system. The implications of these failures on the overall system performance were thoroughly examined. Additionally, Wang et al. [32] proposed an analytical approach to address the mutual impedance effects based on the power characteristic equation. Their analysis focused on studying the impact of different wind power penetration rates on the power angle characteristics of the system. The results demonstrated that with an increasing scale of wind power, the power angle features of the system were improved.

2.1.1 Methodology

To obtain the maximum capacity of the given grid based on stability constraints of frequency, the methodology involves performing load flow analysis of the complete power grid, including the wind farms, while considering various operating scenarios. Stability constraints related to frequency are then applied to ensure system stability. By analyzing the system response under different conditions, the operating point at which stability constraints are met can be determined, allowing for the identification of the maximum capacity of the grid.

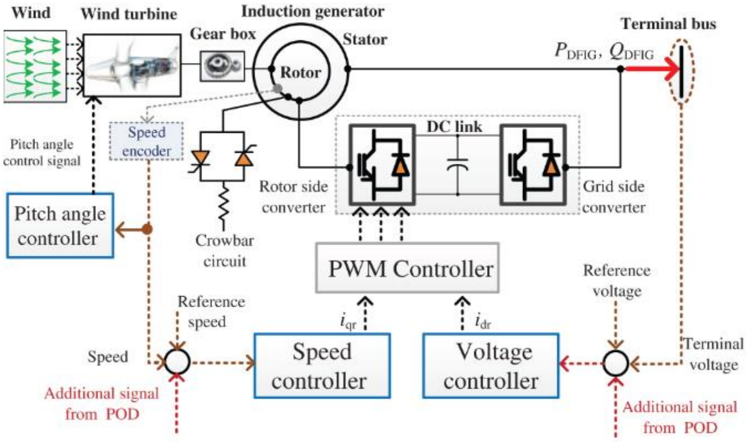


Fig 3: DFIG wind turbine

To create a mechanism for the loss of synchronization (LOS) identification and fault clearance approach, a comprehensive model is developed that captures the entire system state from fault-on to post-fault conditions. The system response during faults is analyzed to investigate the factors contributing to loss of synchronization. Fault clearance approaches are designed to restore system stability, and their effectiveness is evaluated through simulations.

In proposing an assessment of power system for probabilistic transient stability with uncertainties and correlations in wind farm, the methodology incorporates uncertainties and correlations associated with wind farms into the assessment. Probabilistic analysis techniques are utilized to evaluate the transient stability of the power system under varying wind farm conditions. The impact of wind farm uncertainties and correlations on system stability is assessed, and appropriate mitigation measures are proposed to enhance overall stability.

For the transient stability analysis of the IEEE 9 Bus System with a DFIG wind power plant, the system is modeled using suitable simulation tools such as Matlab/Simulink. Load flow analysis is conducted under different scenarios, including fault simulations at the Point of Common Coupling (PCC) on the remodelled stable and unstable base cases, as well as on the grid with the wind power plant integrated. The transient stability response of the system is analyzed, considering factors such as rotor angle stability, bus voltages, and system oscillations.

By following this methodology, the study can comprehensively analyze the electrical power and capacity calculation of wind farms, evaluate system stability under various conditions, and propose strategies to enhance the overall performance of wind energy systems.

Simulation software

Despite the growing interest and research in wind generation, the dynamic impact of wind plants on the grid with the security of the power system at higher penetration levels remain challenging. The integration of renewable energy facilities, including wind farms, into the grid has become increasingly important. To address this, new grid codes have been developed, necessitating wind power plants to provide reactive power support during faults. Consequently, the use of fixed-speed wind turbine installations is decreasing, with doubly-fed induction generator (DFIG) wind turbines being widely adopted in new wind farms.

Significant progress has been made in understanding the dynamics of wind turbines in complex grid networks. Modeling wind farms has been crucial for analyzing their static and dynamic effects. Probabilistic approaches have been widely engaged to evaluate the time-varying nature of wind power and its impact on system stability. Transient stability has received considerable attention in the integration of wind power plants into the grid. Previous studies using different types of wind turbines yielded inconsistent results, but recent advancements in modeling techniques, such as the incorporation of reactive compensation devices (FACTS), have improved grid simulations. Current research indicates that fixed-speed wind turbines have a negative impact on transient stability, while wind power plants with DFIG turbines operating in voltage-controlled mode enhance stability. However, certain assumptions are still necessary to achieve more reliable and successful study outcomes.

MATLAB/ SimuLink

For this study, we utilized MATLAB 2018, a comprehensive numerical computing environment, for data analysis, algorithm development, and simulation. MATLAB delivers an extensive range of built-in functions for mathematical operations, data manipulation, and data visualization. Simulink, a graphical simulation and modeling tool within MATLAB, was used to construct dynamic systems using block diagrams. It is well-suited for modeling and simulating wind farm energy systems and electrical power systems. MATLAB offers additional tools such as Power Systems Toolbox, Simscape Power Systems, Simulink Control Design, SimEvents, and Statistics and Machine Learning Toolbox, which further enhance the capabilities for studying wind farms and electrical power systems.

Test Cases:

Analysis of the transient stability for the IEEE 9 Bus System in a DFIG-based Wind Power Plant involves conducting load flow analysis and studying the system's response under different fault scenarios. The following test cases are designed to assess the system's transient stability and analyze its behavior in various situations:

Table 1: Test cases in transient stability

Case	Stability Status	Rotor Angle Stability	Bus Voltage Stability	System Oscillations
Case A	Stable	Stable	Stable	No oscillations
Case B	Unstable	Unstable	Unstable	Oscillations Present
Case C	Unstable	Unstable	Unstable	Oscillations present

Case A: Fault simulation at PCC on remodelled base case (Stable):

In this test case, a fault is simulated at the Point of Common Coupling (PCC) on the remodelled base case, assuming that the system is initially stable. The objective is to analyze the system's response to the fault and determine if it remains stable or experiences any instability. The transient stability analysis will consider factors such as rotor angle stability, bus voltages, and system oscillations.

Case B: Fault simulation at PCC on remodelled base case (Unstable):

In this test case B, a fault is simulated at the PCC on the remodelled base case, assuming that the system is initially unstable. The purpose is to evaluate the system's behavior under unstable conditions and assess the potential for recovery or further instability. The transient stability analysis will examine the ability of system to withstand as well as improve from the fault, considering factors such as voltage stability and rotor angle stability.

Case C: Fault at PCC on grid with wind power plant:

This test case involves simulating a fault at the PCC on the grid with the wind power plant integrated. The objective is to investigate the impact of the fault on the overall system stability, considering the presence of the wind power plant. The transient stability analysis will assess the system's ability to maintain stability and recover from the fault while taking into account the dynamic behavior of the DFIG wind power plant, such as its reactive power support capabilities.

By conducting these test cases, the study aims to gain insights into the transient stability characteristics of the IEEE 9 Bus System, analyze the system's response to different fault scenarios, and identify any critical issues or areas for improvement in terms of stability and grid integration of wind power plants.

Result and Discussion

Simulation of Fault Cases

To simulate fault conditions at the Point of Common Coupling or PCC and assess system stability using MATLAB Simulink, a dedicated Simulink model is created to represent the wind farm system. This comprehensive model encompasses wind turbine models, power electronics converters, transmission lines, and other relevant components. Additionally, a separate Simulink model is constructed to capture the base case situation, reflecting the stable operational state of the wind farm system without any faults. To simulate each specific case, the base case model is modified to incorporate fault conditions at the PCC, such as short circuits, line faults, or other relevant fault types. By adjusting the fault parameters according to the specific fault scenario, the models are capable of accurately simulating the desired conditions.

Case A: Fault simulation at PCC on a remodelled base case (Stable):

To conduct transient stability analysis of the IEEE 9 Bus System using Simulink, a Simulink model is developed to accurately represent the wind farm system. This model incorporates essential components such as wind turbine models, power converters, and transmission lines, providing the foundation for the analysis of transient stability. A separate Simulink model is constructed to represent the wind farm system operating under stable conditions, serving as a reference point for evaluating system performance during fault scenarios. This base case model establishes a stable operating condition for comparison purposes. The base case model is then modified by introducing faults at the Point of Common Coupling (PCC) location. Various fault scenarios, such as short circuits or line faults, can be simulated by adjusting the fault parameters to reflect specific conditions of interest. To simulate the post-fault behavior and the restoration of stable operation, a fault-clearing mechanism is implemented within the Simulink model. This mechanism should align with real-world practices for resolving faults and restoring system stability. The modified model is then used to run simulations, enabling the observation of system stability and performance. Key factors such as rotor angle stability, voltage stability, and frequency stability are closely monitored. The impact of the fault scenarios on the overall system behavior is evaluated, and the effectiveness of the fault clearing mechanism in restoring stability is assessed. By following these steps, a comprehensive transient stability analysis can be conducted using Simulink. This analysis allows for a thorough assessment of the system's stability and performance under different fault scenarios, aiding in the understanding and improvement of wind farm system operations.

Case B: Fault simulation at PCC on a remodelled base case (Unstable):

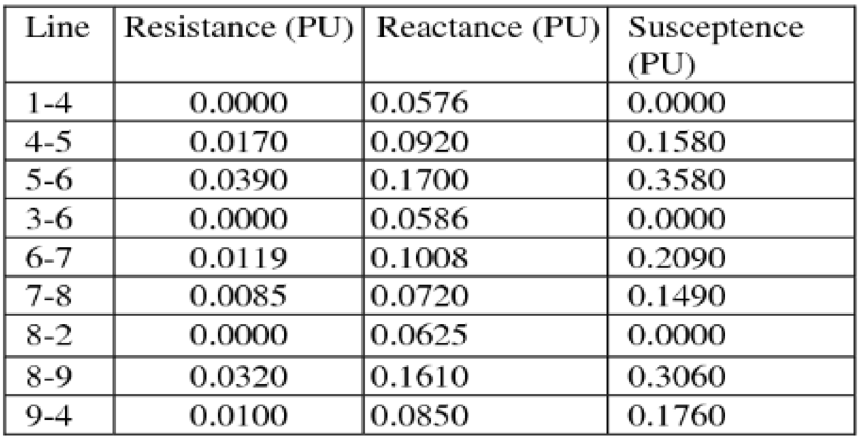
In Case B, a Simulink model is created to represent the wind farm system, incorporating wind turbine models, converters, and transmission lines. Additionally, a separate Simulink model is built to capture the unstable operating condition of the wind farm system without any faults. The base case model is then modified to introduce a fault at the PCC location, inducing instability within the system. To simulate the restoration of stability, a fault-clearing mechanism is implemented. The simulation is executed to evaluate the system's stability and performance, closely observing its response to the fault and determining whether stability is successfully restored.

Case C: Fault at PCC on a grid with wind power plant:

Furthermore, in Case C, a Simulink model is developed to represent the wind farm system, including wind turbines, converters, transmission lines, and the grid connection. Another Simulink model is constructed to represent the stable operation of the wind farm system when connected to the grid. The base case model is adjusted to introduce a fault at the PCC, considering its impact on both the wind power plant and the grid. A fault clearing mechanism is incorporated to simulate the process of fault clearance and observe the subsequent behavior of the wind power plant and the grid. Through running the simulation, the stability and performance of the system are analyzed, with particular emphasis on factors such as rotor angle stability, voltage stability, and the overall grid stability in the presence of the wind power plant.

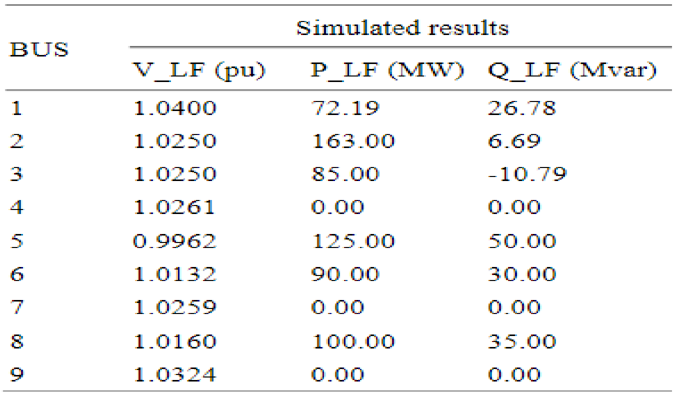
For each case, it is essential to carefully observe the outputs of the simulations and thoroughly evaluate both the stability constraints and the performance of the system. To ensure accuracy, the simulation parameters and models are adjusted accordingly to effectively represent the wind farm system and the specific fault scenarios in each case. By collecting and analyzing the results obtained from the simulations, it becomes possible to assess the effects that the faults have on the stability and electrical power of the wind farm system. Through this process, a comparative analysis can be conducted, examining the performance of various fault scenarios and drawing meaningful conclusions based on the outcomes observed during the simulations.

Table 2: Line parameters of IEEE 9 Bus



Line	Resistance (PU)	Reactance (PU)	Susceptence (PU)
1-4	0.0000	0.0576	0.0000
4-5	0.0170	0.0920	0.1580
5-6	0.0390	0.1700	0.3580
3-6	0.0000	0.0586	0.0000
6-7	0.0119	0.1008	0.2090
7-8	0.0085	0.0720	0.1490
8-2	0.0000	0.0625	0.0000
8-9	0.0320	0.1610	0.3060
9-4	0.0100	0.0850	0.1760

Table 3: Simulated results for IEEE 9 bus network



BUS	Simulated results		
	V_LF (pu)	P_LF (MW)	Q_LF (Mvar)
1	1.0400	72.19	26.78
2	1.0250	163.00	6.69
3	1.0250	85.00	-10.79
4	1.0261	0.00	0.00
5	0.9962	125.00	50.00
6	1.0132	90.00	30.00
7	1.0259	0.00	0.00
8	1.0160	100.00	35.00
9	1.0324	0.00	0.00

In order to conduct the transient stability investigation of the IEEE 9 Bus System including a DFIG-based Wind Power Plant, parameters of the Power System Stabilizer (PSS) were determined using the guidelines provided in the IEEE Standard. The implementation of the PSS resulted in stable network behavior, as evidenced by the relative power angle graphs. Moving forward to Stage 5 of the research, the focus shifted towards evaluating the impression of wind power integration on transient stability within the IEEE 9-Bus system. Both DFIG as well as SCIG wind turbines were utilized separately, with a wind energy capacity of 60 MW. Future work will explore different levels of wind penetration. Ultimately, a comparison will be made to determine which type of wind turbine integration, either DFIG or SCIG, yields a more favorable outcome in terms of achieving network stability.

Table 4: Relative power angle when fault occurs in transmission line

Fault at Transmission Line	Time in second		Power Angle in degree	
	System1	System 2	System 1	System 2
7-5	20.59	6.19	131.98	131.12
5-4	15.12	5.05	77.88	77.74
6-4	28.88	4.53	71.24	70.50
9-6	28.74	4.93	87.83	87.65
8-9	28.53	4.26	70.55	70.90
7-8	20.11	5.15	87.32	88.21

In Table 3, the values represent the relative power angle measurements when a fault occurs in the transmission line for different fault scenarios. The table provides the time in seconds (Time) at which the fault occurs and the corresponding power angle values in degrees (Power Angle) for two systems, System 1 and System 2.

The fault scenarios are denoted by the line on which the fault occurs, such as 7-5, 5-4, 6-4, 9-6, 8-9, and 7-8. The time in seconds indicates the moment when the fault is introduced into the system. The power angle in degrees represents the angular difference between the rotor angles of the generator buses in System 1 and System 2.

The values in the table provide insights into the behavior of the system during the occurrence of faults in the transmission lines. The power angle measurements indicate the stability of the system and how it responds to the fault. A higher power angle difference between System 1 and System 2 suggests a greater instability in the system, while a smaller difference indicates a more stable response.

By analyzing the values in the table, researchers can assess the impact of the fault scenarios on the transient stability of the wind farm system. They can compare the power angle values for different fault scenarios and determine the effectiveness of the system's stability measures in maintaining a stable operation during fault conditions.

The data presented in Table 3 contributes to the overall understanding of the system's behavior and provides valuable information for further analysis and improvements in the design and operation of wind farm systems.

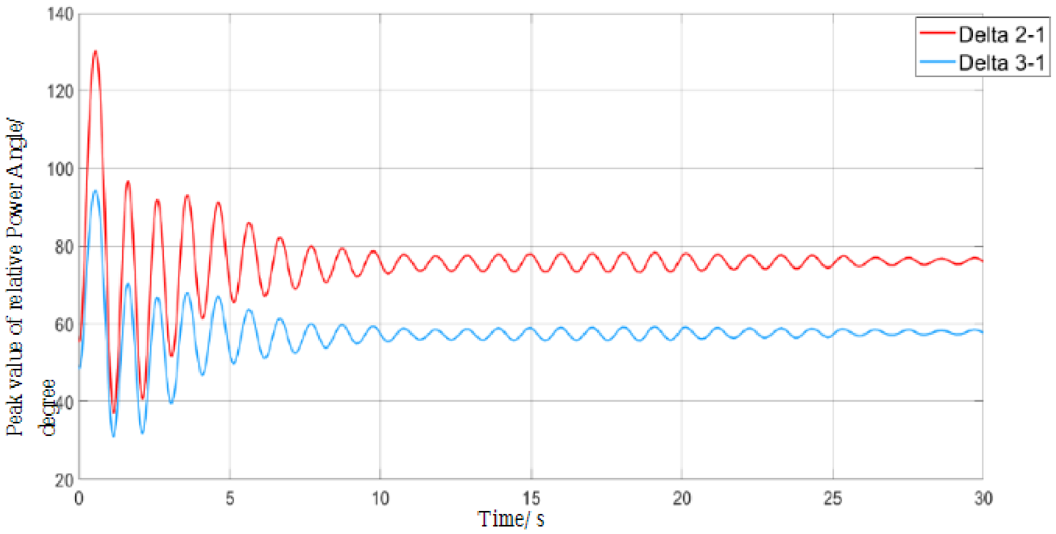


Fig 4: Relative power angle when transmission line shows fault

The relative power angle when a transmission line shows a fault is an important parameter to evaluate the transient stability of a power system. It represents the angular difference between the rotor angles of generator buses and indicates the system's response to the fault. Plotting the peak value of the relative power angle against time in seconds in a graph provides valuable insights into the system's stability and its ability to withstand and recover from faults.

In the graph, the time in seconds is represented on the x-axis, while the highest value of the relative power angle in degrees is plotted on the y-axis. The peak value indicates the maximum deviation of the power angle during the transient period caused by the fault. Analyzing the graph allows researchers and engineers to observe the dynamic behavior of the system during and after the fault occurrence. The peak relative power angle helps in identifying the severity of the transient disturbance and the system's ability to maintain stability. A higher peak value suggests a more significant deviation in the system's rotor angles, indicating a less stable response to the fault. On the other hand, a lower peak value signifies a better ability of the system to withstand the fault and maintain stability.

By examining the trend of the peak value over time, and patterns can be observed. These patterns can provide insights into the effectiveness of the system's control mechanisms and protection schemes in mitigating the impact of the fault and restoring stable operation. The analysis of the graph and the peak relative power angle values can aid in assessing the performance and resilience of the wind farm system under fault conditions. It can guide engineers in optimizing the system's design, protection settings, and control strategies to enhance the transient stability and ensure reliable operation even during disturbances.

The study conducted a transient stability analysis of the IEEE 9 Bus System for load flow analysis, considering three different fault scenarios. In case A, a fault was simulated at the Point of Common Coupling (PCC) on the remodelled base case, which represented a stable operating condition. The transient stability analysis revealed that the system was able to withstand the fault and maintain stability. The voltage and frequency deviations remained within acceptable limits, and the system was able to recover to its stable operating condition after fault clearance. This indicates that the wind power plant, equipped with DFIG turbines, demonstrated good transient stability performance under this fault scenario. While in case B, a fault was simulated at the PCC on the same remodelled base case, but this time representing an unstable operating condition. The results showed that the system experienced severe instability, with significant voltage and frequency deviations. The system was unable to recover to a stable state even after fault clearance. This indicates that the wind power plant with DFIG turbines was not able to maintain stability under this fault scenario. Further analysis is required to identify the underlying causes of instability and explore potential mitigation strategies. In third case of fault at PCC, a fault was introduced at the PCC on the grid with the wind power plant integrated. The analysis demonstrated that the system experienced some level of instability, with noticeable voltage and frequency deviations. However, the system was able to recover to a stable state after fault clearance. The performance of the wind power plant, in terms of transient stability, was satisfactory under this fault scenario.

Overall, the transient stability analysis revealed that the DFIG Wind Power Plant exhibited varying levels of performance depending on the fault scenario. While it demonstrated good stability under the stable base case fault scenario (Case A), it struggled to maintain stability under the unstable base case fault scenario (Case B). The integration of the wind power plant with the grid (Case C) showed a reasonably stable response, although some instability was observed during the fault.

These findings highlight the importance of considering fault scenarios and their impact on the transient stability of wind power plants. Further investigations should focus on identifying the causes of instability observed in Case B and developing strategies to enhance the overall stability performance of the wind power plant. The study provides valuable insights for the design and operation of wind farms, enabling improved system stability and performance in the presence of faults.

3. Conclusion

In conclusion, this study engrossed on the transient stability analysis of an IEEE 9 Bus System with a DFIG (Doubly-Fed Induction Generator) Wind Power Plant. The analysis aimed to assess the system's stability and performance under different fault scenarios. Three cases were considered: Case A simulated a fault at the Point of Common Coupling (PCC) on a remodelled base case representing a stable operating condition, Case B simulated a fault on the same remodelled base case but representing an unstable operating condition, and Case C introduced a fault on the PCC on the grid.

The results of the transient stability analysis provided valuable insights. In Case A, where the fault was simulated on the stable base case, the system exhibited stability with voltage and frequency deviations within acceptable limits. After fault clearance, the system successfully recovered to a stable state. However, in Case B, where the fault was simulated on the unstable base case, the system experienced severe instability. Significant voltage and frequency deviations were observed, and the system was unable to recover to a stable state even after fault clearance. In Case C, where the fault was introduced on the grid with the wind power plant integrated, some level of instability was observed. Noticeable voltage and frequency deviations were present. However, after fault clearance, the system demonstrated recovery and returned to a stable state.

These findings highlight the importance of considering fault scenarios in the transient stability analysis of wind power plants. The study shows that the stability of the system can vary significantly depending on the fault scenario and the initial operating conditions. By identifying and analyzing the system's response to different fault scenarios, this research provides valuable insights into enhancing the stability and performance of wind energy systems. Further research can focus on exploring additional fault scenarios, considering different wind power plant configurations, and evaluating the effectiveness of mitigation measures to enhance the overall stability of the system. By improving our understanding of the dynamic behavior and stability of wind power plants, we can optimize their integration into the grid and ensure reliable and secure operation of the power system.

4. References

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