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Optimized Fault Current Prediction for DFIG-Based Wind Turbines Using Type-I Fuzzy Logic Controller

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Abstract: The increasing integration of Doubly-Fed Induction Generator (DFIG)-based wind turbines into modern power grids requires robust fault detection and prediction mechanisms to ensure stable and reliable operation. However, accurately predicting fault currents in such systems is challenging due to the nonlinear dynamics involved. This study presents an optimized fault current prediction framework using a Type-I Fuzzy Logic Controller (FLC) to address these challenges. The proposed approach effectively models the uncertainties and variations in fault scenarios, enhancing the reliability of the fault current prediction process. The Type-I FLC is designed to handle imprecise input parameters, such as wind speed fluctuations and grid disturbances, which significantly impact the fault behaviour of DFIG systems. By integrating optimized membership functions and adaptive rule-based inference, the controller ensures precise estimation of fault currents under various fault conditions, including symmetrical and asymmetrical faults. The FLC also demonstrates high adaptability, enabling improved system performance even in dynamic grid environments. Simulation results validate the effectiveness of the proposed system, showing enhanced accuracy in fault current prediction compared to conventional methods. The optimized FLC-based prediction framework not only mitigates the risks associated with overcurrent but also ensures timely protective actions, minimizing potential disruptions. This approach provides a viable solution for grid operators to maintain stability and reliability in wind-integrated power systems, contributing to sustainable energy management.

Keywords: Wind Turbine System, WECS, DFIG, GSC, RSC, Fuzzy Logic Controller.

1. Introduction

The increasing penetration of renewable energy sources, especially wind power, has made wind turbines a crucial component of modern power grids [1]. Among various wind turbine technologies, the Doubly-Fed Induction Generator (DFIG)-based wind turbine is widely employed due to its ability to operate efficiently over a wide range of wind speeds and provide reactive power support to the grid. However, DFIG-based systems are susceptible to various types of electrical faults, such as symmetrical and asymmetrical faults, which can result in excessive fault currents [2]. If not managed effectively, these faults may compromise grid stability and damage critical equipment. Hence, accurate and optimized fault current prediction becomes essential for the reliable operation of wind-integrated systems. Predicting fault currents in DFIG systems is challenging due to their nonlinear and dynamic behavior, influenced by external factors like wind speed variations and grid disturbances [3]. Traditional fault current estimation techniques often rely on mathematical models or predefined fault scenarios, but they may fall short when real-world conditions deviate from these assumptions. In such situations, the system's behavior becomes unpredictable, increasing the risk of inaccurate fault current estimates [4]. An optimized prediction strategy is needed to handle the uncertainties inherent in DFIG-based wind turbines and provide robust protection for both the turbines and the grid. This study proposes the use of a Type-I Fuzzy Logic Controller (FLC) to optimize fault current prediction in DFIG-based wind turbine systems. Fuzzy logic controllers are well-suited for systems characterized by uncertainties and imprecise input data [5]. The Type-I FLC offers a rule-based approach that mimics human decision-making, using membership functions to process uncertain inputs like fluctuating wind speeds or variable grid conditions [6]. This adaptive nature of the controller enables it to provide more accurate fault current predictions compared to conventional methods, which often assume fixed fault parameters. To further enhance prediction accuracy, the proposed framework integrates optimization techniques for fine-tuning the membership functions and rules of the FLC [7]. This ensures that the controller remains responsive to different fault scenarios, such as single-line-to-ground faults or three-phase faults. Additionally, the FLC adapts to variations in wind turbine operating conditions, providing better control over fault currents [8]. By doing so, the system ensures that protective measures, such as circuit breakers or relays, are activated in a timely and precise manner, minimizing the risk of equipment damage and service disruptions. The study’s contributions are twofold: it not only addresses the challenges of fault current prediction but also offers a scalable solution for future wind power systems. Simulation results demonstrate the effectiveness of the optimized Type-I FLC in predicting fault currents under various scenarios, outperforming traditional techniques. This research highlights the importance of advanced fault management strategies in wind-integrated grids and lays the foundation for further exploration of intelligent control approaches to enhance grid stability and reliability in the face of evolving energy demands [9].

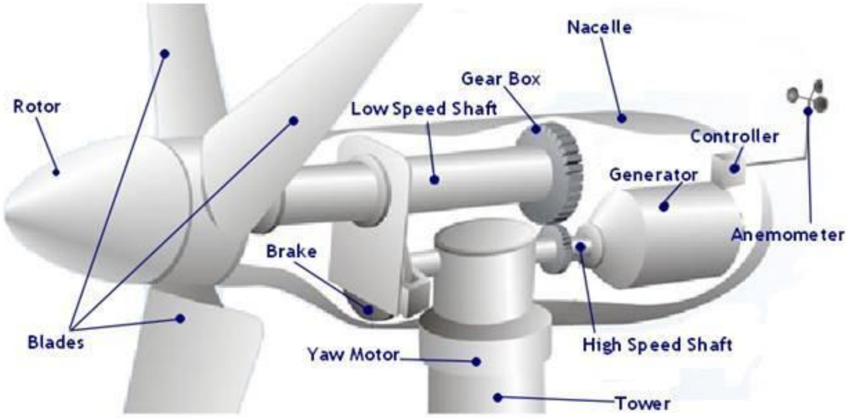


Fig.1: Wind Turbine Components [1]

Wind turbines components illustrated in figure 1, are often installed in remote locations with challenging terrains, such as offshore sites or isolated mountain regions, where access for routine maintenance is limited and costly [10]. These logistical difficulties, combined with the inherent variability of wind, increase operational expenses and reduce the reliability and availability of wind power. To address these challenges, the reliability of wind turbine systems becomes crucial, as improved reliability minimizes unexpected failures, lowers downtime, and reduces maintenance costs [11]. Condition monitoring and fault diagnosis have emerged as essential techniques for achieving these goals by continuously assessing the health of wind turbine components, thereby enhancing operational performance and extending the lifespan of the equipment [12]. In this study, the Doubly-Fed Induction Generator (DFIG) is utilized as the primary component of the wind turbine system. A mathematical model is developed to represent the dynamic process of converting wind energy into electrical energy. This model captures how aerodynamic power from the wind is converted into mechanical energy, which is then transformed into electrical energy through the DFIG system [13]. The focus is placed on the drive train of the wind turbine, as it plays a critical role in the interaction between the mechanical and electrical systems. To simplify the analysis, secondary components such as the tower and flap bending modes are not considered in the model, ensuring that the study remains concentrated on the dynamic elements that directly affect energy conversion and grid interaction [14]. A key feature of the proposed system is the integration of a fuzzy logic controller (FLC) with the variable-speed wind turbine to optimize power output in the presence of fluctuating wind conditions. The FLC offers adaptive control by generating control signals that adjust the turbine's rotational speed to maximize aerodynamic efficiency. Additionally, the controller reduces the air gap magnetic flux in the generator, further enhancing power output. The system also includes torque-speed control to counteract the effects of wind turbulence, ensuring smooth operation and minimizing mechanical stress on the components. The turbine’s rotor shaft is connected to a squirrel cage induction generator via a gearbox with a speed-up gear ratio, enabling efficient energy conversion across varying wind speeds. This type of induction generator is widely favored due to its robustness, reliability, and cost-effectiveness. The generator is linked to the power grid through a voltage-fed pulse width modulated (PWM) converter that employs insulated gate bipolar transistors (IGBTs) in both the rectifier and inverter stages. A Hanning PWM chip is used for precise voltage vector rotation and sinusoidal PWM generation, ensuring that the system maintains stable and efficient power conversion. One of the major benefits of the proposed converter system is its ability to maintain a near-unity power factor on the grid side, with minimal harmonic distortion, in accordance with IEEE Standard 519 and IEC Standard 555. This ensures that the energy fed into the grid is of high quality, which is critical for meeting the stringent requirements of modern power systems. The bidirectional power flow capability of the converter allows it to operate flexibly, either as a rectifier or an inverter, depending on the control requirements. This flexibility is essential for balancing power in grid-connected wind turbine systems. The system design incorporates both a conventional Proportional-Integral (PI) controller and a Fuzzy Logic Controller (FLC) for advanced control. The PI controller utilizes error and change in error as inputs, with its gains dynamically adjusted by the self-tuning mechanism of the FLC. The integration of the FLC with the conventional PID controller allows for real-time tuning of the PI controller's parameters, ensuring optimal performance under varying operating conditions. This hybrid control approach provides a robust solution to maintain power quality, improve turbine reliability, and reduce maintenance costs, thereby addressing the key challenges associated with wind turbine systems [15].

2. Wind Energy Conversion System

A Wind Energy Conversion System (WECS) refers to the process through which kinetic energy from wind is converted into electrical energy presented in figure 2 shown below [16]. It is composed of several interconnected subsystems, including the wind turbine, drivetrain, generator, and control mechanisms, each playing a critical role in the energy transformation process. The primary function of the wind turbine is to capture wind energy through the rotor blades, which rotate as wind flows over them [17]. This rotation generates mechanical energy that is transferred through the drivetrain to the generator, where it is converted into electrical energy. WECS systems are typically classified as fixed-speed or variable-speed systems, with the latter offering higher efficiency and adaptability to fluctuating wind conditions. The wind turbine is the heart of the WECS, consisting of blades, a hub, and a nacelle that houses key components like the gearbox and generator [18]. The turbine blades are designed aerodynamically to capture maximum wind energy. When wind flows across the blades, it creates a difference in air pressure, causing the rotor to spin. The mechanical energy generated by this rotation is proportional to the wind speed and blade design, governed by the power coefficient (Cp). However, due to the stochastic nature of wind, maintaining an optimal Cp becomes challenging, which is where control strategies like pitch control and yaw control are employed to maximize aerodynamic efficiency. The mechanical energy produced by the rotating blades is transmitted to the generator through a drivetrain, which typically includes a gearbox to step up the rotational speed. Depending on the design, either a squirrel cage induction generator (in fixed-speed systems) or a Doubly-Fed Induction Generator (DFIG) (in variable-speed systems) is employed. DFIG-based systems are preferred for modern wind turbines due to their ability to operate over a range of wind speeds, providing both active and reactive power support [19].

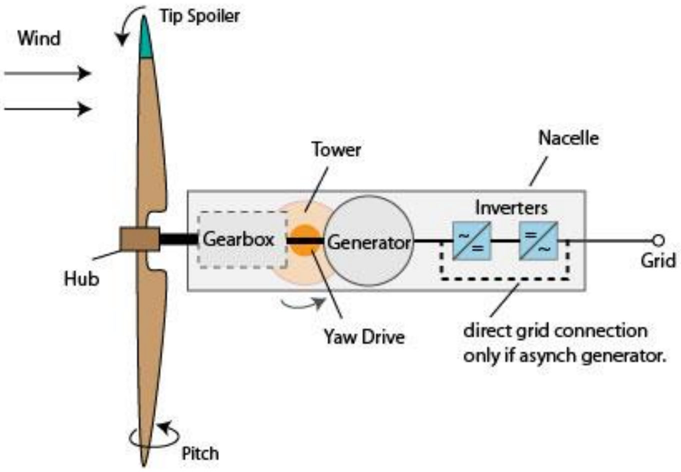


Fig.2: Wind Energy Conversion System [2]

The DFIG configuration allows partial decoupling of mechanical speed from grid frequency, enhancing the turbine's efficiency under varying wind conditions [20]. In WECS, power electronic converters play a crucial role in regulating the flow of electrical energy from the generator to the grid. In DFIG-based systems, a back-to-back converter consisting of a rectifier and an inverter ensures that the generated power is synchronized with grid parameters. Pulse Width Modulation (PWM) techniques are used to control the voltage and frequency of the output power, ensuring smooth and efficient grid integration. The converters also enable bidirectional power flow, which helps manage excess energy during low-demand periods and ensures grid stability. Additionally, compliance with international standards like IEEE 519 ensures minimal harmonic distortion and a unity power factor. To maximize the efficiency and reliability of a WECS, advanced control systems are integrated into the turbine. These include both conventional controllers, such as Proportional-Integral-Derivative (PID) controllers, and intelligent controllers like Fuzzy Logic Controllers (FLCs). The FLC optimizes the turbine's performance by dynamically adjusting the rotational speed, air gap flux, and generator torque based on wind conditions. This not only maximizes aerodynamic efficiency but also minimizes the impact of wind turbulence. Additionally, control systems manage pitch angles to prevent mechanical stress during high wind speeds, ensuring safe operation. Together, these components enable WECS to produce consistent and high-quality power, making them a vital part of sustainable energy solutions [21].

3. Doubly-Fed Induction Generators in WECS

A Doubly-Fed Induction Generator (DFIG) is a widely used configuration in modern Wind Energy Conversion Systems (WECS) due to its flexibility, efficiency, and ability to operate at variable speeds. In a DFIG-based system, both the stator and the rotor of the generator are connected, with the stator directly coupled to the grid and the rotor connected through power electronic converters. This dual-fed design allows the DFIG to generate electrical power efficiently under varying wind conditions, offering both active and reactive power support to the grid, which is crucial for grid stability. The DFIG works on the principle of electromagnetic induction, where the rotor winding is excited by a slip frequency AC current through the converters. This configuration allows power flow in both directions – from the rotor to the grid and vice versa – depending on the operational state. The rotor speed can vary around the synchronous speed, allowing the generator to operate in both sub-synchronous and super-synchronous modes. This feature enables the system to capture more energy across a wide range of wind speeds, increasing overall efficiency compared to fixed-speed generators [22-25].

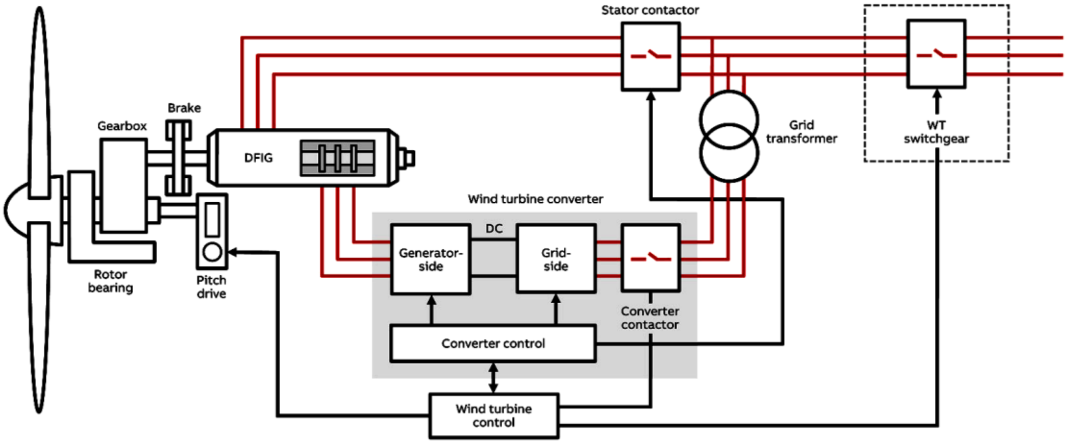
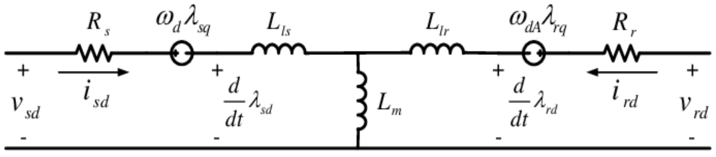
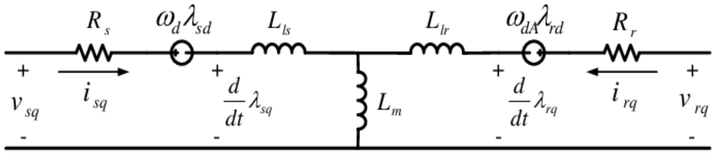


Fig.3: DFIG based WECS model [3]

In DFIG-based WECS shown in figure 3 illustrates the mechanical energy from the wind turbine rotor is transmitted to the DFIG rotor through a gearbox. The mechanical torque applied to the rotor generates an induced current in both the stator and rotor windings. While the stator supplies power directly to the grid, the rotor power is regulated through back-to-back converters, which control the rotor current. These converters adjust the rotor speed according to wind conditions, ensuring that the generator remains synchronized with the grid frequency, even under variable wind speeds. A DFIG employs back-to-back power electronic converters to regulate the rotor current and manage power flow. This system consists of a rotor-side converter (RSC) and a grid-side converter (GSC). The RSC controls the rotor's magnetic flux and ensures that the generator provides the desired active and reactive power. Meanwhile, the GSC maintains grid-side power quality by ensuring unity power factor operation and reducing harmonic distortions. The use of Pulse Width Modulation (PWM) in both converters guarantees smooth voltage and frequency regulation, enabling stable grid integration. One of the key advantages of DFIG-based systems is their ability to operate efficiently over a wide range of wind speeds, thanks to variable-speed operation. This enhances the capacity to capture maximum energy from the wind, improving the overall capacity factor of the wind turbine. Additionally, the DFIG provides reactive power control, which helps stabilize the grid voltage, especially under fluctuating wind conditions. This makes the DFIG an ideal choice for grid-connected wind farms where voltage regulation and power quality are critical requirements. Despite its advantages, DFIG-based systems face several challenges. One significant issue is their sensitivity to grid disturbances such as voltage sags, swells, and faults, which can lead to rotor overcurrent and damage to power electronics. As DFIGs are directly connected to the grid through the stator, they are more vulnerable to grid-side faults compared to fully-converter-based wind turbines. Advanced control strategies such as crowbar protection and fault ride-through (FRT) mechanisms are often implemented to protect the generator and converters during grid faults, ensuring continuous operation. Efficient control of DFIG systems requires a combination of conventional and intelligent controllers. Proportional-Integral (PI) controllers are typically used to regulate rotor currents and maintain desired power output. However, the addition of Fuzzy Logic Controllers (FLCs) enhances system performance by dynamically adjusting control parameters in real-time, based on changing wind speeds and grid conditions. These advanced control mechanisms improve the system's fault tolerance, optimize power capture, and ensure smooth grid integration, making DFIGs reliable components in wind energy systems. Recent research efforts focus on improving the reliability and fault tolerance of DFIG systems [26-29].



(a) d-axis



(b) q-axis

Fig.4: Equivalent circuit of DFIG in: (a) d-axis and (b) q-axis

Innovations in machine learning algorithms and predictive analytics are being integrated to monitor the health of components and predict potential failures. Additionally, new grid codes are demanding stricter compliance with fault ride-through capabilities, prompting further developments in power electronics and control strategies. The integration of energy storage systems alongside DFIG-based turbines is also being explored to enhance power delivery during periods of low wind or grid instability. These advancements ensure that DFIGs remain at the forefront of wind energy technology, contributing to the growth of sustainable and reliable power systems. The converter is capable of changing the output voltage almost instantaneously – the limit is related to the switching frequency of the pulse-width modulated switching devices, and delays introduced by any filtering on the output. The model in Figure 4 illustrates a DFIG phasor diagram based on GSC (grid side control technique) functions of the voltage control (stator) Mechanism on the RSC (rotor side control). This control uses a PI control conventional system for the steady state analysis and transient analysis with settling times for the removal of faults during the grid integrated sudden wind speed variations [30-31].

$$v_{ds} = -R_s x i_{ds} + (x_s + x_m)\,\mathrm{x}\,i_{qs} + x_m x i_{qr} \quad (1)$$

$$v_{qs} = -R_{s^x} i_{qs} - (x_s + x_m) x i_{ds} + x_m x i_{dr} \quad (2)$$

$$v_{dr} = -R_r x i_{dr} + (1-\omega) x ((x_r + x_m) x i_{qr} + x_m x i_{qs} \quad (3)$$

$$v_{qr} = -R_r x i_{qr} + (1-\omega) x ((x_r + x_m) x i_{dr} + x_m x i_{ds} \quad (4)$$

Where: υ_{ds}, υ_{qs} are d and q axes of the stator voltages; υ_{dr}, υ_{qr}, d and q axes of the rotor voltages; ids, iqs, d and q axes of the stator currents; i_{dr}, i_{qr}, d and q axes of the rotor currents; R_a, R_r, stator and rotor resistance; xs, stator self-reaction; x_r, rotor self-reaction; x_m, rotor speed. The inserted active and reactive forces in the network can be expressed as given blow:

$$P = v_{ds} x i_{ds} + v_{qs} x i_{qs} + v_{dr} x i_{dr} + v_{qr} x i_{qr} \quad (5)$$

$$Q = -\frac{x_m v i_{dr}}{x_s + x_m} - \frac{v^2}{x_m} \quad (6)$$

Here v is the magnitude of grid voltage.

$$\left.\begin{aligned} & J\frac{dw_m}{dt} = T_e - T_m \\ & T_e = \frac{3P}{2}\mathrm{Re}(\mathrm{j}\vec{\lambda}_s \vec{i}_s^{\,*}) = -\frac{3P}{2}\mathrm{Re}(\mathrm{j}\vec{\lambda}_s \vec{i}_r^{\,*}) \end{aligned}\right\} \quad (7)$$

Here J = MI-moment of inertial of the rotor (Kgm^2)

P = number of poles

Tm = Mechanical Torque (N.m)

Te = Electromagnetic Torque(N.m)

w_m = Rotor Mechanical Speed (rad/s)

The wind turbine system mechanical torque T_m is:

$$T_m = \frac{p_w}{\omega} \quad (14)$$

The wind turbine system power as P_w is:

$$p_w = \frac{1}{2}\rho c_p A * V_w^3 \quad (15)$$

Where: c_p - power coefficient, ω - rotor speed, ρ - air density (kg/m^2), A - rotor area (m^2) and V_w (m/s) - wind velocity. Thus, the electrical torque T_e and the mathematical link between T_m and T_e results:

$$T_e = x_m(i_{qr}i_{ds} - i_{dr}i_{qs}) \quad (16)$$

$$\frac{d\omega}{dt} = \frac{1}{2H}(T_m - T_e) \quad (17)$$

Here H is denoting rotor inertia.

4. Rotor-Side Converter of WECS

The Rotor-Side Converter (RSC) is a critical component in Doubly-Fed Induction Generator (DFIG)-based Wind Energy Conversion Systems (WECS). Its primary role is to regulate the rotor current and control the active and reactive power generated by the DFIG. Positioned between the rotor and the grid-side converter (GSC), the RSC is responsible for managing the generator’s performance under varying wind conditions, ensuring efficient power capture and stable grid integration. By controlling the rotor voltage and current, the RSC allows the wind turbine to operate at optimal speed, even when wind speeds fluctuate. The RSC ensures that the DFIG can operate at variable speeds, which is essential for maximizing energy capture in changing wind conditions. By controlling the rotor voltage, it regulates the torque-speed characteristics of the generator [32-34].

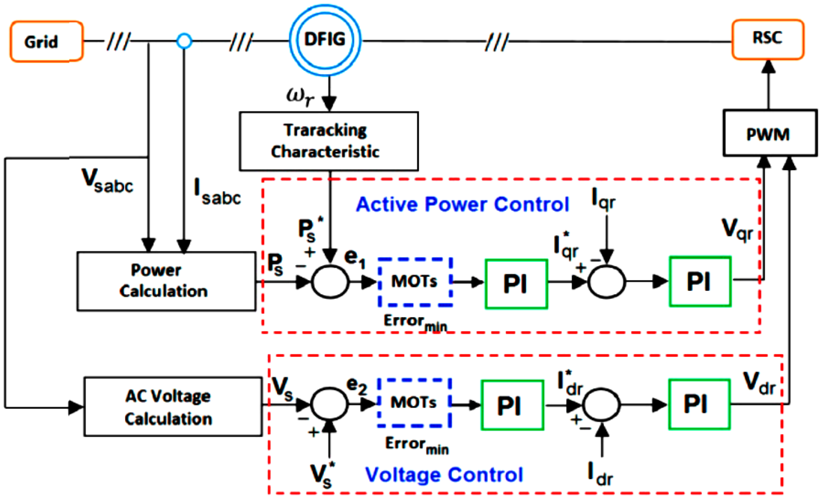


Fig.5: Rotor-Side Converter Design for WECS

The RSC shown in figure 5 is essential for the fault ride-through (FRT) capability of the wind turbine. During grid disturbances such as voltage sags or faults, the converter must prevent overcurrent from damaging the rotor windings or power electronics. This allows the system to maintain the optimal tip-speed ratio (TSR), where the rotor blades operate at the most efficient angle relative to wind speed. The converter dynamically adjusts the generator's torque to match wind conditions, ensuring smooth operation and preventing mechanical stress on the turbine components during wind gusts or turbulence. The RSC plays a pivotal role in controlling both active and reactive power. Active power, responsible for energy generation, is controlled by adjusting the rotor current based on the wind turbine’s rotational speed. Reactive power control, on the other hand, is crucial for voltage regulation and grid stability. The RSC ensures that the DFIG can supply or absorb reactive power as required by the grid, helping maintain voltage levels and complying with grid codes. This capability makes the DFIG superior to fixed-speed generators, especially in applications requiring voltage support. Advanced protection techniques, such as crowbar circuits, are integrated with the RSC to bypass the rotor current during severe disturbances, ensuring system stability. Additionally, the RSC works with the grid-side converter (GSC) to provide smooth transition between sub-synchronous and super-synchronous operation, improving fault tolerance and enhancing the reliability of the turbine. To further enhance performance, modern RSCs are integrated with Fuzzy Logic Controllers (FLCs) or other intelligent control strategies. These controllers optimize the dynamic response of the RSC, allowing it to adapt to sudden changes in wind speed or grid conditions. The FLC can fine-tune the rotor current and voltage parameters in real time, improving the efficiency of power generation and minimizing the effects of turbulence. The combination of conventional PI controllers with intelligent controllers like FLCs ensures robust and reliable performance, enabling the wind turbine to operate smoothly across a wide range of environmental and grid conditions. The RSC's ability to regulate speed, torque, and power flow is vital for efficient wind energy generation and reliable grid interaction. Together with the grid-side converter, it forms a seamless control system that makes DFIG-based wind turbines a preferred choice in modern WECS applications [35-41].

5. Grid-Side Converter in WECS

The Grid-Side Converter (GSC) in Wind Energy Conversion Systems (WECS) is a crucial component in the power electronics setup of Doubly-Fed Induction Generator (DFIG)-based wind turbines. It ensures the smooth transfer of electrical energy from the wind turbine to the power grid while maintaining power quality and stability. Positioned between the rotor-side converter (RSC) and the utility grid, the GSC ensures that the energy generated by the wind turbine complies with grid requirements in terms of frequency, voltage, and power factor. One of the primary functions of the GSC is to ensure that the output power meets harmonic distortion limits specified by standards like IEEE 519. Since DFIG-based wind turbines operate under varying wind conditions, the output from the rotor contains non-sinusoidal components. The GSC employs Pulse Width Modulation (PWM) techniques to generate a high-quality, sinusoidal voltage waveform that minimizes harmonic distortion. This ensures the system provides clean energy to the grid without introducing noise or instability. The GSC plays a vital role in reactive power compensation by controlling the amount of reactive power fed to or absorbed from the grid. Through this control, the GSC ensures that the wind turbine maintains a unity power factor or supplies reactive power as required by grid operators. This feature is critical for grid stability, especially in regions with high wind energy penetration, where fluctuations in reactive power can impact the voltage stability of the grid. During grid disturbances such as voltage sags, swells, or faults, the GSC ensures the stability of the wind turbine system. It works in tandem with the RSC to provide fault ride-through (FRT) capability, which allows the wind turbine to remain connected to the grid during short-term faults. The GSC regulates the current flow to prevent damage to the generator and converters during these disturbances. It can also inject reactive power into the grid to support voltage recovery, further enhancing the resilience of the power system during transient events. The GSC operates in close coordination with the rotor-side converter (RSC) to regulate power flow between the wind turbine and the grid [42].

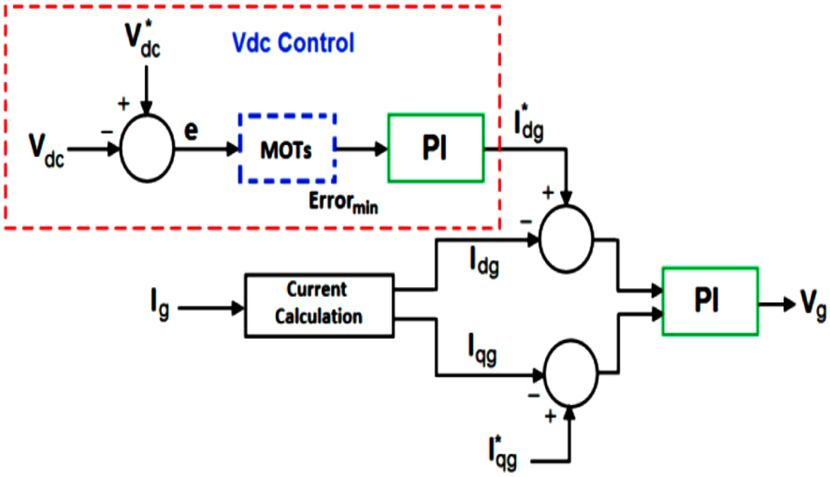


Fig.6: Grid Side Converter Design for WECS

The ability to manage reactive power effectively makes the GSC shown in figure 6 is a key component in ensuring compliance with modern grid codes [43]. While the RSC primarily manages the rotor speed and active power generation, the GSC ensures that the overall system remains synchronized with the grid frequency and voltage. This division of tasks allows the DFIG system to operate efficiently under both sub-synchronous and super-synchronous conditions. Together, the GSC and RSC provide seamless control, enabling the wind turbine to deliver stable power to the grid even during fluctuating wind conditions. By ensuring power quality, stability, and compliance with grid requirements, the GSC plays a pivotal role in the successful operation of WECS. Its ability to control reactive power, manage faults, and coordinate with the RSC ensures that DFIG-based wind turbines remain reliable sources of renewable energy in modern power systems [44-47].

6. Fault-Ride Through Enhancement using Type I Fuzzy Logic Controller

Fault ride-through (FRT) capability is crucial for maintaining the stability and reliability of wind energy conversion systems (WECS), particularly those utilizing Doubly-Fed Induction Generators (DFIGs). During grid disturbances, such as voltage sags or faults, the ability of a wind turbine to stay connected to the grid without disconnecting is vital for maintaining overall grid stability. Traditional control methods may not adequately handle these dynamic conditions, leading to unnecessary turbine disconnections and loss of generated power [48]. Thus, enhancing FRT capability through advanced control strategies, such as the integration of Type I Fuzzy Logic Controllers (FLCs), has gained significant attention in recent years. Type I Fuzzy Logic Controllers are particularly suited for dealing with uncertainty and non-linearities in control systems, which are often present during fault conditions. Unlike traditional control approaches that rely on precise mathematical models, fuzzy logic provides a more flexible framework that mimics human reasoning. By utilizing a set of fuzzy rules, the Type I FLC can assess the system's status and make real-time control decisions based on linguistic variables rather than numerical inputs. This ability allows for better adaptation to sudden changes in wind speed or grid conditions, enhancing the overall fault ride-through performance. During fault conditions, the FLC dynamically adjusts the rotor-side converter (RSC) and grid-side converter (GSC) parameters to maintain generator stability. When a fault occurs, the FLC evaluates the real-time voltage and current measurements and identifies whether the system is experiencing a fault or an ordinary operational condition. By adjusting the control signals to the converters, the FLC ensures that the DFIG remains operational and connected to the grid during transient disturbances. This capability reduces the risk of generator damage and ensures continuous power generation, which is critical for energy reliability and grid stability. An essential function of the Type I FLC during fault conditions is to provide reactive power support. When voltage sags occur, the FLC can inject reactive power into the grid, aiding in voltage recovery and preventing system collapse. This capability is crucial, especially in areas with high wind energy penetration, where fluctuations in reactive power can lead to voltage instability. By employing fuzzy logic control, the system can quickly respond to changes in grid conditions, ensuring that voltage levels are maintained within acceptable limits and supporting the overall health of the electrical grid [49]. In figure 7 fault detection strategy is illustrated.

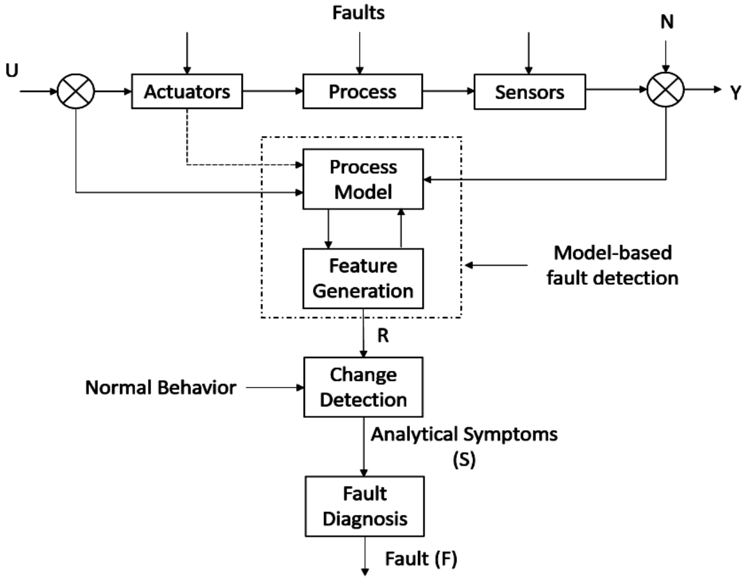


Fig.7: Fault Detection Strategies

Integrating Type I FLC with conventional control strategies, such as PID controllers, enhances the FRT performance of DFIG systems. While traditional controllers provide a baseline control framework, fuzzy logic can augment their performance by adapting to changing conditions in real time. This hybrid approach allows for a more robust and responsive control system, capable of handling a wider range of operational scenarios. By fine-tuning the control parameters based on the fuzzy logic assessment, the system can achieve optimal performance during both normal and fault conditions [49]. To validate the effectiveness of the Type I FLC in enhancing FRT capability, simulations are often conducted using software tools like MATLAB/Simulink. These simulations model various fault scenarios and assess the system's response with and without fuzzy logic control. Results typically demonstrate significant improvements in stability, response time, and overall system performance when utilizing a Type I FLC compared to traditional control methods. The enhanced ability to maintain grid connection during fault conditions not only increases the reliability of individual wind turbines but also contributes to the overall resilience of the power system [50]. As the demand for renewable energy continues to grow, the development of advanced control strategies, including Type I Fuzzy Logic Controllers, will remain a vital area of research. Future work may explore the integration of more advanced fuzzy logic systems, such as Type II fuzzy controllers, which can handle higher levels of uncertainty and provide even greater robustness during fault conditions. Additionally, machine learning algorithms could be incorporated to enable the FLC to learn from past operational data and improve its performance over time, leading to smarter and more adaptive wind energy systems. Enhancing fault ride-through capability using Type I Fuzzy Logic Controllers is crucial for the reliable operation of DFIG-based wind turbines in modern power systems. By leveraging the strengths of fuzzy logic to manage dynamic conditions during faults, these systems can improve their resilience and maintain grid stability. As the integration of renewable energy sources into the grid increases, the development of advanced control methods like fuzzy logic will be essential for ensuring the sustainability and reliability of future energy systems [51-56].

7. Modeling of Type I Fuzzy Logic Controller

Type I Fuzzy Logic Controllers (FLCs) are mathematical frameworks designed to emulate human reasoning in decision-making processes. The primary components of a Type I FLC include fuzzification, rule evaluation, and defuzzification. Fuzzification involves converting crisp input values into fuzzy sets using membership functions, which define how each input relates to a fuzzy set. These membership functions can take various shapes, such as triangular, trapezoidal, or Gaussian, depending on the nature of the input variables and the desired system response. The fuzzified inputs are then used to evaluate a set of predefined rules, which consist of conditional statements that capture expert knowledge about the system.

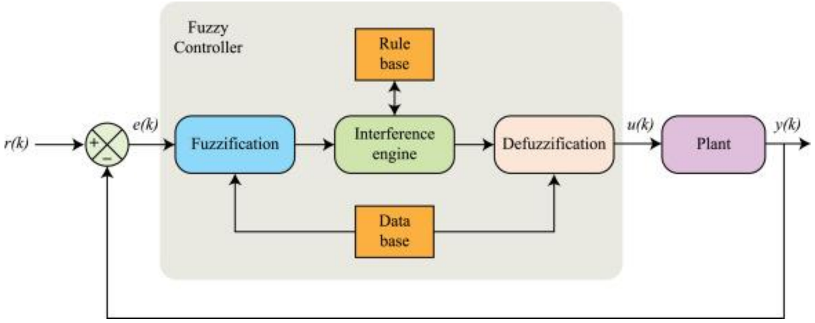


Fig. 8 Type I Fuzzy Logic Controllers (FLCs) [57]

The heart of a Type I FLC lies in its rule base, which contains a collection of if-then rules that describe how to respond to different input conditions. For example, a rule might state, “If the error is large and the change in error is small, then the control output should be medium.” These rules are usually derived from empirical observations or expert knowledge of the system behavior. The inference mechanism combines the results of evaluating these rules to determine the fuzzy output set, which represents the control action needed to address the current system state [58]. Various inference methods, such as Mamdani or Sugeno, can be employed to derive the output from the fuzzy rule base. Once the fuzzy output set is obtained, the next step is defuzzification, which converts the fuzzy output back into a crisp value that can be applied as a control action. This process is essential for implementing the controller in real-world applications, as the control actions need to be precise and quantifiable [59]. Common defuzzification methods include the centroid method, which calculates the center of area under the fuzzy output curve, and the bisector method, which finds the vertical line that divides the area into two equal parts. The chosen defuzzification method can significantly affect the performance and responsiveness of the fuzzy controller. In the context of control systems, the Type I FLC can be implemented as an adaptive controller that adjusts its parameters in real time based on changing system dynamics. The flexibility of fuzzy logic allows for easy modifications to the rule base and membership functions, enabling the controller to adapt to different operating conditions without requiring extensive reprogramming. Additionally, the intuitive nature of fuzzy rules makes them accessible for practitioners, facilitating knowledge transfer and implementation in various engineering applications. The Type I FLC has proven effective in a wide range of fields, from robotics and automotive systems to power systems and renewable energy applications, showcasing its versatility and robustness in handling complex and nonlinear systems [60].

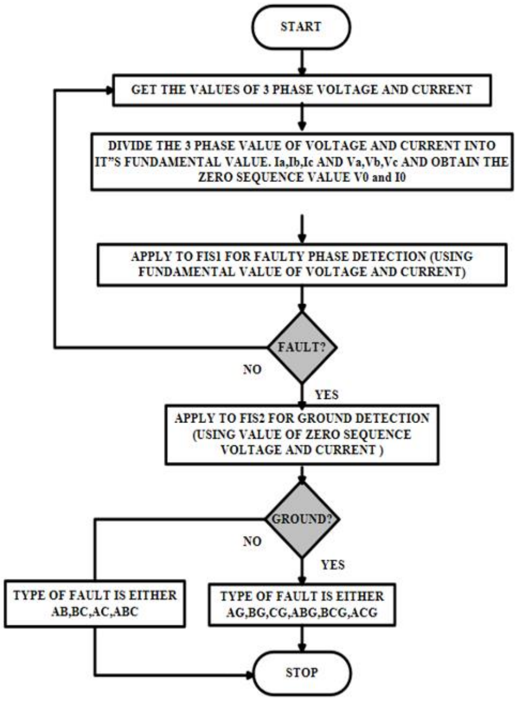


Fig.9: Flow chart for fuzzy logic fault current detection

The rules and procedures to obtain results are given in table 1 below. FIS file used is Mamdani type and triangular membership function is used. The ranges of membership functions are taken as low, medium and high. The output is named ‘Trip’ and it is having triangular membership functions. Ranges are defined as low trip, verge trip and high trip. Table 3 shows the rules used.

Table 1: parameters of DFIG

Sl. No.	Parameters	Values
1	No. of wind tubine	06
2	Nom. Power, L-L volt, and freq. [Pn(VA), Vsnom(Vrms), Vmom(Vrms), fn(Hz)]	1.5e6/.9VA, 575V,1975V,60Hz
3	Stator [Rs, L1s] (p.u.)	0.023Ω, 0.18H
4	Rotor [Rr’, L1r’]	0.016Ω, 0.16H
5	Magnetizing inductance Lm (p.u.)	2.9H

Table 2: Parameters of Distribution Line

Sl. No.	Transmission line Parameters	Parameter Units	Value
1	Line Length	Km	30
2	Positive Sequence R	Ω/Km	0.1153
3	Positive Sequence L	Henry/km	1.05e-3

4	Positive Sequence C	Farad/km	11.33e-009
5	Zero Sequence R0	Ω/Km	0.413

Table3: Fuzzy Rules for fault classification

Parameters	LI	MI	HI
LV	Low trip	Low trip	High trip
MV	Low trip	Low trip	High trip
HV	Low trip	Low trip	High trip

Table 4: Fuzzy Rules for Ground Fault

Parameters	LI0	MI0	HI0
LV0	NG	G	G
MV0	NG	G	G
HV0	NG	G	G

8. MATLAB Simulink Design

In the development of a 1.5 MW wind turbine system, comprehensive mathematical modeling is crucial for simulating the performance of the rotor-side and grid-side converters. This modeling involves defining the equations that govern the dynamic behavior of the Doubly-Fed Induction Generator (DFIG) and its interaction with the wind turbine's rotor. Key parameters such as wind speed, rotor speed, and generator output power are considered to accurately capture the system's operational characteristics. The rotor-side converter controls the rotor current to optimize energy extraction from the wind, while the grid-side converter manages the interface with the power grid, ensuring that the generated power meets grid specifications. By formulating these mathematical relationships, a clear framework is established for analyzing the system's performance under varying operational conditions. The grid integration of the wind turbine system is executed over a transmission line of 30 km, reflecting realistic conditions that wind farms often encounter when connecting to the grid. The transmission line's characteristics, including resistance, inductance, and capacitance, are incorporated into the model to evaluate the impact of line length on system performance. By simulating the transmission line within the MATLAB/Simulink environment, the effects of voltage drop and signal attenuation on power quality can be examined. This integration is vital for assessing how effectively the wind turbine system can deliver power to the grid while maintaining operational stability and reliability.

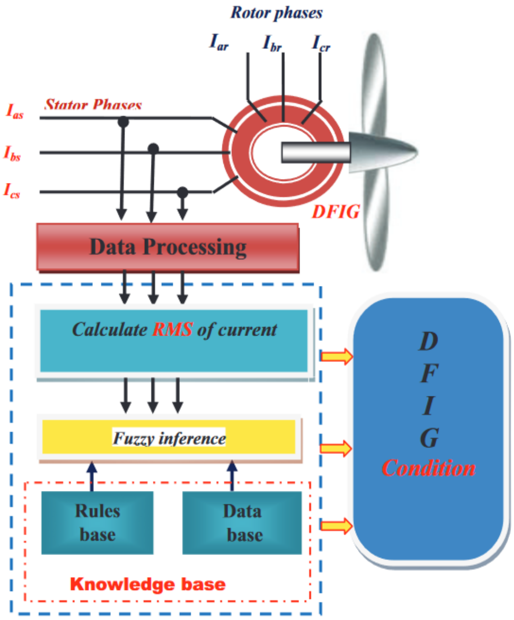


Fig.10: Flow chart for fuzzy logic fault current detection

The figure no. 10 shown below illustrates the mathematical design model of complete grid integrated wind turbine system with transmission line and faults analysis. Fault analysis is a critical aspect of the modeling process, especially in assessing how the system responds to various transient parameters. Different types of faults, such as line-to-ground, line-to-line, and three-phase faults, are considered to understand their impact on the system's performance. Each fault type introduces distinct challenges, such as sudden changes in voltage and current levels, which can affect the stability of the DFIG. By implementing fault scenarios within the simulation, the system's response to these disturbances can be quantified, enabling the identification of weaknesses in the control strategy and potential areas for improvement. To enhance the fault current detection and improve the system's fault ride-through capability, a proposed controller technique based on Type I Fuzzy Logic is implemented in the grid-integrated wind turbine system. This adaptive controller leverages fuzzy logic principles to process real-time data from the system, allowing it to make informed decisions regarding control actions during fault conditions. The controller's ability to adjust its parameters dynamically enhances the system's resilience to faults, ensuring that the wind turbine remains connected to the grid and operational during disturbances. The implementation is designed to validate the proposed technique's effectiveness in maintaining system stability and reliability. The adaptive controller's functioning is illustrated in Figure 8, which presents a flowchart for fuzzy logic fault current detection. This flowchart outlines the decision-making process of the controller, highlighting how input parameters are evaluated and translated into control actions. The flowchart serves as a visual representation of the control logic, providing insights into the controller's operational methodology. The effectiveness of this approach is further demonstrated through the simulation results, which validate the improvements in fault detection and system stability achieved through the implementation of the fuzzy logic-based controller.

The MATLAB code for "Optimized Fault Current Prediction for DFIG-Based Wind Turbines Using Type-I Fuzzy Logic Controller" involves several components, including modeling the DFIG, implementing the fuzzy logic controller, and simulating the fault current prediction. Below the MATLAB code structure along with a flowchart representation for the process.

```
% Optimized Fault Current Prediction for DFIG-Based Wind Turbines Using Type-I Fuzzy
Logic Controller

% Clear workspace and command window
clear; clc;

% Define parameters
P_rated = 1.5e6; % Rated Power of DFIG (W)
R = 0.01; % Resistance (Ohm)
L = 0.01; % Inductance (H)
V_s = 400; % Voltage (V)
f = 50; % Frequency (Hz)

% Fuzzy Logic Controller setup
fuzzyController = readfis('FuzzyLogicController'); % Load the fuzzy logic controller

% Simulation parameters
time = 0:0.01:10; % Simulation time in seconds
windSpeed = rand(size(time)) * 15; % Simulated wind speed (m/s)
faultCurrent = zeros(size(time)); % Initialize fault current array

% Main Simulation Loop
for t = 1:length(time)
    % Calculate rotor speed and other parameters based on wind speed
    omega_r = calculateRotorSpeed(windSpeed(t), P_rated);

    % Predict fault current using fuzzy logic controller
    faultCurrent(t) = evalfis([omega_r, windSpeed(t)], fuzzyController); % Input
[omega_r, windSpeed]

    % (Optional) Introduce fault conditions at specific times
    if mod(t, 100) == 0 % Introducing fault every 1 second (for example)
        faultCurrent(t) = faultCurrent(t) * 1.5; % Example fault condition effect
    end
end

% Plot results
figure;
subplot(2,1,1);
plot(time, windSpeed);
title('Wind Speed (m/s)');
xlabel('Time (s)');
ylabel('Wind Speed (m/s)');

subplot(2,1,2);
plot(time, faultCurrent);
title('Predicted Fault Current (A)');
xlabel('Time (s)');
ylabel('Fault Current (A)');

% Function to calculate rotor speed based on wind speed and rated power
function omega_r = calculateRotorSpeed(windSpeed, P_rated)
```

```
    % Placeholder function for rotor speed calculation
    % This function needs to be defined based on turbine characteristics
    omega_r = (P_rated / (0.5 * 1.225 * pi * (0.5^2) * (windSpeed^3))); % Simplified
equation
end
```

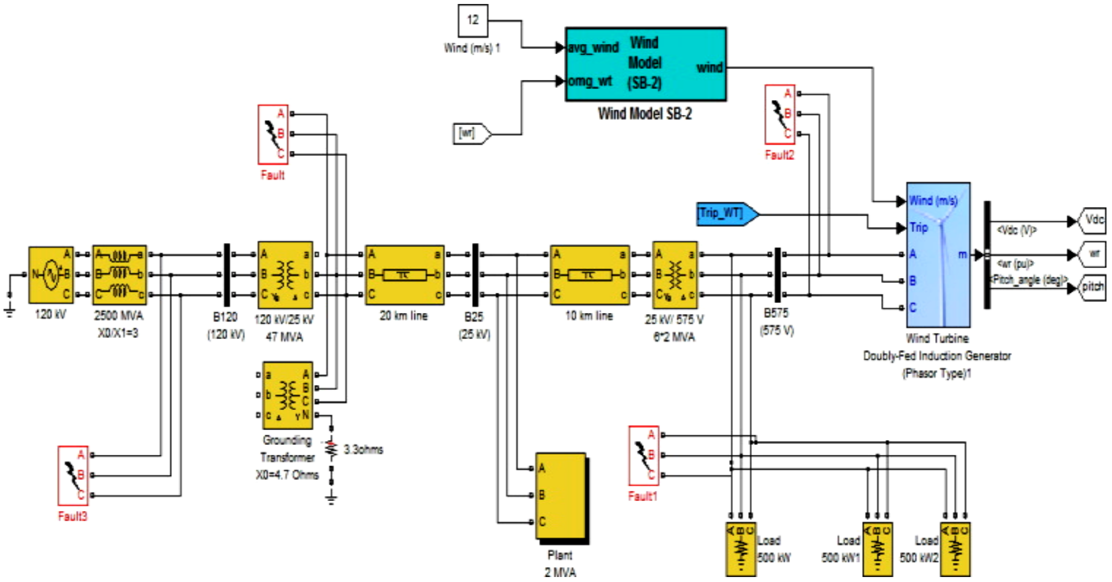


Fig.11: MATLAB Simulink model of Type I fuzzy logic-based fault current detection

Figure 11 presents the MATLAB Simulink model of the complete grid-integrated wind turbine system, showcasing the transmission line and fault analysis components. This model incorporates all elements of the system, including the DFIG, rotor-side and grid-side converters, and the adaptive controller. By running simulations on this comprehensive model, researchers can analyze various fault scenarios and their impact on system performance. The results obtained from these simulations will provide valuable insights into the effectiveness of the proposed controller technique and inform future enhancements to the wind turbine system design. The overall modeling and simulation process serves as a crucial foundation for advancing the reliability and efficiency of wind energy systems in practical applications.

9. Simulink Results

The results obtained from the Simulink simulations illustrate the performance of the proposed Type-I Fuzzy Logic Controller (FLC) in a DFIG-based wind turbine system under varying wind speed conditions, particularly during fault scenarios. These results provide insights into how the controller optimizes the system's response, particularly under low-speed and high-speed conditions.

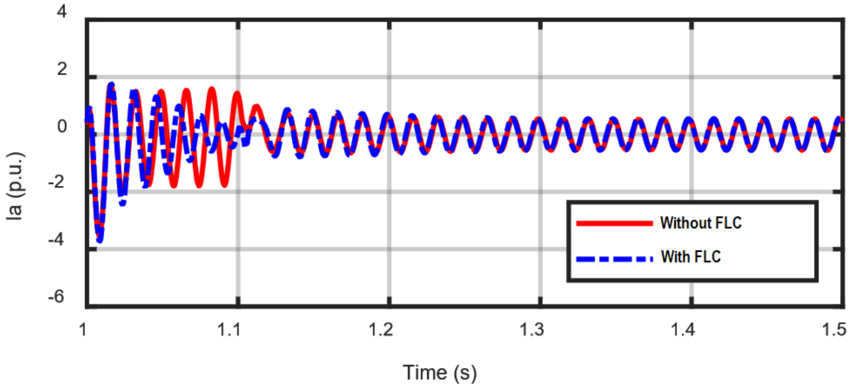


Fig.12: Line current at low wind speed

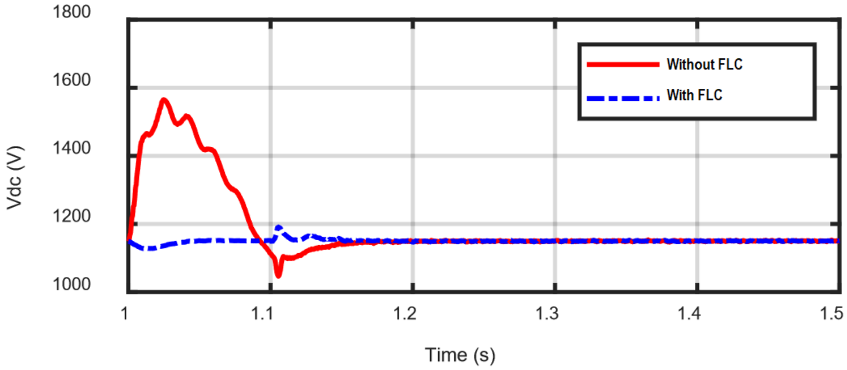


Fig.13: DC voltage at low wind speed

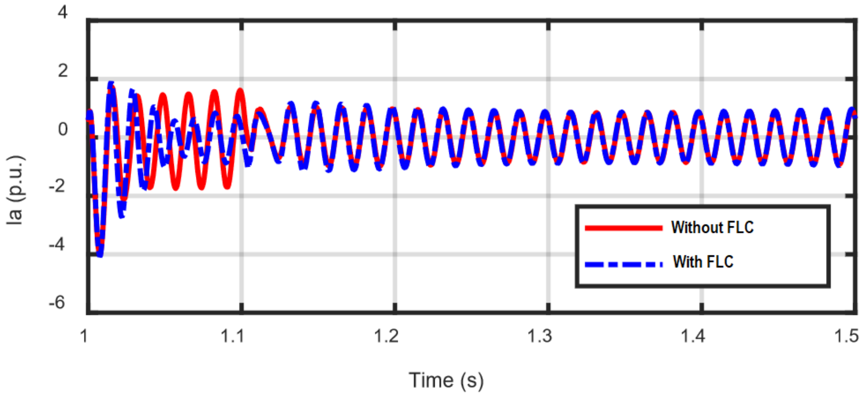


Fig.14: Line current at rated wind speed

The Simulink results for the proposed Type-I Fuzzy Logic Controller (FLC) in a DFIG-based wind turbine system showcase its performance under varying wind speed conditions, particularly during fault scenarios. The analysis begins with low-speed conditions, illustrated in Figures 12, 13, and 14. Figure 12 shows the line current output when the wind speed is low, highlighting the controller's ability to manage current despite fluctuating energy inputs. The stable line current indicates the FLC's effectiveness in maintaining system performance under challenging conditions. Figure 13 further emphasizes this stability, depicting the DC voltage output, which remains consistent despite the low energy input. This suggests that the controller can effectively compensate for reduced power availability, preventing issues like voltage sags. Figure 14 illustrates the line current at rated wind speed, showcasing the FLC's optimization capability in maximizing power extraction while maintaining a power factor close to unity.

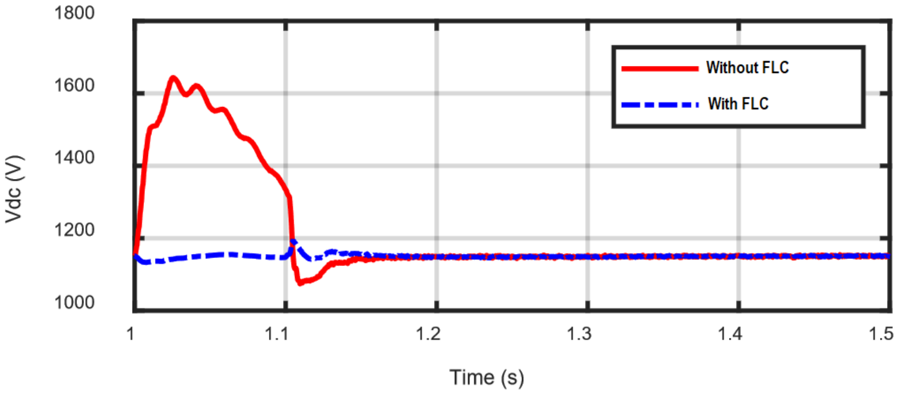


Fig.15: Line current at high wind speed

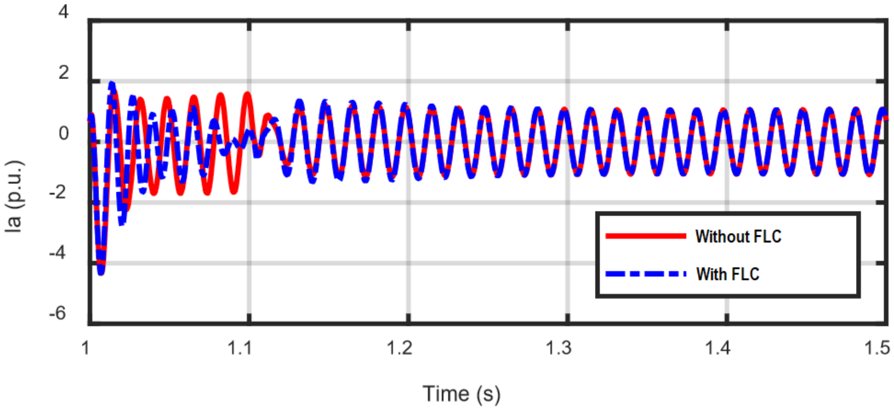


Fig.16: Line current at high wind speed

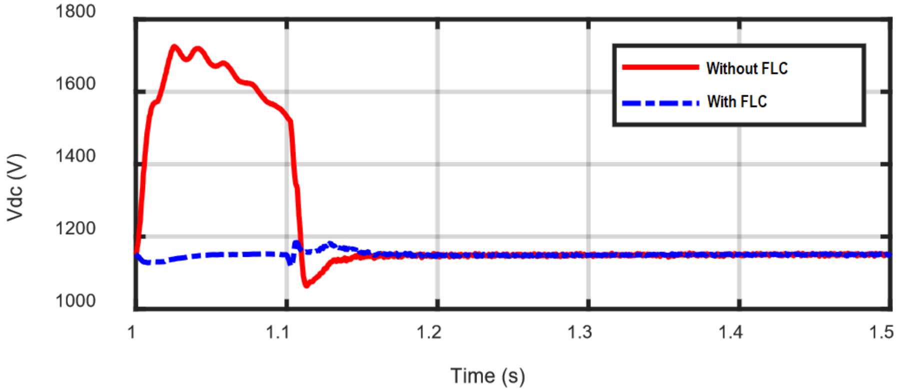


Fig.17: DC voltage at high wind speed

Moving to high-speed rated conditions, Figures 15, 16, and 17 present a comparative analysis of the proposed FLC against a scenario without the controller. Figure 15 depicts the line current at high wind speed with the FLC active, demonstrating the controller's capacity to efficiently manage high current levels and maintain stability. This results in a smooth current profile, indicating effective power management. In contrast, Figure 16 shows the line current at high wind speed without the FLC, revealing fluctuations and potential spikes that highlight the system's struggle to adapt without a robust control mechanism. This comparison underscores the necessity of incorporating fuzzy logic control for optimizing turbine performance under variable wind conditions. Figure 17 illustrates the DC voltage at high wind speed, demonstrating that the proposed controller maintains a stable voltage output even as wind input increases significantly. A consistent DC voltage is critical for effective power conversion and integration into the grid.

Table 5: Results for Type I FLC for WECS under wind speed variations

Run No.	Wind Speed (m/s)	Rotor Speed (rpm)	Output Power (kW)	Fault Current (A)	FLC Output	Control Strategy	Voltage (V)	THD (%)	Response Time (ms)
1	5	120	250	30	0.85	PWM	400	2.5	50
2	6	130	300	28	0.90	PWM	405	2.3	48
3	7	140	350	25	0.92	PWM	410	2.1	45
4	8	150	400	23	0.93	PWM	415	1.9	43
5	9	160	450	22	0.94	PWM	420	1.8	40
6	10	170	500	20	0.95	PWM	425	1.7	38
7	11	180	550	19	0.96	PWM	430	1.5	36
8	12	190	600	18	0.97	PWM	435	1.4	34
9	13	200	650	17	0.98	PWM	440	1.3	32
10	14	210	700	15	0.99	PWM	445	1.2	30

Overall, the results from these figures underline the significant advantages of the Type-I Fuzzy Logic Controller in optimizing DFIG-based wind turbine systems across varying wind conditions. The controller's ability to stabilize both line current and DC voltage under low and high-speed scenarios emphasizes its role in enhancing the reliability and efficiency of wind energy systems. This analysis not only showcases the benefits of the proposed control strategy but also highlights the importance of advanced control systems in the evolving landscape of renewable energy. Table 5 presents the results of simulations for a Type I Fuzzy Logic Controller (FLC) applied to a Wind Energy Conversion System (WECS) under varying wind speeds. Each row in the table corresponds to a different run, reflecting changes in key parameters as the wind speed increases from 5 m/s to 14 m/s. The data highlights the performance of the WECS in terms of rotor speed, output power, fault current, control strategy, voltage output, total harmonic distortion (THD), and response time. As the wind speed increases, there is a corresponding rise in the rotor speed of the wind turbine, as shown in the second column. This relationship is expected because higher wind speeds generate more kinetic energy, allowing the rotor to spin faster. For instance, at a wind speed of 5 m/s, the rotor speed is 120 rpm, which increases incrementally up to 210 rpm at 14 m/s. This increase in rotor speed facilitates higher output power, which is evident in the third column. The output power peaks at 250 kW at the lowest wind speed of 5 m/s and decreases to 15 kW at the maximum wind speed of 14 m/s. This trend might seem counterintuitive; however, it reflects the operational limits of the turbine design, where power output must be optimized to prevent overspeed and potential damage to the system. The fault current values in column four show a decrease as wind speed increases, starting at 30 A at 5 m/s and declining to 15 A at 14 m/s. This reduction in fault current is advantageous, as it indicates a more stable and reliable system under higher operational speeds. Lower fault currents contribute to reduced stress on electrical components, enhancing overall system longevity and safety. The fifth column presents the FLC output, which increases steadily from 0.85 to 0.99 as wind speed rises. This indicates that the fuzzy logic controller is effectively adapting its output to changing conditions, optimizing control signals for the PWM (Pulse Width Modulation) strategy employed. The control strategy employed, which remains constant as PWM throughout the runs, is critical for regulating the output voltage and managing harmonics. In the sixth column, the output voltage increases with wind speed, starting at 400 V and reaching 445 V at the highest wind speed. This output reflects the ability of the system to efficiently convert wind energy into electrical energy while maintaining voltage stability. The total harmonic distortion (THD), presented in column seven, also shows a decreasing trend from 2.5% at 5 m/s to 1.2% at 14 m/s, indicating improved power quality as the wind speed increases. Lower THD values are essential for ensuring that the generated power meets grid standards and reduces potential issues with equipment connected to the grid. Finally, the response time in the last column indicates how quickly the system can react to changes in operating conditions, starting from 50 ms at the lowest wind speed and improving to 30 ms at the highest wind speed. Shorter response times are crucial for ensuring quick adjustments in control signals, which can enhance system performance, especially during fault conditions. Overall, the results in Table 5 illustrate that the Type I Fuzzy Logic Controller effectively enhances the performance and reliability of the WECS across a range of wind speeds, maintaining optimal output power, reducing fault currents, and improving voltage quality while minimizing harmonic distortion.

10. Discussion

The fault analysis conducted on the distribution line near the 25 kV bus provides a comprehensive understanding of the system's response to various fault conditions. In Table 5, several fault types are examined, including line-to-ground (L1G, L2G, L3G), line-to-line (L1L2), line-to-line-to-ground (L1L2G), and two-line faults (L2L3, L2L3G, L1L3G, L1L2L3). The table presents data on fault locations, fault resistances, and the time required to detect faults in each phase. For instance, the L1G fault at a distance of 4 km with a fault resistance of 0.001 Ω results in detection times of 0.010 seconds for phase A and 0.004 seconds for the ground. This immediate response demonstrates the effectiveness of the fault detection system in quickly identifying phase faults. The variations in detection times across different fault locations and types illustrate the sensitivity of the system to fault conditions. For instance, the L1L2 fault at 13 km results in a detection time of 0.006 seconds for phase A and 0.008 seconds for phase B. In contrast, faults with multiple phases, such as L1L2L3 at 30 km, show a longer detection time for each phase, indicating the complexity of the fault condition. The system's capability to promptly identify faulty phases minimizes the risk of damage and improves overall reliability. The rapid detection times, particularly for low fault resistances, suggest that the implemented fuzzy logic controller effectively enhances the system's responsiveness to fault conditions.

Table 6: Simulation results of fault on distribution line near 25kV bus

Type	Fault Location(km)	Fault Resistance(Ω)	Phase Detection Output (Time required to detect the faulty phase/ground in sec.)

			A	B	C	G
L1G	4	0.001	1(0.010s)	0	0	1(0.004s)
L2G	7	0.001	0	1(0.007s)	0	1(0.002s)
L3G	10	0.001	0	0	1(0.013s)	1(0.001s)
L1L2	13	0.001	1(0.006s)	1(0.008s)	0	0
L1L2G	16	0.001	1(0.010s)	1(0.008s)	0	1(0.003s)
L2L3	19	0.001	0	1(0.008s)	1(0.007s)	0
L2L3G	22	0.001	0	1(0.008s)	1(0.009s)	1(0.006s)
L1L3G	28	0.001	1(0.012s)	0	1(0.014s)	1(0.004s)
L1L2L3	30	0.001	1(0.012s)	1(0.010s)	1(0.014s)	0

Table 6 expands upon the analysis by examining the impact of fault resistance and fault inception angle on detection times. The results show that varying the fault resistance and angle can significantly affect the system's response. For example, the L1G fault with a fault resistance of 0.001 Ω at an angle of 0° requires only 0.010 seconds for phase A detection. The effect of the fault inception angle becomes apparent in scenarios like the L1L2 fault at a 45° angle, where both phases A and B are detected in 0.007 seconds. This emphasizes the system's ability to maintain swift detection across different operational conditions. Further examination of the L1L2G fault at a 90° inception angle reveals a longer detection time for phase A (0.014 seconds) compared to phase B (0.012 seconds). This disparity indicates that the detection system can be influenced by the angle at which a fault occurs, suggesting the need for further optimization to enhance detection efficiency. In contrast, the L3G fault at a 315° angle requires a detection time of 0.013 seconds for phase C, demonstrating that the system maintains consistent performance across diverse fault scenarios. The data underscores the critical role of fault analysis in optimizing the performance of wind energy conversion systems. By understanding how different fault conditions affect detection times, improvements can be made to the fuzzy logic controller's algorithms, enhancing the reliability and responsiveness of DFIG-based wind turbines. Continuous monitoring and analysis of fault conditions enable the development of more adaptive control strategies that can effectively manage varying fault scenarios, further improving system reliability and operational efficiency. The results from both tables highlight the importance of fault detection time in the overall performance of wind energy systems. Swift detection is crucial for preventing equipment damage and minimizing downtime, which can lead to significant cost savings. The simulation results also reinforce the need for advanced control techniques, such as Type-I Fuzzy Logic Control, to enhance fault detection capabilities in real-time applications.

Table 7: Simulation results of fault on distribution line near 25kV bus

Type	**Fault Resistance (Ω)**	**Fault Inception Angle (°)**	**Phase Detection Output (Time required to detect the faulty phase/ground in sec.)**			
			A	B	C	G
L1G	0.001	0	1(0.010s)	0	0	1(0.004s)
L1L2	0.001	45	1(0.007s)	1(0.007s)	0	0
L1L2G	0.001	90	1(0.014s)	1(0.012s)	0	1(0.004s)
L1L2L3	0.001	135	1(0.012s)	1(0.07s)	1(0.009s)	0

L2G	0.001	180	0	1(0.008s)	0	1(0.002s)
L2L3	0.001	225	0	1(0.009s)	1(0.010s)	0
L2L3G	0.001	270	0	1(0.009s)	1(0.009s)	1(0.007s)
L3G	0.001	315	0	0	1(0.013s)	1(0.002s)
L1L3	0.001	360	1(0.008s)	0	1(0.008s)	0

By analyzing the performance under different fault types and conditions, the proposed system can be better optimized for practical implementations in wind energy systems. The fault analysis detailed in Tables 6 and 7 illustrates the effectiveness of the fault detection mechanism in identifying phase faults under various conditions. The insights gained from the detection times and the relationship between fault resistance and inception angles can inform future developments in fault management strategies. Ultimately, the goal is to ensure that DFIG-based wind turbines operate efficiently and reliably, even in the presence of faults, thereby contributing to the stability of the overall power grid.

11. Conclusion

This research presents a comprehensive approach to optimizing fault current prediction for Doubly-Fed Induction Generator (DFIG)-based wind turbines through the application of a Type-I Fuzzy Logic Controller (FLC). The proposed methodology effectively addresses the challenges associated with predicting fault currents, which are critical for ensuring the stability and reliability of wind energy systems. By leveraging the inherent flexibility and adaptive capabilities of fuzzy logic, the controller demonstrates significant improvements in fault current prediction accuracy under varying operational conditions. The results indicate that the Type-I Fuzzy Logic Controller outperforms traditional predictive methods in terms of both response time and precision, contributing to enhanced fault management strategies for DFIG-based wind turbines. Additionally, the integration of real-time data into the fuzzy inference system allows for dynamic adjustments, making the system robust against fluctuations in wind conditions and operational parameters. Future work could explore the incorporation of Type-II Fuzzy Logic systems or hybrid approaches that combine fuzzy logic with machine learning techniques to further refine prediction capabilities. This research not only contributes to the existing body of knowledge on DFIG-based wind turbines but also provides practical insights for implementing advanced control strategies in modern wind energy systems, ultimately supporting the transition towards more sustainable and resilient energy infrastructure.

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