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Advanced Fault Ride Through Techniques for Double Fed Induction Generator Wind Turbines Integrated with Modular Multilevel Converter based HVDC systems: A Comprehensive Review

Ankhi Gulati[a] and Anil Kumar[b]

[a]*Research Scholar, Department of Electrical Engineering, School of Engineering & Technology, IFTM University, Lodhipur Rajpoot, Moradabad, Uttar Pradesh, India.*

[b]*Professor & Head, Department of Electrical Engineering, School of Engineering & Technology, IFTM University, Lodhipur Rajpoot, Moradabad, Uttar Pradesh, India.*

Abstract:- Faults in electrical networks pose significant challenges and can lead to disruptions in the system's operation. Control and automation strategies play a crucial role in ensuring the safety and stability of the network. The constraints such as slow dynamic response, inability to remote network switching, high fault clearing time, and loss minimization issues, are critical concerns that impact the effectiveness of fault clearing techniques. Resolving these limitations is essential for ensuring the reliability and efficiency of the system. In the context of wind energy technologies, the perturbation of power flow from a wind turbine during a fault can cause the intermediate circuit voltage between the machine side converter and line side converter to rise significantly. This elevation in voltage occurs due to the accumulation of energy in the DC link capacitor [1]. This paper deals with low voltage ride through (LVRT) capability of wind turbines (WTs) and in particular those driven by Doubly Fed Induction Generator (DFIG). The Low Voltage Ride through (LVRT) capability of wind turbines, particularly those employing Doubly Fed Induction Generators (DFIGs), is indeed a critical concern for widespread wind farm deployment. As the penetration of wind turbines into grids increases, grid connection codes often mandate that these turbines remain connected during and after short-term faults to uphold grid reliability. This necessity leads to the requirement of maintaining LVRT, where wind turbines must continue operating with as little as 15% (or even less) remaining voltage at the point of common coupling (PCC). In addition, it is required for Wind Turbine's to contribute to system stability during and after fault clearance. Meeting LVRT standards for DFIG-based wind turbines involves addressing two main challenges: namely rotor inrush current that may exceed the converter limit and the dc link overvoltage [3]. Indeed, Fault Ride-Through (FRT) capability is a crucial aspect for offshore wind farms (OWFs), especially when they are connected to onshore AC grids through Voltage Source Converter (VSC) based High Voltage Direct Current (HVDC) transmission systems [2].

Keywords*: Low Voltage-ride-through (LVRT), offshore wind farms (OWFs), doubly-fed induction generator (DFIG), Wind Turbines (WTs), Point of common coupling (PCC), voltage source converter (VSC), pulse-width modulated (PWM) converters, Grid-side converter (GSC), Rotor-side converter (RSC), distributed energy sources (DERs).*

1. Introduction - The global energy demand has been on a consistent rise due to several factors including population growth, industrialization, and modernization [5]. The integration of Distributed Energy Resources (DERs) into utility grids has become increasingly popular as a method to diversify electricity generation and expand electrification rates, particularly in regions aiming to improve energy access and reliability. DERs encompass a variety of technologies that generate electricity closer to the point of use or distribution, offering several advantages [6].The increasing focus on sustainable energy sources, particularly wind energy, is driven by the need to transition to cleaner and more environmentally friendly alternatives. Wind energy is indeed considered one of the most important and promising renewable energy sources, and its capacity has been steadily increasing worldwide. As the share of wind power in the energy mix grows, there is a recognition of the importance of integrating wind power plants more effectively into the overall power grid [4]. Doubly Fed Induction Generators (DFIGs) are a common technology in the realm of renewable energy, specifically in wind turbines, allowing the conversion of wind energy into usable electricity. DFIGs are a type of induction machine that incorporates windings both on the rotor and the stator, enabling the transfer of active power through both the shaft and the electrical system. In a Doubly Fed Induction Generator (DFIG) configuration, both the stator and rotor windings are physically connected to the grid. However, their electrical connections are different, and power electronic converters are typically used in the rotor circuit for control purposes. Doubly Fed Induction Generators (DFIGs) are typically used in applications where variable shaft speed is required within a restricted range around the synchronous speed. This characteristic makes DFIGs well-suited for wind energy applications [7]. The variable nature of wind speed poses significant challenges for the reliable, stable, and dynamic operation of power grid networks that include wind farms. Researchers and grid operators are actively working on solutions to address these challenges [8]. Incorporating effective FRT control in wind turbines, especially those utilizing DFIGs in conjunction with MMC-HVDC systems, plays a significant role in maintaining grid stability, ensuring uninterrupted power supply, and bolstering the reliability of renewable energy integration into modern power grids. Ongoing advancements in FRT control strategies continue to enhance the performance and reliability of these systems in challenging grid scenarios.

2. The Principal Concepts of Wind Power Plants Technologies

Wind power plants are designed and optimized based on the specific conditions of their installation sites; the plant normally fits into one of three main concepts as illustrated in Figure 1.

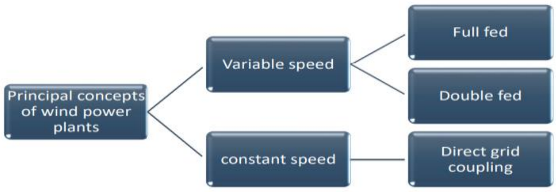

Figure 1: Principal concept of wind power plants

2.1: Fixed Speed Wind Power Plants

The wind turbine system is designed to be connected to the utility grid through a synchronized SCIG. The static transfer switch allows the system to operate in both grid-connected and islanded modes. Capacitor banks are used to compensate for the reactive power drawn by the induction generator, and a soft starter ensures a smooth start-up process. These components contribute to the stability and reliability of the wind turbine system as shown in Figure 2. Fixed-speed wind turbines have cost and dynamic response advantages, but they face limitations in terms of fixed frequency and voltage. Modern wind power plants address these limitations by incorporating advanced power control methods to optimize energy production across varying wind speeds [5,6].

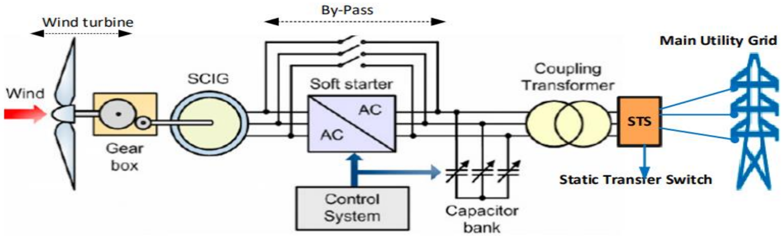

Figure 2: Schematic diagram of a fixed-speed wind turbine

2.2: Variable Speed Wind Power Plants

Asynchronous generators are frequently used in variable speed wind turbines due to their ability to operate efficiently across a range of speeds [6]. To achieve effective dynamic load reduction and optimize the operation of a wind power plant, a significant portion of the rated speed range needs to be variable. This is typically accomplished through the use of a variable speed generator and a frequency converter, and both synchronous and asynchronous generators can be suitable for this application. [5]. The choice between synchronous and asynchronous generators in wind turbines involves considerations of power conversion requirements. Synchronous generators require full power conversion, while asynchronous generators, with the use of slip, allow for partial power conversion. Additionally, the choice of rotor design, such as avoiding a squirrel cage rotor, may be influenced by factors like cost and maintenance requirements [7].

a) Synchronous Generator with a Fully Rated Converter

By incorporating a frequency converter with a DC link, the wind power plant effectively decouples the rotational speed of the generator from the grid frequency, allowing for variable speed operation. This flexibility helps optimize power capture in varying wind conditions and enhances the overall efficiency of the wind turbine system as shown in Figure 3 [8].

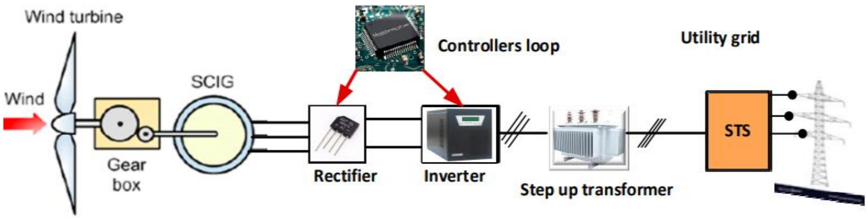

Figure 3: Schematic diagram of a wind turbine (WT) based synchronous generator with full feed

b) Doubly Fed Induction Generators

The doubly fed asynchronous generator configuration allows for variable speed operation with the ability to separately manage active and reactive power. The elaborate control system ensures precise regulation of slip power and rotor field frequency, contributing to efficient wind turbine operation.

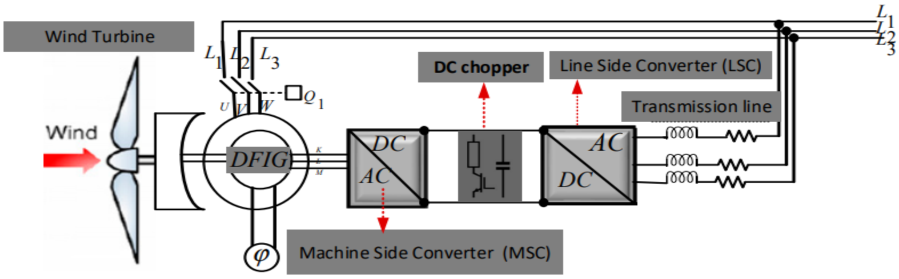

Figure 4: General schematic diagram of a wind turbine with a DFIG

The steady-state operation of a Doubly Fed Induction Generator involves the generation or consumption of active power, and imbalances in active power input can impact voltage regulation and frequency stability. The control system of the DFIG is designed to address these variations and ensure reliable and efficient operation within the utility grid [9]. Ensuring the Fault Ride Through capability, dynamic voltage regulation, and managing the DC link during grid faults are crucial aspects of wind power plant design and operation. The absence of a DC chopper and a crowbar during faults can pose challenges, and addressing these issues is essential for maintaining the stability and reliability of wind power systems. [10]. The blades of a wind turbine play a crucial role in the initial step of converting wind energy into mechanical energy. The mechanical energy is then further transformed into electrical energy by the generator, resulting in the output of a wind power plant. This process allows harnessing renewable wind resources for electricity generation [11]. While DFIGs can contribute to stabilizing the grid and mitigating voltage fluctuations, the overall performance depends on effective communication and control systems. Addressing poor communication issues is crucial for maintaining grid stability, especially during fault conditions. This could involve improvements in communication protocols, redundancy in communication channels, or enhanced fault detection and response mechanisms [12]. The communication issue was partially solved but the overloading issue for an intermediate electronic circuit located between the machine side converter (MSC) and the line side converter (LSC) was not resolved [13].Voltage dips are classified based on magnitude and phase with different controllers even if the excess energy is still not solved [14]. Fault Ride Through (FRT) is a critical feature for wind power plants to contribute to grid stability, reliability, and power quality. The ability to stay synchronized during voltage dips ensures that wind turbines can continue to operate seamlessly, minimizing the impact of disturbances on the overall power system [15].

3. DFIG in Sub Synchronism & Super Synchronism Operation Mode

The back-to-back converters used in the rotor connection can operate in both directions (current can flow into or out of the rotor) [16], which allow for two different operational modes: sub-synchronism (Figure 5) and super-synchronism (Figure 6). In super synchronism mode, the active power delivered to the grid is greater than the power produced through the stator while in sub-synchronism the power delivered to the grid is lower than the power produced by the stator.

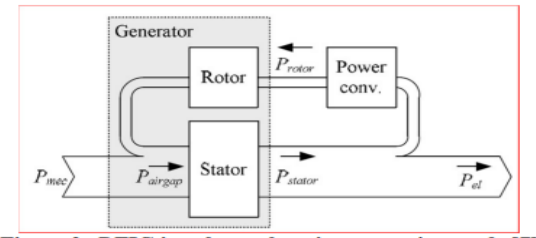

Figure 5: DFIG in sub synchronism operation mode

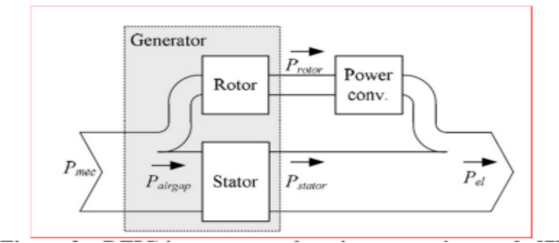

Figure 6: DFIG in super synchronism operation mode

During a voltage dip or disturbance in the connection to the AC grid, induced voltages in the rotor windings of a Doubly Fed Induction Generator (DFIG) can cause high rotor currents. These increased currents can potentially damage the rotor-side converter if not properly managed or protected against. The occurrence of high currents poses a risk to the components within the rotor-side converter due to increased stress and heat. To prevent damage caused by excessive rotor currents during voltage dips or faults, protective measures are commonly implemented in DFIG systems [17,18,19].

3.1: Slip Control Strategy for Wind Turbines Based on DFIG

The slip control mechanism in wind power plants acts as a dynamic adjustment to handle sudden changes in wind conditions. By modifying the coupling strength between the rotor and stator, wind turbines can mitigate the impact of gusts, allowing for controlled adjustments in power output and ensuring grid stability. The trade-off involves considerations of generator efficiency and heat production, necessitating effective cooling mechanisms, as schematized in Figure 7 [22, 23].

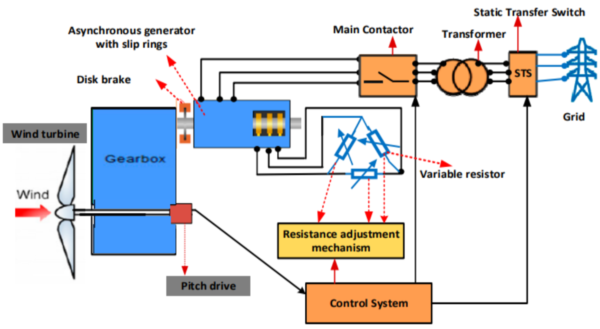

Figure 7: Simplified schematic diagram of a slip control system for a wind turbine

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3.2: Speed Control Strategy for Wind Turbines Based on DFIG

The DFIG system's dual feed configuration, along with smart inverters and adjustable rotor speed, provides a versatile and controllable solution for wind power generation. This flexibility allows for efficient adaptation to changing wind conditions and contributes to grid stability by minimizing undesirable variations in power output as shown in Figure 8 [24,25].

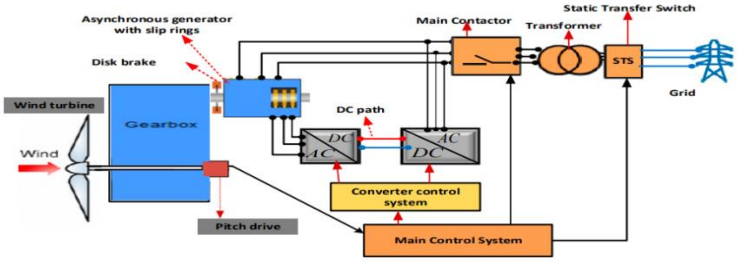

Figure 8: Simplified schematic diagram of a speed control system for a wind turbine

The DFIG's operational strategies involve utilizing the rotor's magnetic field, adjusting the rotor field's direction, and controlled energy flow through converters to contribute power back to the grid. The system's ability to provide reactive power control within grid specifications helps stabilize the grid during varying wind conditions, showcasing its role in enhancing grid reliability and stability [26].

4. Comparison of Exisiting Work

Reference Number	Contribution	Findings
[1]	To analyse the fault ride through capability of a grid connected wind power plant with a Doubly Fed Induction Generator	Analysis and validation of the designed model providing insights into the performance of the FRT capability
[3]	To provide a comprehensive understanding of the current state-of-the-art in LVRT Techniques for DFIG based wind turbines and to highlight potential future directions in this field	A comprehensive review of existing solutions for enhancing low-voltage ride-through (LVRT) capability in doubly-fed induction generator (DFIG)-based wind turbines
[4]	An Adaptive Fuzzy PI controller for the DVR is proposed to enhance the LVRT capability and fulfill the grid codes without disconnecting the turbine from the grid	A wind turbine system of 2 MW is modelled. The simulation results have demonstrates the capability of using DVR with the proposed controller to enhance the LVRT
[5]	The outlines of the basic wind farm protection systems that are usually utilized with modern wind farms nowadays	The study emphasized the need for enhancing the existed protection schemes for wind farms to realize better power system performance as well as minimize the possible damages
[6]	Overview of the interaction between variable-speed DFIG wind turbines and the power system during disturbances	The control performance highlights the ability to hold electrical power constant and store rapid fluctuations as kinetic energy
[10]	The dynamic behavior of the wind farm under different case studies in response to unsymmetrical faults and grid voltage dips	Simulating the dynamic behavior of the wind farm under different operating conditions
[13]	The behavior of DFIG-based wind turbines	DFIG-based wind turbines can achieve

	during grid faults and emphasizes the importance of implementing special protection measures to enable wind turbines to ride through low voltage periods	zero voltage ride-through during grid faults, ensuring continuous operation and compliance with grid codes
[15]	The use of dynamic analysis and static analysis methods for accurate time responses of the power system and efficient examination of power system conditions	The study of increased penetration of wind turbine generators on the small signal and transient stability of the system
[17]	To deal with the LVRT control of wind turbines with DFIGs under symmetrical voltage dips.	Investigated the LVRT capability of WTs with DFIGs under symmetrical voltage dips.

5. Traditional Grid Technologies versus Smart Grid Technologies

Smart grid technologies represent a more modern and technologically advanced approach to managing and distributing electrical power. They emphasize automation, integration of distributed energy resources, and enhanced reliability through advanced monitoring and control systems. Traditional grid technologies, while reliable, may lack the advanced features and capabilities that smart grids offer. The transition to smart grids is driven by the need for increased efficiency, sustainability, and resilience in power distribution systems [26]. Table 1 shows the differentiation between them.

Traditional Grid Technologies	Smart Grid Technologies
Few sensors in the network	Sensors all over the network
Electromechanical systems	Digital system
Few customer choices	Many customer choices
Limited control strategies	Pervasive control strategies
Failures and blackouts issues	Adaptive and islanding mode
Manual restoration capability	Self-healing capability
Centralized generation	Distributed generation
One way communication technologies	Two way communication technologies
Manual monitoring	Remote self-monitoring

Table 1: Comparison between traditional grid technologies and smart grid technologies [26-28]

6. Smart Grid Technologies Challenges and Benefits

While smart grid technologies come with challenges, their implementation brings significant benefits, including enhanced reliability, efficiency, sustainability, and the ability to adapt to changing energy landscapes. Addressing challenges through ongoing research, standards development, and collaboration is essential to unlocking the full potential of smart grids, which are listed in Figure 9.

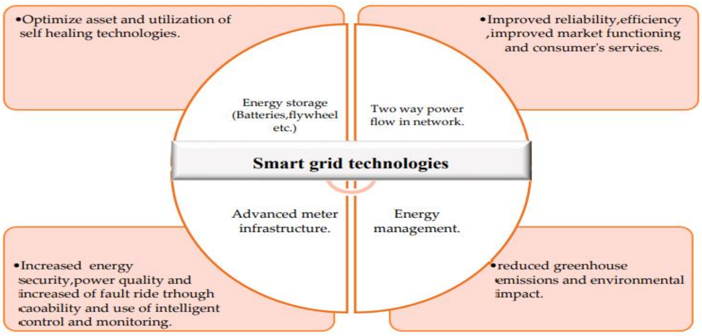

Figure 9: Representation of the challenges and benefits associated with smart grid technologies [28-31]

7. Dynamic Voltage Regulation Strategies

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7.1: Grid Connection Regulations:

a) Fault Ride-Through (FRT):

- Countries like Germany have specific regulations mandating dynamic voltage regulation during utility grid faults.
- Reactive current injection is used to manage voltage deviations during low-voltage ride-through (LVRT) and high-voltage ride-through (HVRT) scenarios.

b) Dynamic Voltage Regulation:

- **LVRT:** When voltage drops (negative ΔU), capacitive reactive current is injected to raise the voltage.
- **HVRT:** When voltage increases (positive ΔU), inductive reactive current is supplied to lower the voltage.
- The gain factor (K) is calculated from the slope of the characteristics, and the set point reactive current is determined using the formula IB = $(\Delta U - \Delta U_{dead})K$, where ΔU represents voltage difference, K is the gain factor, and ΔU_{dead} is the dead band.

c) System Service Ordinance for Wind Power Plants:

- Defines rise times for reactive power supply during severe faults or network transients to maintain grid stability.
- Mandates wind turbines to supply at least 1.0 per unit (p.u) reactive current when voltage sags under 50% to prevent the loss of synchronism with the utility grid.
- A dead band of 10% is commonly employed to avoid technical issues.

d) Continuous Voltage Control Strategy for DFIG Wind Turbines:

- Some wind turbines based on DFIG technology implement continuous voltage control strategies without a dead band.
- This continuous control allows for uninterrupted regulation of reactive power, potentially optimizing performance and response to grid conditions.

In essence, these regulations and control strategies for wind turbines with DFIGs are crucial for maintaining grid stability during voltage deviations or faults. While dead bands are often employed for safety and technical reasons, some systems implement continuous voltage control strategies to ensure efficient and uninterrupted reactive power regulation in response to grid fluctuations. The gain factor, abbreviated K in this case, is calculated from the slope of the characteristics. The voltage control strategy and its characteristics are summed up in Figure 10. [15, 32-36].

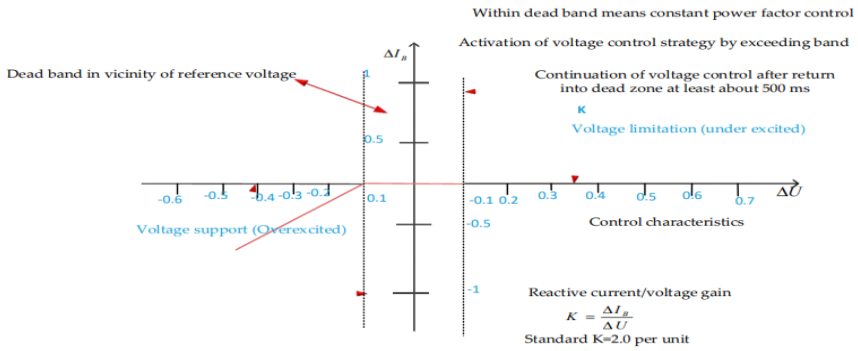

Figure 10: Dynamic voltage regulation for DFIG based wind turbines

8. Fault Ride-Through Capability-Topologies

The significance of Fault Ride Through (FRT) control for wind turbines lies in its crucial role in ensuring grid stability and reliable operation during grid faults. Grid faults, such as short circuits or voltage dips, can occur due to various reasons, and their impact on the electrical grid can be significant. FRT control is essential for the following reasons:

1. Grid Stability: During a grid fault, the voltage and frequency of the grid can deviate from their normal values. Wind turbines are required to support the grid by contributing to voltage and frequency control. FRT control allows wind turbines to remain connected to the grid and continue injecting power even during fault conditions. By providing grid support, wind turbines help stabilize the grid and prevent widespread power outages.

2. Grid Code Compliance: Many countries and regions have grid codes and regulations that specify the requirements for wind turbines to remain connected and operational during grid faults. FRT control ensures that wind turbines comply with these grid codes, enabling the integration of renewable energy sources like wind power into the grid.

3. Reducing Power Fluctuations: When a grid fault occurs, traditional power plants might reduce their output, causing a sudden decrease in power supply. Wind turbines equipped with FRT control can provide a smoother power output during and after faults, helping to mitigate the effects of these fluctuations on the grid.

4. Maximizing Energy Capture: By maintaining their connection to the grid during faults, wind turbines can continue generating power and capturing available wind energy, even under challenging grid conditions. This maximizes the energy capture efficiency and overall energy production from wind farms.

5. Minimizing Grid Disturbances: Uncontrolled disconnection of a large number of wind turbines during a fault event can lead to significant disturbances in the grid. FRT control ensures that wind turbines respond appropriately to grid faults, minimizing the impact of these disturbances and preventing cascading failures.

6. Grid Resilience and Reliability: FRT control enhances the resilience and reliability of the grid by allowing wind turbines to provide continuous power supply and support, even in the presence of grid faults. This reduces the risk of blackouts and enhances the overall stability of the power system.

7. Economic Benefits: Grid operators often impose penalties on power producers if they fail to meet grid code requirements during fault events. By implementing FRT control, wind turbine operators can avoid penalties and ensure a more stable revenue stream.

Overall, FRT control is vital for wind turbines to maintain their connection to the grid, ride through fault events, and support the grid's stability and reliability. It plays a crucial role in facilitating the integration of renewable energy sources into the power grid and contributes to a more sustainable and resilient energy system.

The Doubly Fed Induction Generator (DFIG) wind turbines have indeed faced challenges with voltage disturbances, especially during grid faults, which can lead to issues like uncontrollable currents in the rotor side converter, potentially damaging power electronic switches. Additionally, DFIG turbines are susceptible to output power fluctuations, impacting their operational efficiency. To address these challenges and enable DFIG turbines to remain connected to the grid during faults, technologies have been developed to enhance their capability to withstand voltage dips, known as Low Voltage Ride-Through (LVRT) or Fault Ride-Through (FRT) capability. These LVRT approaches generally fall into two main categories:

a) **Passive Methods:** These methods utilize additional components or systems integrated into the turbine to withstand voltage dips and maintain grid connection during faults.Examples include:

- **Crowbar Systems:** Used to protect the turbine by diverting excess currents during faults.
- **Blade Pitch Angle Control:** Adjusting the angle of turbine blades to mitigate the impact of sudden changes in wind speed.
- **Energy Capacitor Systems:** Providing short-term energy storage to support the turbine during faults.
- **DC Bus Energy Storage Circuits:** Storing energy in DC form to aid in maintaining turbine operation during voltage dips.

b) **Active Methods:** These methods involve the use of various control strategies within the turbine's converter systems to actively respond and manage the impact of voltage disturbances. Different converter controls and modulation techniques are employed to regulate current and voltage responses during faults, enabling the turbine to ride through these disturbances without disconnecting.

Both passive and active methods are employed to enhance the LVRT or FRT capability of DFIG wind turbines. By implementing these approaches, the turbines can remain connected to the grid during voltage dips or faults, improving grid stability and ensuring continuous operation, thereby increasing their overall reliability and efficiency.

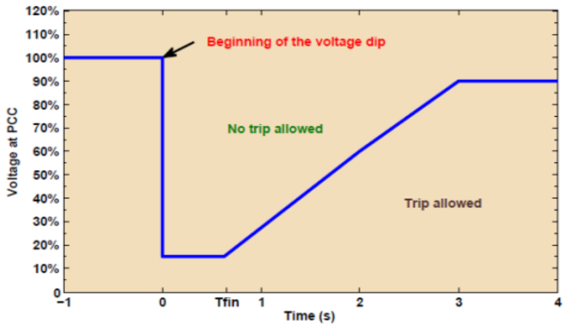

Figure 11: Typical LVRT curve

i) Passive Methods:

(a)Crowbar method:

Indeed, the conventional crowbar method in Doubly Fed Induction Generator (DFIG) wind turbines involves using a resistive network connected to the rotor circuit. During rotor overcurrents or DC-link overvoltages, the rotor side converter (RSC) is disabled, and the crowbar is activated. However, this method has several drawbacks:

1. **Reactive Power Draw and Grid Code Compliance:**
   - Activation of the crowbar results in a high short-circuit current, causing a significant draw of reactive power from the grid.
   - This reactive power draw might not comply with grid code requirements, which is a disadvantage in terms of adhering to grid regulations.
2. **Loss of Controllability and Grid Impact:**
   - When the crowbar is triggered, the DFIG loses its controllability.
   - The DFIG absorbs a large amount of reactive power from the grid, contributing to further reductions in grid voltage, potentially affecting stability.
3. **Crowbar Resistance and Energy Consumption:**
   - Proper calculation and sizing of the crowbar resistance are crucial.
   - The crowbar resistance should offer sufficient damping to control the fault currents effectively while minimizing unnecessary energy consumption.

Figure 12 shows the schematic diagram of DFIG wind turbine with crowbar protection.

To address these disadvantages, a proposed alternative crowbar arrangement involves connecting the crowbar in series with the stator windings. This arrangement aims to mitigate some of the drawbacks associated with the conventional crowbar method by altering the connection point of the crowbar within the wind turbine system. This series connection might offer improved controllability and potentially reduce the impact on grid stability by altering the reactive power flow and fault handling strategy during abnormal grid conditions. It's designed to address the issues of controllability loss, excessive reactive power absorption, and potential grid voltage reductions associated with the traditional crowbar method in DFIG wind turbines as shown in figure 13 [16,20].

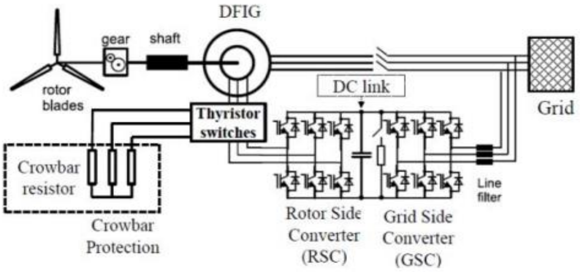

Figure 12: Schematic diagram of DFIG wind turbine with Crowbar protection

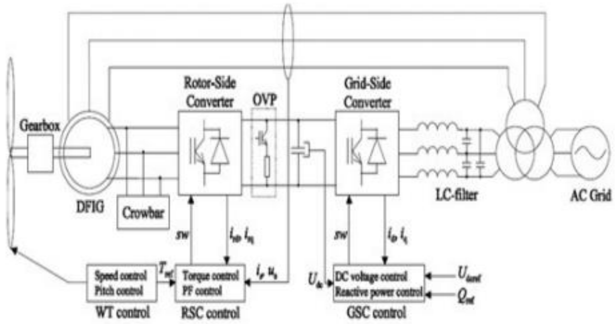

Figure 13: Crowbar in series with stator windings

(b) DC Chopper: A braking resistor (DC chopper) is connected in parallel with the dc-link capacitor to limit the overcharge during the fault condition [40,41]. A DFIG dc-link brake chopper is shown schematically in Figure 14. The dc-link brake chopper shorts the dc-link through a power resistor when the dc-link voltage exceeds a fixed threshold level. The brake is used to maintain the dc-link voltage when transient rotor overcurrent occurs. There are six antiparallel diodes in the rotor-side converter that are highly rated to withstand short-circuit currents. The brake chopper works on a hysteresis band, i.e., the turn-OFF voltage is set below the turn-ON threshold value.

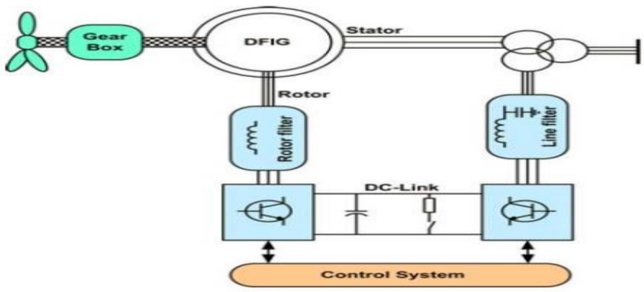

Figure 14: DFIG wind turbine with DC-link Brake Chopper

(c) Series Dynamic Braking Resistor: the integration of a braking resistor with a DC chopper, in combination with the DC-link capacitor and antiparallel diodes, provides a comprehensive solution for managing DC-link voltage during fault conditions. The use of a hysteresis-based control strategy adds stability to the operation, preventing unnecessary switching and ensuring effective limitation of overcharging. This overall setup enhances the resilience of the DFIG wind turbine system in the face of transient events and fault conditions [11].

The DFIG rotor equivalent circuit with all protection schemes is shown in Figure 15.

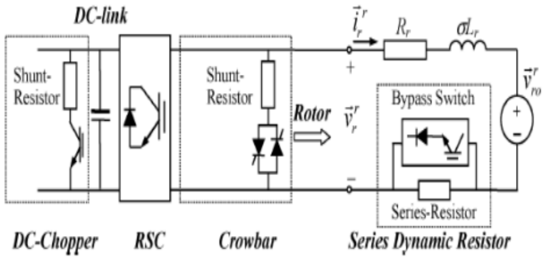

Figure 15: DFIG rotor equivalent circuit with all protection schemes

ii) Active Methods:

(a) Decoupled DFIG: In decoupled operation, the Doubly Fed Induction Generator (DFIG) shifts to function similarly to an Induction Generator (IG), and its converter unit plays a role as an active power source, often referred to as a Static Synchronous Compensator (STATCOM), especially during fault conditions. The aim during this mode is to optimize the crowbar resistance to maximize the power capability of the DFIG (Figure 16) [13].

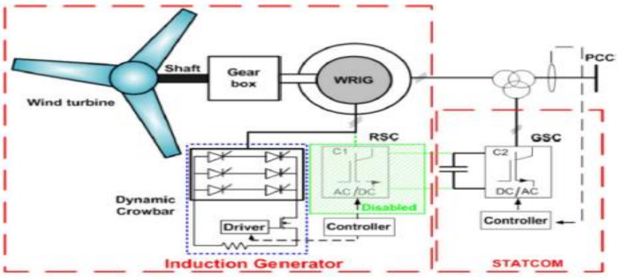

Figure 16: Schematic diagram of decoupled operation strategy

(b) Dynamic Voltage Restorer (DVR): Indeed, the Dynamic Voltage Restorer (DVR) plays a critical role in protecting the Doubly Fed Induction Generator (DFIG) from problematic grid voltages, particularly voltage sags. Here's a summary of the key aspects related to DVR's function and its impact on the DFIG system:

- **Purpose of DVR in DFIG Systems:**

- ***Voltage Compensation:*** The DVR, acting as a voltage source converter, is connected in series with the grid through a coupling transformer.

- ***Addressing Voltage Sags:*** Its primary function is to compensate for degraded line voltages, particularly during voltage sags or disturbances in the grid.

- **DFIG Integration with DVR:**

- ***Active Power Channeling:*** Active power generated by the DFIG is directed to the grid through the DVR during its compensation activities.

- ***Maintaining Wind Farm Terminal Voltage:*** The goal during fault conditions is to inject compensating voltage and ensure stability in the DFIG-based wind farm's terminal voltage.

- **Advantages of Using DVR in DFIG Systems:**

- **Reduced Complexity:** Incorporating a DVR as an external protection device can streamline voltage management within the DFIG system.

- **Simplified Functionality:** The DVR takes on the responsibility of handling voltage-related issues during faults, alleviating some of the complexity within the DFIG setup.

- **Disadvantages of DVR Implementation:**

- **Cost Implications:** The installation and operation of a DVR can contribute to increased system costs due to the technology and components involved.

- **Complexity:** While it reduces complexity within the DFIG system, the DVR itself introduces a level of complexity due to its advanced power electronics and control systems.

-***Maintenance Challenges:*** The added complexity might result in higher maintenance requirements, potentially affecting overall system reliability.

In essence, while the DVR serves as an effective external protection measure for managing grid voltage issues and maintaining stability in DFIG-based wind farms, it does come with trade-offs. The benefits include simplified voltage control within the wind farm system, while the drawbacks encompass increased costs, complexity, and potential maintenance needs associated with the DVR technology. The decision to utilize a DVR involves careful consideration of its advantages against the cost and complexity it introduces as shown in figure 17 [42, 43].

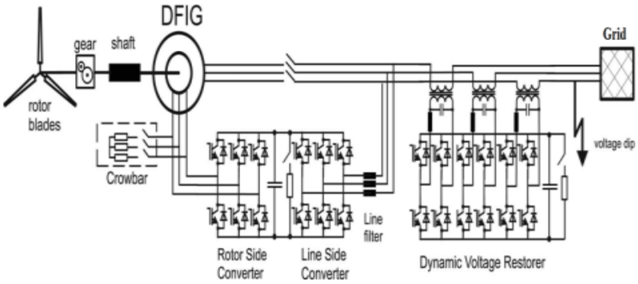

Figure 17: Schematic diagram of DFIG wind turbine with DVR

(c) Flux linkage tracking: The strategy of controlling the rotor flux linkage through the rotor-side converter in response to voltage sag is presented as a simple yet effective method to mitigate the impact of such disturbances in wind turbine systems. Ongoing technological developments suggest a continuous effort to advance fault mitigation strategies in the field of wind energy**.**

9. Simulation Results

This concept involves using a back-to-back High Voltage Direct Current (HVDC) converter with a modular multilevel topology to mitigate transient voltage dips. The system leverages the internal energy stored in the submodule capacitors of the modular multilevel converter (MMC) and extracts the maximum allowable current from the grid to stabilize the voltage. This approach is particularly relevant for particle accelerators, which are sensitive to transient voltage dips. As these accelerators grow in size and complexity, effective protection against such disturbances becomes increasingly crucial.

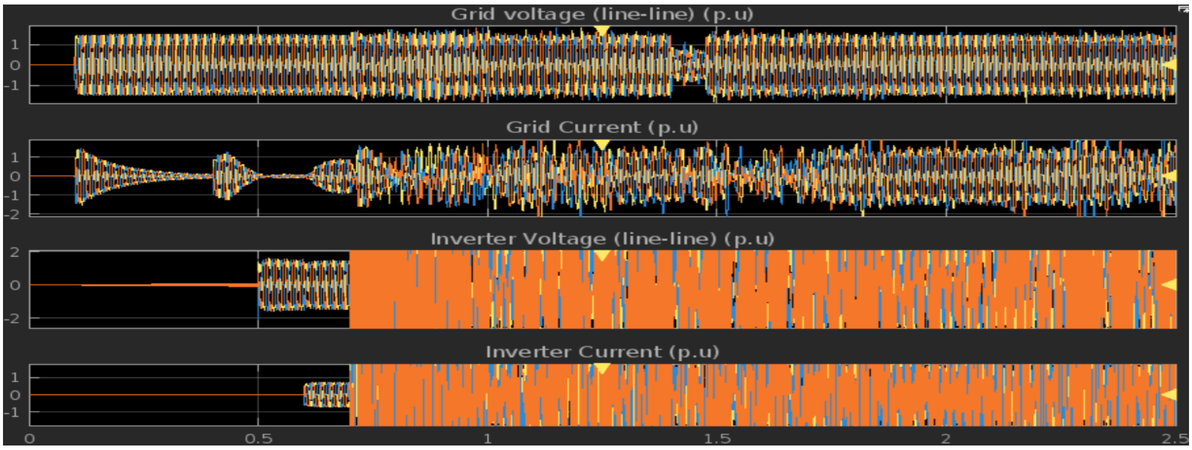

Figure 18: Current & Voltage of Back to Back HVDC Modular Multilevel Converter through simulation

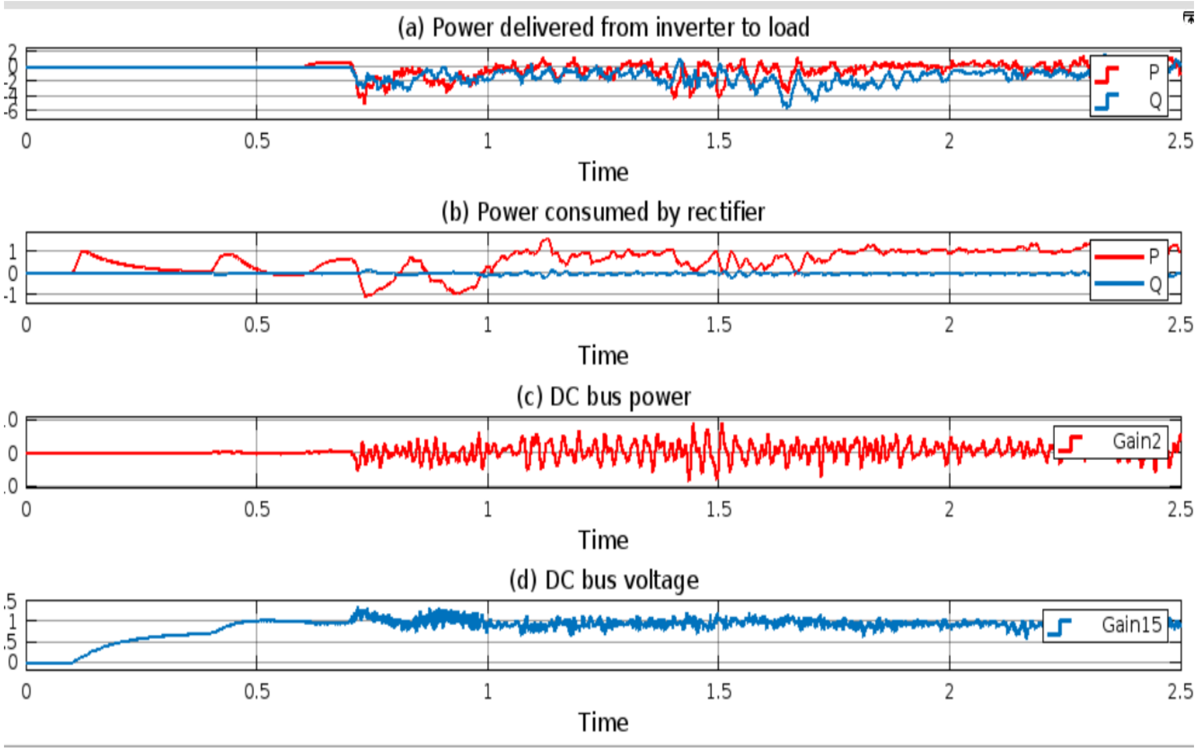

Figure 19: Power outputs of Back to Back HVDC Modular Multilevel Converter through simulation

Conclusion

The combination of Doubly Fed Induction Generator (DFIG) wind turbines with Modular Multilevel Converter-based High-Voltage Direct Current (MMC-HVDC) systems offers several advantages that enhance Fault Ride Through (FRT) capabilities. The MMC-HVDC system acts as the interface between the DFIG wind turbine and the grid, providing advanced control and flexibility, which significantly improves the wind turbine's ability to ride through grid faults. Here are the key aspects of how this combination enhances FRT capabilities:

1. Independent Control of Active and Reactive Power: The MMC-HVDC system enables independent control of active and reactive power exchanged between the wind turbine and the grid. During grid faults, the control system can adjust the converter settings to maintain the desired power flow, supporting grid voltage and frequency stabilization.

2. Higher Controllability: The MMC-HVDC system offers higher controllability compared to conventional converter systems. Its modular and scalable architecture allows for precise control of the voltage and current levels. This capability is crucial for quickly adjusting the power output of the wind turbine during fault conditions.

3. Rapid Voltage Regulation: In the event of a grid fault, the voltage at the point of grid connection may drop significantly. The MMC-HVDC system can rapidly regulate the voltage at the wind turbine terminals, helping to keep the wind turbine connected to the grid and continue supplying power.

4. Reduced Stress on the Grid during Faults: The MMC-HVDC system's ability to control the voltage and current levels during faults reduces stress on the grid. It can mitigate the impact of grid disturbances and provide grid support by absorbing or injecting reactive power as needed.

5. Power Decoupling: The DFIG wind turbine with MMC-HVDC allows power decoupling between the rotor and grid sides. During grid faults, this decoupling enables the wind turbine to continue operating at a reduced power output, preventing sudden disconnection and allowing a smoother transition through fault events.

6. Virtual Inertia and Frequency Support: The MMC-HVDC system can emulate the behavior of conventional synchronous generators, providing virtual inertia and frequency support to the grid during faults. This feature enhances the wind turbine's ability to stabilize grid frequency and ride through disturbances effectively.

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7. Enhanced Grid Support during Voltage Sags: During voltage sags or dips in the grid, the MMC-HVDC system can provide dynamic voltage support to maintain the voltage at the point of connection within acceptable limits. This support enables the wind turbine to continue operating during these transient conditions.

8. Faster Fault Detection and Response: The advanced control capabilities of MMC-HVDC facilitate faster fault detection and response. The control system can detect grid faults promptly and take appropriate actions to ensure a seamless transition through the fault event.

Future Work

For future research, modelling and simulation of a high voltage HVDC transmission system using Modular multilevel converter should be done. Instead of using conventional voltage source converter, a generalized mathematical model for MMC in realistic HVDC applications should be developed. In the model, as the number of levels in the converter increases, consequently, the number of redundant switching states increases. The modelling of control scheme of the proposed system will be simulated using MATLAB/SIMULINK software.

Also, a pioneering non-iterative framework for dynamically assessing wind energy dominated multi-machine power systems will aim to address the shortcomings of traditional iterative methods, providing a more efficient and reliable approach to power system analysis.

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