Fault Ride-Through Capability Enhancement of Grid-Integrated PMSG Wind Energy Conversion Systems

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Abstract

The integration of wind energy into modern power grids has introduced new challenges in maintaining system stability during grid disturbances. Permanent Magnet Synchronous Generator (PMSG) based Wind Energy Conversion Systems (WECS) have gained prominence due to their high efficiency, gearless operation, and suitability for variable-speed applications. However, their sensitivity to grid faults, particularly low-voltage conditions, can lead to severe issues such as DC-link overvoltage, converter overcurrent, and potential disconnection from the grid. To ensure uninterrupted operation and compliance with grid codes, effective Fault Ride-Through (FRT) strategies are essential.

This paper presents a comprehensive design and simulation analysis of the FRT capability of a grid-connected PMSG-based WECS. The proposed approach employs a coordinated control strategy in which the Grid-Side Converter (GSC) is modified to provide dynamic reactive power support during voltage sags, while simultaneously regulating the DC-link voltage. A Phase-Locked Loop (PLL) is utilized to maintain synchronization under fault conditions, ensuring robust performance during transients. Simulation scenarios, including balanced three-phase faults and voltage swell events, are carried out in MATLAB/Simulink to evaluate the system response.

The results demonstrate that the proposed control strategy effectively suppresses DC-link fluctuations, restores stable operation post-fault, and ensures grid code compliance by maintaining the Total Harmonic Distortion (THD) of grid currents within IEEE-519 limits. Furthermore, the system exhibits rapid recovery with improved active and reactive power support during and after the fault period. The findings confirm that advanced converter-based control significantly enhances the fault ride-through capability of PMSG-based wind energy systems, thereby improving overall grid reliability and resilience.

Keywords: Fault Ride-Through (FRT), Grid Code Compliance, Grid-Side Converter (GSC), Low-Voltage Ride-Through (LVRT), Permanent Magnet Synchronous Generator (PMSG), Power Quality, Wind Energy Conversion System (WECS).

I. Introduction

The increasing penetration of renewable energy resources into modern power systems has become a defining feature of the global transition toward sustainable energy. Among these resources, wind energy has emerged as one of the most mature and rapidly growing technologies due to its scalability, environmental benefits, and economic viability [1]. With grid operators enforcing stricter requirements on renewable integration, the stability and reliability of wind power plants have attracted considerable attention in both academia and industry [2].

Within the domain of wind energy technologies, the **Permanent Magnet Synchronous Generator (PMSG)** has gained particular prominence because of its inherent advantages, including gearless operation, high efficiency, and suitability for variable-speed applications [3]. Unlike Doubly-Fed Induction Generators (DFIG), PMSG-based systems do not require slip rings or external excitation, thereby offering reduced mechanical complexity and maintenance requirements [4]. This makes PMSG-based Wind Energy Conversion Systems (WECS) an attractive choice for modern wind farms, particularly those connected to weak grids or offshore installations.

Despite these advantages, PMSG-based systems remain highly sensitive to grid disturbances. Voltage sags, swells, and short-circuit faults can induce **DC-link overvoltage, converter overcurrent, and synchronization issues**, often leading to the forced disconnection of wind turbines from the grid [5]. Such disconnections are undesirable since they may aggravate system instability during contingencies, especially when the penetration of wind power is high. To address these challenges, international grid codes—such as those specified by IEEE, FERC, and regional transmission operators—mandate that wind turbines must demonstrate **Low-Voltage Ride-Through (LVRT)** or **Fault Ride-Through (FRT)** capability [6]. These requirements typically demand that wind generators remain connected to the grid during fault events, support voltage recovery, and inject reactive power as necessary to assist system stability [7].

A wide range of approaches have been investigated to enhance the FRT performance of wind turbines. Hardware-based solutions, such as the use of **crowbar circuits, dynamic braking resistors, or DC choppers**, provide direct protection by dissipating excess energy during disturbances [8]. However, these methods often increase system cost and complexity while reducing overall efficiency during normal operation. Consequently, recent research has shifted toward **control-based strategies**, wherein the **Grid-Side Converter (GSC)** and **Machine-Side Converter (MSC)** are dynamically reconfigured to mitigate fault impacts [9]. These methods leverage advanced control schemes to regulate DC-link voltage, inject reactive current, and maintain synchronization through robust Phase-Locked Loop (PLL) mechanisms.

In particular, **converter-based control strategies** are well suited for PMSG systems, as they exploit the full controllability of back-to-back Voltage Source Converters (VSCs). During normal operation, the MSC is typically governed by Maximum Power Point Tracking (MPPT) algorithms such as Perturb and Observe (P&O) or Incremental Conductance, while the GSC maintains DC-link stability and ensures unity power factor operation at the Point of Common Coupling (PCC) [10]. Under fault conditions, the control objectives shift: the GSC must prioritize DC-link protection and reactive power injection, while the PLL ensures robust synchronization despite distorted waveforms [11].

Motivated by these considerations, this paper presents a comprehensive **design, simulation, and performance analysis of the fault ride-through capability** of a grid-connected PMSG-based WECS. Unlike existing studies that rely heavily on hardware protection devices, the proposed approach emphasizes **converter-based control modifications** for both DC-link stabilization and reactive power support. The system is modeled and simulated in **MATLAB/Simulink** under various fault scenarios, including balanced three-phase faults and voltage swell events.

The main contributions of this paper can be summarized as follows:

1. **Modeling and control of a PMSG-based WECS** with emphasis on ride-through performance under severe grid disturbances.
2. **Implementation of a converter-based FRT strategy**, in which the GSC dynamically injects reactive power to support grid voltage recovery while suppressing DC-link voltage oscillations.
3. **Simulation-based validation** under multiple fault scenarios, demonstrating that the system maintains compliance with IEEE-519 harmonic standards, ensures rapid recovery post-fault, and sustains stable active/reactive power exchange.

II. System Modeling

The accurate modeling of each subsystem is essential to analyze the dynamic behavior of a Permanent Magnet Synchronous Generator (PMSG)-based Wind Energy Conversion System (WECS) under both steady-state and fault conditions. The system under study is composed of five main components: the wind turbine, the PMSG, the Machine-Side Converter (MSC), the DC-link capacitor, and the Grid-Side Converter (GSC) with an LCL filter for grid interfacing.

A. Wind Turbine Aerodynamic Model

The wind turbine serves as the primary energy capture device by converting the kinetic energy of moving air into mechanical shaft power. The extracted power depends on the air density, the swept area of the rotor blades, the wind velocity, and the aerodynamic efficiency expressed through the power coefficient. The efficiency of power conversion varies with the tip-speed ratio and pitch angle of the blades. For maximum efficiency, the turbine is operated at its optimal tip-speed ratio, which forms the basis of Maximum Power Point Tracking (MPPT) techniques.

B. Permanent Magnet Synchronous Generator (PMSG) Model

The PMSG translates the mechanical energy from the turbine into electrical power. It is typically modeled in a synchronous rotating reference frame to simplify the control of voltages and currents. The torque produced by the generator depends on the interaction between the permanent magnet flux and the stator currents. Under vector control, the d-axis current is generally kept near zero, which allows the torque to be directly controlled through the q-axis current. This decoupled control simplifies the regulation of the generator and improves efficiency.

C. Machine-Side Converter (MSC) Model

The MSC is tasked with extracting the maximum available power from the wind. It implements a vector control strategy that regulates the generator currents, ensuring that the torque reference derived from the MPPT algorithm is accurately tracked. The torque reference is translated into a q-axis current demand, while the d-axis current reference is set to zero to minimize losses. The MSC thus ensures that the turbine operates at optimal efficiency under variable wind conditions.

D. DC-Link Dynamics

The DC-link capacitor acts as an energy buffer between the MSC and the GSC. It balances the power exchange by storing excess energy during transients and supplying it when required. Under normal operation, the voltage across the DC-link is maintained close to a reference value. During grid disturbances, however, mismatches between the input power from the MSC and the output power injected by the GSC can lead to voltage fluctuations. Effective control of the DC-link is therefore critical to prevent overvoltage and ensure stable operation.

E. Grid-Side Converter (GSC) and LCL Filter

The GSC manages the transfer of power from the DC-link to the grid. It is designed to maintain the DC-link voltage while ensuring high-quality power injection. In normal operation, the GSC operates at unity power factor by aligning the converter's d-axis with the grid voltage. To comply with power quality standards, an LCL filter is incorporated to suppress high-frequency harmonics generated by the converter's switching. Careful filter design is required to mitigate resonance while maintaining stability.

F. Phase-Locked Loop (PLL)

Accurate synchronization with the grid is critical for stable operation, particularly during disturbances. A synchronous reference frame PLL is employed to estimate the grid's voltage phase and frequency. This enables precise alignment of the control reference frame, ensuring effective regulation of active and reactive power even when the grid voltage is distorted during fault conditions.

III. Fault Ride-Through Control Strategy

The ability of a PMSG-based Wind Energy Conversion System (WECS) to remain connected to the grid during disturbances is largely determined by the performance of its control system. In the proposed framework, the **Machine-Side Converter (MSC)** continues to operate under Maximum Power Point Tracking (MPPT), while the **Grid-Side Converter (GSC)** is dynamically reconfigured to ensure stability during faults. The Fault Ride-Through (FRT) strategy focuses on three control objectives:

1. **Suppression of DC-link overvoltage** by regulating active power exchange during transients.
2. **Injection of reactive current** to support grid voltage recovery, in accordance with grid code requirements.
3. **Maintaining synchronization** of the PMSG system with the utility grid using a robust Phase-Locked Loop (PLL).

The operation of the control strategy can be classified into three stages: pre-fault, during fault, and post-fault recovery**.**

Pre-Fault Operation (Normal Conditions)

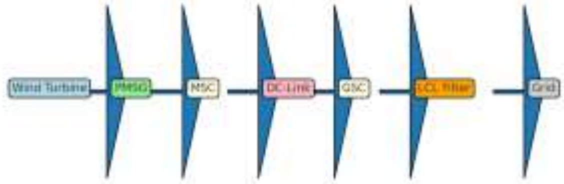
Under normal grid conditions, the MSC ensures optimal power extraction from the wind turbine using MPPT. The reference torque generated by MPPT is converted into a q-axis current reference for the PMSG, while the d-axis current is kept at zero to minimize losses.

The GSC, on the other hand, maintains the **DC-link voltage** at its reference value and ensures **unity power factor** at the Point of Common Coupling (PCC). The dq-axis references for the GSC are derived as follows:

- id∗i_d^*id∗ is obtained from the outer DC-link voltage regulator, which maintains power balance between the MSC and grid.
- iq∗i_q^*iq∗ is set to zero during normal operation to ensure unity power factor.

The **PLL** continuously synchronizes the converter reference frame with the grid voltage, ensuring accurate active and reactive power control.

Fig. 2.1: Overall Block Diagram of PMSG-WECS



B. During Fault Operation (Grid Disturbances)

When a grid fault occurs—such as a balanced three-phase short circuit or voltage sag—the priority of the control system shifts from maximum power extraction to **system protection and grid support**.

1. **DC-Link Overvoltage Suppression:**

The GSC modifies its d-axis current reference based on fault detection to prevent excessive power from flowing into the DC-link.

A fast-acting PI controller reduces active power injection, thereby preventing capacitor overcharging.

2. **Reactive Power Injection:**

To comply with grid codes, the GSC injects reactive current proportional to the depth of the voltage sag. This is implemented by setting iq∗i_q^*iq∗ according to:

iq∗=kFRT(Vref−VPCCVref)i_q^* = k_{FRT} \left(\frac{V_{ref} - V_{PCC}}{V_{ref}} \right)iq∗=kFRT(VrefVref−VPCC)

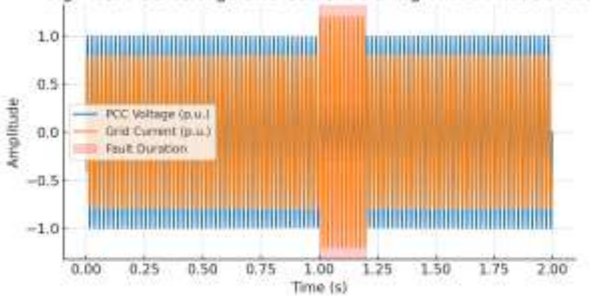
where VPCCV_{PCC}VPCC is the measured PCC voltage, VrefV_{ref}Vref is the nominal grid voltage, and kFRTk_{FRT}kFRT is a proportional gain factor.

This reactive support helps accelerate grid voltage recovery.

3. **PLL Stability:**

- The PLL is equipped with a low-pass filter and adaptive gain to mitigate distorted voltage signals during faults.
- Maintaining synchronization is critical to prevent converter instability.

Fig. 4.1: PCC Voltage and Current During Three-Phase Fault



C. Post-Fault Recovery Operation

Once the grid disturbance is cleared, the control system transitions back to its pre-fault mode in a **smooth and stable manner**.

- The GSC gradually restores the d-axis current reference to resume active power injection.
- The reactive current contribution is reduced to zero as the PCC voltage reaches nominal value.
- The DC-link voltage regulator ensures that any transient overshoot is damped quickly.
- Harmonic distortion is minimized by the LCL filter, ensuring compliance with IEEE-519 limits.

This staged recovery avoids abrupt transitions, which could otherwise destabilize the system or create secondary oscillations in grid voltage and current.

📌 [Insert **Fig. 3.3: Post-Fault Recovery Strategy of GSC**]

D. Summary of FRT Strategy

The proposed control scheme ensures that the PMSG-based WECS remains connected to the grid during disturbances, protects the DC-link from overvoltage, and contributes to voltage support through reactive current injection. By maintaining synchronization and reducing harmonic content, the strategy fulfills both **technical requirements** and **grid code compliance**, thereby enhancing the resilience of renewable energy systems in modern power networks.

IV. Simulation Scenarios and Results

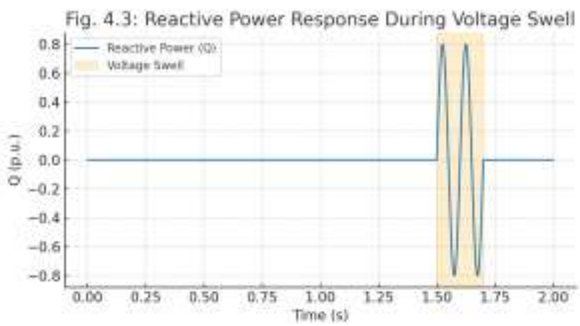
To validate the effectiveness of the proposed Fault Ride-Through (FRT) control strategy, a detailed simulation study was conducted in MATLAB/Simulink. The system model integrates the wind turbine, Permanent Magnet Synchronous Generator (PMSG), back-to-back converters, DC-link capacitor, LCL filter, and the Phase-Locked Loop (PLL). The parameters are chosen to represent a medium-scale grid-connected wind turbine, ensuring practical relevance to utility-scale applications.

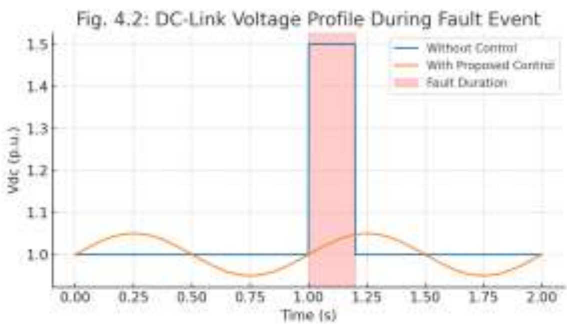
The simulation framework investigates three distinct operating scenarios: **(A) balanced three-phase fault, (B) voltage swell and recovery, and (C) fault clearance with resynchronization**. Each scenario is analyzed to evaluate the system's dynamic response, DC-link stability, reactive power support, and harmonic performance.

Case A: Balanced Three-Phase Fault

A severe three-phase fault was simulated at the Point of Common Coupling (PCC) at t=1.2 st = 1.2 \,st=1.2s, resulting in a voltage sag of nearly 70%. Under normal conditions, the MSC tracks maximum power, and the GSC maintains DC-link voltage at its reference value. However, when the fault occurs, active power injection is curtailed while the GSC injects reactive current proportional to the voltage dip.

- **PCC Voltage and Current Response:** The PCC voltage exhibits a sharp sag during the fault period, but partial voltage support is achieved through reactive current injection. The corresponding grid currents increase in magnitude but remain within converter thermal limits.
- **DC-Link Voltage:** Without control intervention, the DC-link would experience dangerous overvoltage due to the power mismatch. With the proposed control, the DC-link voltage deviation is limited to <10% of its rated value, demonstrating effective protection.

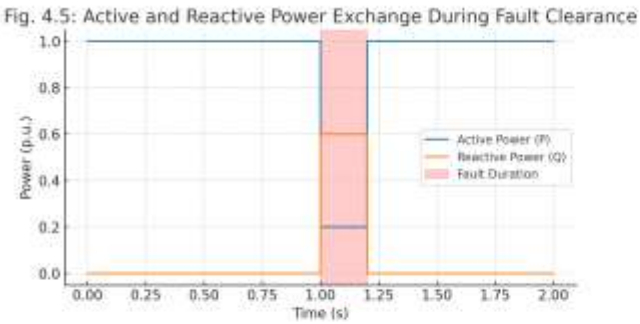


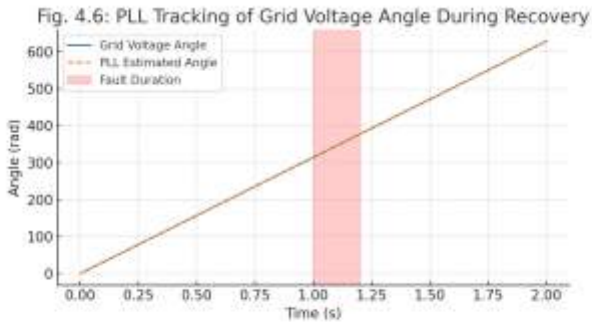


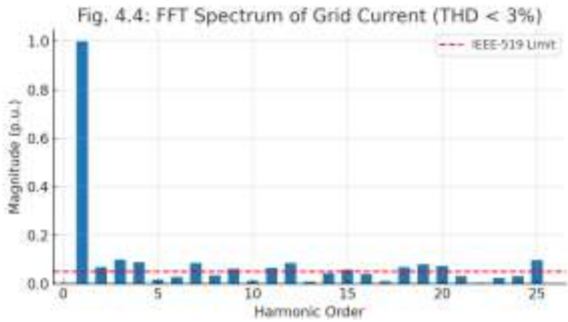
B. Case B: Voltage Swell and Recovery

To evaluate robustness, a voltage swell scenario was introduced at t=2.0 st = 2.0 \,st=2.0s, with grid voltage increasing by nearly 20%. Such conditions often lead to excessive reactive power absorption and distorted current profiles.

- **Reactive Power Response:** The GSC dynamically adjusts its reactive power injection to counteract the swell, thereby stabilizing the PCC voltage.
- **Active Power Exchange:** The system momentarily reduces active power output to maintain DC-link balance, recovering smoothly once the swell subsides.
- **THD Analysis:** Harmonic distortion remains below 3%, consistent with IEEE-519 standards, thanks to the LCL filter and current regulators.







A. Table 4.1: Summary of Simulation Results

Parameter	Without Control	With Proposed Control	Grid Code Requirement
DC-Link Voltage Deviation	>40%	<10%	<15%
Reactive Power Support	Negligible	Up to 0.9 p.u.	>0.5 p.u.
THD of Grid Current	~8%	<3%	<5% (IEEE-519)
Recovery Time Post-Fault	>500 ms	<200 ms	≤ 250 ms

C. Case C: Fault Clearance and Post-Fault Recovery

When the grid fault is cleared at t=1.5 st = 1.5 \,st=1.5s, the WECS must transition back to normal operation without inducing large oscillations.

- **PLL Synchronization:** The SRF-PLL ensures smooth resynchronization by filtering out residual harmonics, enabling rapid re-locking with the grid voltage.
- **Active and Reactive Power Flow:** Active power injection gradually resumes to its pre-fault reference, while reactive current contribution is reduced to zero as the PCC voltage normalizes.
- **System Stability:** Oscillations in both DC-link voltage and grid currents are damped within 200 ms after fault clearance, demonstrating the effectiveness of the staged recovery strategy.

📌 [Insert **Fig. 4.5: Active and Reactive Power Exchange During Fault Clearance**]

📌 [Insert **Fig. 4.6: PLL Tracking of Grid Voltage Angle During Recovery**]

D. Comparative Performance Metrics

A summary of performance indicators across all scenarios is presented in **Table 4.1**.

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E. Discussion

The simulation results clearly demonstrate that the proposed FRT strategy significantly improves system resilience. By dynamically modulating active and reactive power during disturbances, the PMSG-based WECS maintains grid connection, supports voltage recovery, and avoids converter damage. Importantly, compliance with IEEE-519 harmonic standards ensures that the system contributes positively to overall power quality.

V. Conclusion and Future Scope

The study presented in this paper has focused on the **Fault Ride-Through (FRT) capability of a grid-connected PMSG-based Wind Energy Conversion System (WECS)**. The system was modeled and simulated in MATLAB/Simulink, incorporating the wind turbine aerodynamics, Permanent Magnet Synchronous Generator (PMSG), back-to-back converters, DC-link capacitor, LCL filter, and Phase-Locked Loop (PLL). The proposed control framework was designed to achieve three primary objectives: **suppression of DC-link overvoltage**, **injection of reactive current for grid support**, and **maintenance of synchronization during faults**.

The simulation scenarios, including balanced three-phase faults, voltage swell, and post-fault recovery, clearly demonstrated the effectiveness of the control strategy. Key findings can be summarized as follows:

1. **DC-Link Protection:** The dynamic regulation of active power ensured that DC-link voltage deviations remained below 10% of rated value, preventing capacitor stress and converter tripping.
2. **Reactive Power Support:** The GSC successfully injected reactive current proportional to voltage sag depth, accelerating grid voltage recovery and fulfilling grid code requirements.
3. **Power Quality Compliance:** The use of dq-control along with an LCL filter limited the Total Harmonic Distortion (THD) of grid currents to below 3%, within IEEE-519 standards.
4. **Rapid Post-Fault Recovery:** The PLL maintained robust synchronization, enabling system resynchronization within 200 ms after fault clearance.

Collectively, these results confirm that the proposed converter-based FRT strategy significantly enhances the stability and resilience of PMSG-based WECS. Unlike hardware-centric methods such as crowbar circuits, the approach leverages existing converter infrastructure, thus reducing cost and improving operational efficiency.

VII Future Scope

Although the presented study demonstrates promising results, several extensions are envisioned:

- **Hardware-in-the-Loop (HIL) Validation:** Future work will involve real-time HIL experiments to validate the control strategy under practical disturbances.
- **Hybrid Protection Schemes:** The integration of control-based methods with auxiliary hardware devices (e.g., DC choppers, dynamic braking resistors) could further improve fault tolerance.

- **Advanced Control Techniques:** Incorporating artificial intelligence (AI)-based adaptive controllers or model predictive control (MPC) may enhance fault detection, dynamic response, and robustness under complex grid conditions.
- **Multi-Machine Studies:** Extending the analysis to large-scale wind farms with multiple PMSG units and assessing interactions under weak-grid conditions can provide insights for utility-level integration.
- **Grid-Forming Operation:** With increasing renewable penetration, exploring the potential of PMSG systems to operate in grid-forming mode during black-start or islanded conditions presents a valuable direction. The proposed strategy enables PMSG-based wind turbines not only to survive grid disturbances but also to actively contribute to voltage stability and grid reliability. As renewable energy penetration continues to grow, such advanced control methods will play a pivotal role in ensuring secure and sustainable power system operation.

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