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Research article

Improving the Dynamic Response and Passing the Low Voltage of Wind Turbines by Using a Combined System to Improve the Quality of Power

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Extended Abstarct:
The integration of variable renewable energy sources, particularly wind power, into modern power grids presents a significant and multifaceted challenge to system operators and planners. Among the various types of wind turbine technologies, the Doubly-Fed Induction Generator (DFIG) has become a dominant choice in the wind industry due to its advantages of high efficiency, variable speed operation, and independent control of active and reactive power. However, a well-known and critical vulnerability of the DFIG, as well as its synchronous generator counterpart, lies in its operational stability during grid-side faults. These disturbances, such as short circuits or severe voltage sags, can lead to a catastrophic loss of excitation in the rotor circuit for the DFIG, or a complete failure of the field system in a Permanent Magnet Synchronous Generator (PMSG). The consequences of such a failure—commonly referred to as a Loss of Excitation (LOE) for a synchronous machine or a grid fault for a DFIG—are severe. They include a dramatic over-current in the rotor-side converter, a dangerous acceleration of the rotor speed due to the loss of electromagnetic torque, and severe power oscillations. If not mitigated swiftly, these events can damage the power electronics, overheat the stator and rotor windings, and potentially trigger a cascading event that forces the wind turbine to disconnect from the grid, thereby exacerbating the initial disturbance and compromising overall system stability.

The conventional protective strategy for addressing these vulnerabilities, especially for DFIGs, has historically been the use of a crowbar circuit. This passive device, typically consisting of a set of resistors connected across the rotor terminals via power electronic switches, is designed to be activated during a fault to short-circuit the rotor and thereby protect the sensitive rotor-side converter from destructive over-currents. While effective in its primary role as a safeguard, the crowbar circuit is fundamentally a blunt instrument that introduces its own set of problems. Once activated, it effectively bypasses the rotor-side converter, rendering the DFIG a standard induction machine. This leads to a complete loss of control over both active and reactive power, a significant increase in mechanical stress on the drivetrain due to uncontrolled torque transients, and a prolonged and uncontrolled ride-through process that often fails to meet the stringent requirements of modern grid codes. These grid codes now demand that wind turbines remain connected during faults (a capability known as Low Voltage Ride-Through or LVRT) and even provide reactive power support to aid in grid voltage recovery. The inherent shortcomings of the conventional crowbar approach have therefore motivated a significant body of research into more sophisticated and active protection and control strategies.

In direct response to these critical challenges, the research by Naderi and Tavakoli proposes a novel and highly effective fault management system that fundamentally rethinks the approach

to protecting DFIG and PMSG wind turbines during grid-side faults. The core of their innovation is a new type of Series Resonant Fault Current Limiter (SRFCL). Unlike the passive and disruptive crowbar, this SRFCL is an active, intelligent device that is strategically integrated into the DC-link of the rotor-side converter. This location is crucial, as it allows the SRFCL to act as a dynamic buffer that directly modulates the DC-link current, which is the root source of the problematic rotor over-currents.

The proposed SRFCL is an elegant and carefully engineered circuit comprising several key components: a full-wave diode rectifier bridge, a DC-side inductor (Ld) in parallel with a resistor (rd), and a controlled semiconductor switch (such as an IGBT) in parallel with a discharge resistor (rp). The operational principle is both simple and powerful. During normal grid operation, the DC-link current is smooth and stable, and the SRFCL remains in a transparent, low-impedance state, having no adverse effect on the turbine's performance. However, the moment a grid fault is detected, the system's dynamics change dramatically. The SRFCL's DC inductor (Ld) immediately suppresses the initial, sharp rate-of-rise (di/dt) of the fault current, effectively damping the first and most damaging current spike. Subsequently, for the duration of the fault, the inductor continues to limit the steady-state fault current by presenting a high inductive reactance.

A critical feature of this design is the inclusion of the parallel IGBT and discharge resistor (rp). During a prolonged fault, the energy that would normally circulate destructively within the converter is instead diverted through this path. The IGBT is controlled to dissipate the excess active power generated by the turbine as heat in the resistor (rp). This action serves a dual purpose: it prevents a dangerous over-voltage on the DC-link—a common problem in PMSG systems during faults—and it provides a controlled mechanism to manage the active power imbalance that arises because the turbine cannot deliver its full power to the grid. This active power management is a significant advancement over passive solutions and is key to enabling the turbine to ride through the fault without tripping.

The performance and validity of the proposed SRFCL-based protection scheme were rigorously evaluated using a comprehensive set of MATLAB/Simulink simulations on a standard test system. The evaluation covered a wide spectrum of fault scenarios to test the system's robustness, including three-phase, two-phase, and single-phase-to-ground short circuits, as well as the critical scenario of a line disconnection before or after the wind turbine. The results are compelling and demonstrate the superiority of the proposed method across all key performance metrics.

In the case of a severe three-phase fault, the simulations show that the SRFCL effectively limits the rotor over-current to safe levels, completely prevents the uncontrolled acceleration of the rotor speed, and dramatically reduces the high torque fluctuations that would otherwise occur. Remarkably, the system is able to maintain stable operation even under the most extreme condition of a complete zero-voltage grid fault. The same level of performance was observed for two-phase and single-phase faults, confirming the method's versatility. Furthermore, when a line disconnection—a common and disruptive event in transmission systems—was simulated, the SRFCL again proved its effectiveness by preventing the system from entering a highly oscillatory and unstable state, which would be the likely outcome with a conventional crowbar or no protection at all.

A critical aspect of any LVRT strategy is its impact on the grid itself. The proposed method was carefully designed to have a neutral or even positive effect on grid dynamics. The simulation results confirm that the SRFCL does not negatively impact the voltage profile at the Point of Common Coupling (PCC); in fact, by stabilizing the turbine's operation and preventing a sudden power loss, it helps to support the local grid voltage during the fault recovery period. This feature is a direct response to the requirements of modern grid codes and highlights the

method's practical applicability.
In conclusion, this research presents a significant and practical advancement in the field of wind turbine protection and grid integration. By introducing a novel Series Resonant Fault Current Limiter integrated at the DC-link of the rotor-side converter, the authors have developed a protection scheme that directly addresses the fundamental weaknesses of the conventional crowbar circuit. The proposed SRFCL not only provides superior protection for the power electronics and the generator itself by effectively limiting fault currents and suppressing destructive transients but also enables the turbine to meet the stringent LVRT requirements of modern power grids. The extensive simulation results on a variety of fault types validate its high speed, accuracy, and robustness. The solution is also notable for its relative simplicity, as it leverages standard, commercially available components with a straightforward control logic, making it a highly promising and viable candidate for real-world implementation in both new and existing wind power installations. This work thus provides a valuable contribution to the ongoing effort of integrating renewable energy sources into a reliable, stable, and resilient power grid of the future.

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