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MPC and FOC for LVRT performance in hybrid renewable energy systems

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ABSTRACT

This paper proposes a wind and solar energy-based hybrid generation system integrated with a photovoltaic (PV) array controlled using model predictive control (MPC) and a doubly fed induction generator (DFIG) wind turbine controlled using field-oriented control (FOC). The system employs cascaded-based and bridge-based structures for two renewable sources, and they are connected to an ordinary common load, and designed to meet the stringent conditions of low-voltage ride-through (LVRT) required during fault conditions and grid-side perturbations. In order to safeguard the power electronic converter from sharp voltage dips, a crowbar protection circuit is used on the rotor side of the DFIG. In order to verify the enhanced LVRT capability of the offered system, extensive modeling, control design, implementation steps, and numerous simulation results have been included. The use of sophisticated control methodologies and protective measures improves the reliability and stability of wind-solar power plants. Simulation results reveal that for a serious grid disturbance, the system manages to maintain the output voltage at 70% of its nominal value and keeps the waveform steady and sinusoidal. In addition, the control scheme ensures that the rotor current is not just sinusoidal but also well-balanced, yielding a steady-state electromagnetic torque. This combination of control and protective measures is paramount for achieving stability, power quality, and reliability in current hybrid renewable power systems.

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1. INTRODUCTION

The global integration of renewable energy sources (RES) is imperative for a sustainable energy future. Hybrid systems that combine complementary PV and wind resources offer inherent generation stability and are particularly well-suited to meet these demands [1], [2]. However, the increasing penetration of inverter-based resources presents significant technical challenges for grid stability, particularly during network disturbances. Modern grid codes now mandate that these generation facilities must remain connected and support the grid during voltage dips, a requirement known as low-voltage ride-through (LVRT) capability. Failure to meet these requirements leads to widespread instability and cascading outages [1].

Among various wind turbine technologies, the doubly fed induction generator (DFIG) is highly popular due to its variable speed operation, high efficiency, partial-scale power converter, and low cost. However, this very structure makes it exceptionally vulnerable to grid faults. The stator is directly connected to the grid, and any voltage sag induces a large transient electromotive force in the rotor circuit, leading to dangerously high peak currents and DC-link overvoltage that can destroy the insulated gate bipolar transistors (IGBTs) in the rotor-side converter (RSC) [3]-[5].

Several strategies have been proposed to enhance the LVRT capability of DFIGs. A common hardware-based approach is the use of a crowbar protection circuit, which short-circuits the rotor windings during severe faults to divert current away from the RSC [6]. While effective for protection, conventional crowbar systems often turn the DFIG into a simple induction generator, consuming reactive power from the grid at the very moment it is needed. On the control side, field-oriented control (FOC) has been adopted for its decoupling of active and reactive power, providing excellent performance under balanced conditions. However, its performance can be challenged during asymmetrical faults [7].

For grid-connected PV inverters, advanced control strategies like model predictive control (MPC) are gaining attraction for their fast dynamic response, ability to handle system constraints, and capacity to provide reactive power support during voltage dips [8], [9]. FOC or vector control is the industry standard for RSC control under normal operation, providing decoupled control of active and reactive power. However, during severe and asymmetrical faults, the performance of FOC can deteriorate due to the presence of negative sequence components and magnetic saturation, necessitating more robust algorithms [10].

To address the limitations of hardware protection, research has evolved towards "crowbar-less" strategies and advanced control schemes that allow the DFIG to remain connected and support the grid during faults. These include feedforward compensation techniques [11] to counter the counter-electromotive force and sophisticated algorithms like fuzzy logic control and MPC for improved transient performance [12], [13].

Concurrently, the role of PV systems has shifted from being mere passive power generators to active grid-supporting assets. Modern grid-tied inverters are capable of providing ancillary services, including reactive power support during faults. MPC has emerged as a powerful framework for inverter control due to its fast dynamic response, intuitive handling of multiple constraints (e.g., current and voltage limits), and ability to be tuned for specific objectives like priority-based active and reactive power injection. This makes MPC-controlled PV inverters ideal for providing dynamic voltage support during the voltage dips that affect the hybrid system [14], [15].

This paper fills this gap by proposing a coordinated control and protection strategy for a hybrid PV-DFIG system. The specific contributions of this work are:

- Development of a coordinated strategy: Integrating an MPC-controlled PV system with an FOC-controlled DFIG to ensure stable operation during faults.
- Enhanced protection integration: utilizing a crowbar circuit to protect the RSC while simultaneously using the PV system to offset the resulting reactive power consumption.
- Comparative analysis: Validating the superior LVRT capability of this hybrid approach compared to isolated systems, demonstrating improved transient performance and dynamic voltage support.

The remainder of this paper is organized as follows: i) Section 2 describes the system configuration and modeling; ii) Section 3 details the control strategies for the PV system and DFIG; iii) Section 4 presents the simulation results and discussion; and iv) Finally, section 5 concludes the paper.

2. SYSTEM MODELING

2.1. PV array model

The PV array is modeled using the standard single-diode model, represented by (1) [16]:

$$I_{pv} = I_{ph} - I_s(e^{(V_{pv}+R_sI_{pv})}/nV_t - 1) - (R_{sh} + R_sI_{pv})/V_{pv} \tag{1}$$

where I_{ph} is the photocurrent, I_s is the diode saturation current, n is the ideality factor (1-2), V_t is the thermal voltage, and R_s and R_{sh} are the series and shunt resistances, respectively.

2.2. DFIG wind turbine model

The voltage equations of DFIG stator and rotor can be described in the synchronous d-q frame [17] as below:

2.2.1. Stator voltage equations

The stator voltage equations in the d-q frame are given by (2) and (3).

$$v_{sd} = R_s i_{sd} + L_s \frac{di_{sd}}{dt} - \omega_s L_s i_{sq} + L_m \frac{di_{rd}}{dt} - \omega_s L_m i_{rq} \tag{2}$$

$$v_{sq} = R_s i_{sq} + L_s \frac{di_{sq}}{dt} + \omega_s L_s i_{sd} + L_m \frac{di_{rq}}{dt} + \omega_s L_m i_{rd} \tag{3}$$

2.2.2. Rotor voltage equations

The rotor voltage equations in the *d-q* frame are given by (4) and (5):

$$v_{rd} = R_r i_{rd} + L_r \frac{di_{rd}}{dt} - (\omega_s - \omega_r) L_r i_{rq} + L_m \frac{di_{sd}}{dt} - (\omega_s - \omega_r) L_m i_{sq} \tag{4}$$

$$v_{rq} = R_r i_{rq} + L_r \frac{di_{rq}}{dt} + (\omega_s - \omega_r) L_r i_{rd} + L_m \frac{di_{sq}}{dt} + (\omega_s - \omega_r) L_m i_{sd} \tag{5}$$

where, v_{rd}, v_{rq}, v_{sd} , v_{sq} are the d-q rotor and stator voltages, respectively R_r and R_s is the rotor and stator resistance. i_{rd} , i_{rq}, i_{sd} and i_{sq} are the rotor and stator currents in the *d* and *q* axes, respectively. L_r is the rotor inductance. ω_r is the rotor speed. L_s is the stator inductance. ω_s is the synchronous speed of the rotating field in the stator, L_m is the mutual inductance between the stator and rotor.

2.3. Electromechanical dynamics

The electromagnetic torque T_{em} and rotational dynamics equations that govern the interaction between the stator, rotor voltages, and currents are [17]:

$$T_{em} = \frac{3}{2} . \frac{p}{\omega_r} . (\lambda_{sd} i_{sq} - \lambda_{sq} i_{sd} \tag{6}$$

$$J \frac{d\omega_r}{dt} = T_m - T_{em} - D\omega_r \tag{7}$$

where *p* is the number of poles, λ_{sd} and λ_{sq} are the d-q frame flux linkages, *J* is the moment of inertia of the rotor, T_m is the mechanical torque, *D* is the damping coefficient.

3. CONTROL STRATEGIES

In order to maximize the power output, proper active and reactive power tuning over the DFIG needs to be maintained. Active power (P) and reactive power (Q) may be represented as (8) and (9).

$$P = \frac{3}{2} \cdot \frac{Vs}{Z} \cdot (i_{sd} \cdot V_{sq} + i_{sq} \cdot V_{sd}) \tag{8}$$

$$Q = \frac{3}{2} \cdot \frac{Vs}{Z} \cdot (i_{sq} \cdot V_{sq} - i_{sd} \cdot V_{sd}) \tag{9}$$

3.1. MPC for PV inverter

MPC is an advanced control methodology that performs optimal control actions on the PV inverter based on the forecasted future system state as the control inputs. In the MCS problem, MPC calculates the best inverter switching sequence in a finite horizon in order to minimize an associated cost function that considers both voltage tracking and reactive power injection. The cost function *J* is formulated as (10) [18], [19].

$$J = \sum_{k=1}^{N_p} \parallel V_i * (k) - V_i(k) \parallel^2 + \lambda \sum_{k=0}^{N_c - 1} \parallel \Delta u(k) \parallel^2 \tag{10}$$

Where: V_i*(k) represents the reference voltage at the moment k. V_i(k) is the applied voltage for k-th time step. N_p is the number of predicted steps. N_c denotes the control horizon. λ is the weight. Δu(k) is the variation of the switching actions (control inputs) at the k-th sample instant. The first term of the cost function is the voltage tracking error, which guarantees that the inverter tracks the reference voltage closely. The second term is added to avoid excessive changes in control commands, which guarantees that the converter components will work at a lower temperature. At each control step as in Figure 1.

The optimal control also takes into account system dynamics and operational constraints. Certain constraints for the inverter such as maximum output power, voltage, and current should be maintained. Such constraints can be written as (11) and (12).

$$u_{min} \leq u(k) \leq u_{max} \tag{11}$$

$$V_{min} \leq V_i(k) \leq V_{max} \tag{12}$$

Where u_{min} and u_{max} define the bounds on control inputs, V_{min} and V_{max} set the permissible voltage levels for the inverter output [8].

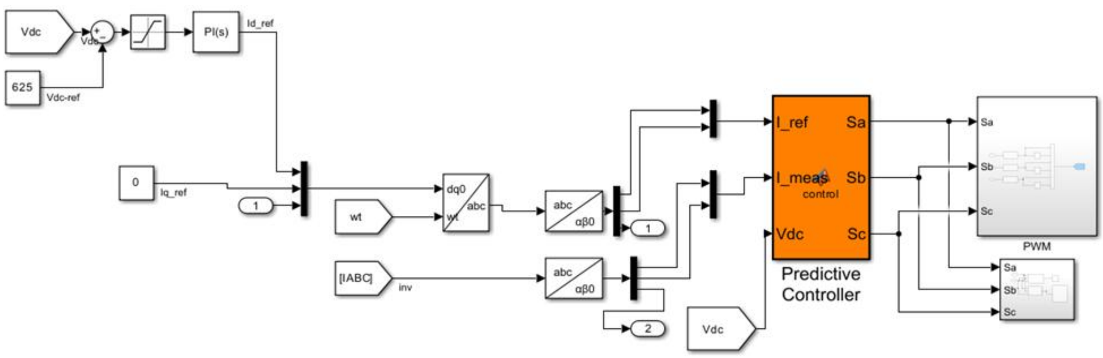


Figure 1. Model predictive control strategy of PV array

3.2. FOC for DFIG rotor converter

In LVRT events, the decoupled control of the rotor currents and is necessary to control the electromagnetic torque and the reactive power of the DFIG as illustrated in Figure 2. The torque reference under voltage dip is based on MPPT of wind turbine model such that the DFIG operates in an efficient manner despite the poor condition of grid [20].

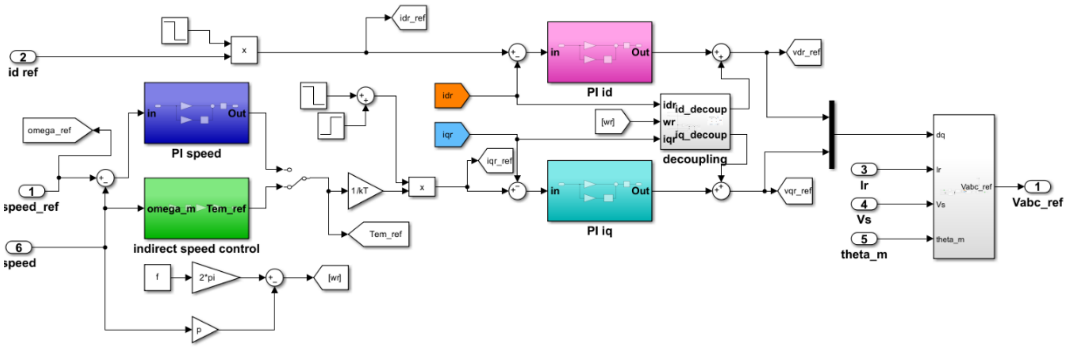


Figure 2. Field-oriented control strategy (FOC) for RSC of DFIG wind turbine

3.2.1. Control laws for rotor currents

The rotor converter control laws for the DFIG can be expressed as follows:

- Quadrature current reference and direct current reference:

$$i_{rq}^{*} = \frac{T_e^{*}}{\frac{3}{2} p L_m i_{sd}} = \tag{13}$$

$$i_{rd}^{*} = \frac{Q^{*}}{\frac{3}{2} p L_m \frac{i_{sq}}{\omega_s - \omega_r}} \tag{14}$$

Where: i_{rq}^{*} *and* i_{rd}^{*} is the reference signal for the quadrature and direct axis current, respectively. T_e^{*} is the electromagnetic torque reference, Q^{*} is the reactive power reference? In the (FOC) strategy, the rotor current references are defined as $\mathrm{i}_{\mathrm{rd}}^{*}$ and $\mathrm{i}_{\mathrm{rq}}^{*}$ which represent the direct and quadrature axis signals, respectively. These are derived from the electromagnetic torque reference ($\mathrm{T}_{\mathrm{e}}^{*}$) and the reactive power reference (Q^{*}). As illustrated in Figure 2, the FOC algorithm executes the following core functions:

- Decoupled control: The strategy independently regulates the d-axis current i_{rd} for reactive power and the q-axis current i_{rq} for torque. This decoupling is essential for system stability [20].
- Torque reference (MPPT): $\mathrm{T}_{\mathrm{e}}^{*}$ is calculated via a maximum power point tracking (MPPT) algorithm to extract maximum energy based on real-time wind velocity.

- Reactive power support: Q^* is set according to grid requirements, ensuring the DFIG provides voltage support during anomalies- a critical factor for grid stability during low-voltage events.
- Crowbar protection: To safeguard the rotor side converter (RSC) from over-currents during deep voltage sags, a crowbar circuit is activated if rotor current components exceed a threshold I_{max} :

$$|i_{rd}| > I_{max} \text{ or } |\, i_{rq}| > \tag{15}$$

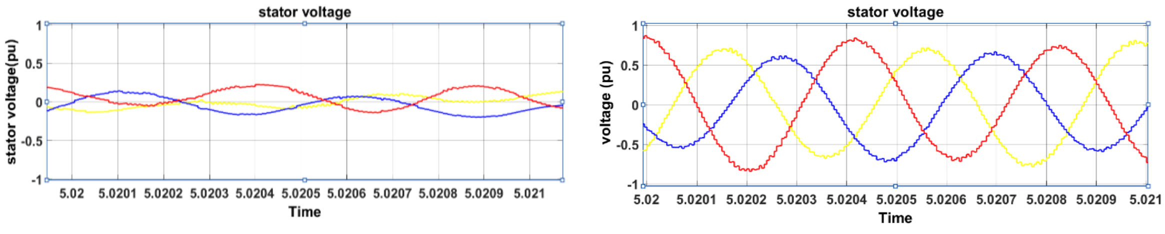
- LVRT enhancement: This integrated scheme ensures that both PV inverters and DFIGs maintain stable operation during grid faults, providing critical grid assistance while protecting internal power electronics [21]. In the event of a grid fault, the system employs a multi-staged operational strategy starting with MPC-based fast response support [22], where the PV inverter quickly injects reactive power $Q_{PV} = K_{MPC}$ $*(V_{ref}$ - V) to stabilize the DC-link and mitigate voltage drops. Simultaneously, torque control via FOC maintains constant electromagnetic torque (T_e) by decoupling active and reactive power, allowing the DFIG to remain stable despite grid perturbations [23]. If rotor currents exceed safe thresholds, crowbar engagement triggers to redirect current through resistors, protecting the rotor-side converter from damage during severe sags. Finally, once the grid voltage recovers to above 0.7 V_{nom}, the system transitions to resuming reactive injection, providing negative reactive power back into the grid to ensure a smooth return to normal operation and continuous renewable energy integration [24].

4. SIMULATION RESULTS AND DISCUSSION
4.1. Simulation results

The hybrid PV-DFIG system was modeled in MATLAB/Simulink (R2024b) to evaluate its low-voltage ride-through (LVRT) capability. The system was subjected to a severe grid disturbance with the simulation parameters and protection thresholds detailed in Table 1. A primary observation is that the conventional DFIG system exhibits catastrophic failure during a grid fault, with its stator voltage collapsing to approximately 0.2 pu and severe waveform distortion (THD >20%), as shown in Figure 3(a). In stark contrast, the proposed hybrid strategy regulates the stator voltage at a stable 0.7 pu with a high-quality sinusoidal waveform (THD <5%), as illustrated in Figure 3(b). This shift from vulnerability to resilience transforms the DFIG from a grid liability into a grid-supporting asset that adheres to modern codes by maintaining stability and power quality during transients.

Table 1. Simulation parameters of LVRT enhancement strategies

Parameter	Value/condition
Fault type	Three-phase symmetrical grid fault
Fault timing	t = 5.0 s to t = 5.5 s
System recovery	t = 6.17 s
Reactive injection resume	V_{grid} > 0.7 p.u
PV inverter constraints	$u_{min} \leq u_k \leq u_{max}$, $V_{min} \leq V_i(k) \leq V_{max}$
Stator voltage limit	0.7 p.u.

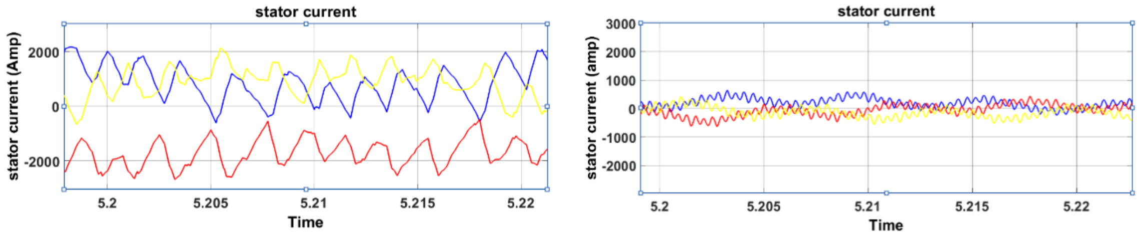


(a) (b)

Figure 3. Comparative performance of the stator voltage (pu) during a grid fault: (a) under the conventional control strategy and (b) under the proposed hybrid PV-DFIG strategy

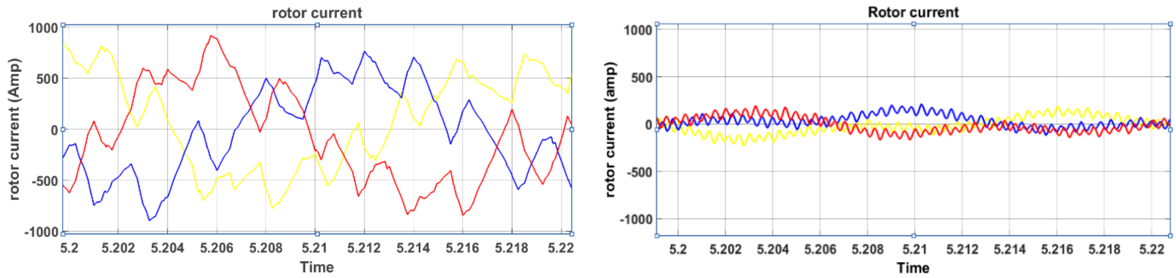
The immense current (2000a), as shown in Figure 4(a), far exceeding the machine's rated value, subjects the stator to critical thermal stress due to Joule heating (which increases with the square of the current), risking rapid insulation degradation and potential burnout. In contrast, the proposed system's stator current in Figure 4(b) is limited to a sinusoidal safe 700 amps, balanced waveform. This dramatic improvement is a direct result of the coordinated control strategy, which stabilizes the electromagnetic field and prevents the uncontrolled energy transfer that causes current surges, thereby ensuring the stator's thermal and structural integrity.

The threat is even more acute for the rotor circuit, where the conventional system's current, depicted in Figure 5(a), peaks at 800 amps with a highly distorted shape. This destructive surge is forced through the vulnerable semiconductor switches IGBTs of the RSC, which are designed for much lower operational currents. The 800-amp peak almost certainly exceeds the absolute maximum rating of these components, risking immediate failure modes like latch-up or thermal runaway, which would destroy the converter. The proposed strategy, evidenced by the rotor current in Figure 5(b), is limited to a safe 100 amps and a clean sinusoidal wave, successfully mitigating this danger. The crowbar circuit provides initial passive protection, while the active support from the PV inverter manages the machine's flux, collectively preventing the dangerous overvoltage in the rotor that drives the current surge. This ensures the RSC operates within its safe limits and the survival of the most critical and expensive power electronic components in the system.



(a) (b)

Figure 4. Comparative performance of the stator current during a grid fault: (a) under the conventional control strategy and (b) under the proposed hybrid PV-DFIG strategy



(a) (b)

Figure 5. Comparative performance of the rotor current during a grid fault: (a) under the conventional control strategy and (b) under the proposed hybrid PV-DFIG strategy

Conventional rotor speed in Figure 6(a) shows large overshoot (224 rad/s) with unstable oscillations, causing severe mechanical stress and accelerated fatigue. The proposed strategy maintains a stable speed (210 rad/s) in Figure 6(b) with minimal overshoot and fast settling, demonstrating superior disturbance rejection. Similarly, conventional torque exhibits violent oscillations, causing shaft knocking, while the proposed system maintains stable torque for gearbox protection.

The proposed hybrid PV-DFIG strategy demonstrates a transformative LVRT enhancement, maintaining stable, grid-compliant operation where conventional systems fail. As quantitatively summarized in Table 2, this performance is highly competitive against more complex crowbar-less configurations [6], [19]. Furthermore, by integrating robust control logic and optimized cost functions, the strategy offers a superior balance of performance, cost, and reliability [25]-[27], ensuring both parametric stability and strict adherence to international grid standards. Ultimately, this approach provides a more practical and computationally efficient alternative to high-end AI-based schemes [28], [29], making it ideal for real-world industrial deployment.

4.2. Novelty and distinction

This paper introduces a coordinated multi-objective control strategy that transforms the hybrid system from a passive fault survivor to an active grid supporter. The novelty manifests in three key aspects:

- Priority-based reactive power orchestration: MPC-controlled PV inverters provide optimized reactive power support through constraint-aware cost functions, enabling net reactive power contribution during faults - overcoming the traditional crowbar's reactive power consumption limitation.
- Decoupled control architecture: The strategy creates distinct control roles: PV handles reactive support while DFIG focuses on torque/speed stability, preventing FOC performance degradation during asymmetrical faults.
- Grid-code compliant power quality: The coordinated control maintains sinusoidal waveforms and low THD during severe faults, achieving compliant power quality rather than mere stability survival. The innovation lies not in individual components but in their system-level integration, creating a synergistic grid-supporting asset during transients.

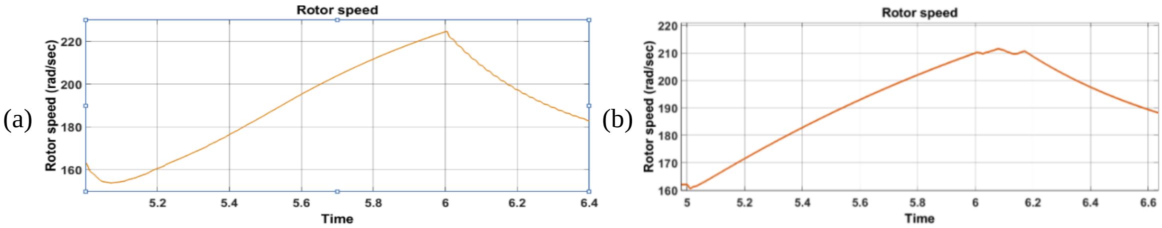


Figure 6. Comparative performance of mechanical speed during a grid fault: (a) under the conventional control strategy and (b) under the proposed hybrid PV-DFIG strategy

Table 2. Comparative analysis of LVRT enhancement strategies

Feature	Conventional DFIG	Proposed MPC-FOC	Crowbar-less	AI-based control
Fault response	Disconnects from the grid (fails LVRT)	Stays connected; very fast reaction	Stays connected; seamless control	Stays connected; performance varies
Control during fault	Uncontrolled (crowbar activated)	Excellent control after crowbar use	Full, continuous control	Adaptive, but can be slow/unpredictable
(THD)	Very high (>20%)	Low (<5%)	Very low (<2%)	Variable

4.3. Robustness, grid compliance, and fault management

While the proposed strategy demonstrates excellent simulated performance, successful practical deployment necessitates addressing parametric sensitivity, grid code compliance, and advanced fault management. Parametric sensitivity remains a challenge as both FOC and MPC rely on precise modeling; FOC is notably sensitive to rotor resistance and mutual inductance variations, which can lead to decoupling loss, while MPC performance can degrade due to prediction model inaccuracies, suggesting a need for future integration of adaptive techniques like model reference adaptive system (MRAS) or robust MPC formulations [25]. Furthermore, ensuring explicit compliance with international standards such as NERC PRC-024 and the German grid code is essential, requiring future control logic to embed specific LVRT curves and standardized reactive current requirements ($I_q^* = k * (0.9 - V_g)*I_{rated}$) directly into the MPC cost function [26], [27]. Finally, transitioning from basic overcurrent protection to advanced fault management using FFT or wavelet-based detection would allow for millisecond-level fault classification and conditioned responses based on fault type and location, ultimately optimizing crowbar engagement and reactive power support to enhance overall system resilience and availability [28], [29].

5. CONCLUSION

This study demonstrates that the proposed hybrid system, combining a DFIG wind turbine with a PV array using coordinated MPC and FOC, significantly outperforms a conventional DFIG system during grid faults. The key findings are i) Superior grid support: The system successfully achieved LVRT, maintaining a stable stator voltage (70% of nominal) during a severe fault, whereas the conventional system collapsed (20% of nominal); ii) Effective component protection: The coordinated control drastically limited dangerous current surges in the stator and rotor, protecting the vulnerable power electronics; and iii) Improved system stability: The proposed strategy resulted in a more stable rotor speed and eliminated heavy torque oscillations, ensuring smoother mechanical operation. In essence, this hybrid MPC-FOC strategy is a highly effective solution for maintaining grid connection and stability during faults, proving essential for the reliable, large-scale integration of renewable energy.

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AUTHOR CONTRIBUTIONS STATEMENT

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Kassim A. Al-Anbarri	✓	✓				✓	✓		✓	✓		✓		

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

The authors declare that they have no conflict of interest.

DATA AVAILABILITY

The authors confirm that the data supporting the findings of this study are available within the article.

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