

Transmission and Distribution Smart Grid System Based on Self-Hailing Controllable Crowbar

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Abstract: *The modernization of electrical power networks has intensified the adoption of smart grid technologies to ensure secure, reliable, and efficient energy delivery under dynamic operating conditions. Nevertheless, fault disturbances in hybrid renewable energy systems may significantly degrade voltage stability and interrupt continuous power transmission. This study presents a self-healing smart transmission and distribution framework employing a controllable crowbar integrated with hybrid photovoltaic and wind energy sources. A fuzzy logic-based protection strategy is utilized to identify fault conditions through continuous monitoring of transmission line current and DC-link voltage, thereby enabling autonomous activation of the crowbar protection mechanism. The proposed framework is developed and analyzed in the MATLAB/Simulink environment under multiple fault scenarios. Simulation outcomes demonstrate enhanced fault mitigation capability, improved voltage regulation, accelerated system recovery, and increased operational reliability, highlighting the effectiveness of the proposed approach for resilient smart grid applications.*

Keywords: Intelligent Smart Grid, Hybrid Renewable Energy Integration, Self-Healing Protection, Adaptive Crowbar Control, Fuzzy Logic-Based Fault Detection, Doubly-Fed Induction Generator (DFIG), Power System Resilience

1. Introduction

The continuous growth in global electricity demand and the increasing penetration of renewable energy resources have accelerated the transition from conventional power systems to intelligent smart grid infrastructures [1]. Smart grid technology integrates advanced sensing, communication, automation, and control mechanisms to enhance the reliability, efficiency, and operational flexibility of electrical transmission and distribution networks [2]. Furthermore, the incorporation of renewable energy sources, particularly photovoltaic (PV) and wind generation systems, has become an essential strategy for reducing greenhouse gas emissions and ensuring sustainable energy production [3]. However, the intermittent characteristics of renewable energy resources introduce several operational challenges, including voltage fluctuations, power quality degradation, and reduced grid stability during abnormal operating conditions [4].

Power system disturbances such as single-line-to-ground and double-line-to-ground faults may significantly affect the dynamic performance of transmission and distribution networks by producing excessive fault current, voltage instability, and equipment stress [5]. Among renewable energy conversion technologies, the Doubly-Fed Induction Generator (DFIG) has been extensively adopted in wind energy systems because of its high efficiency and flexible power control capability. Nevertheless, DFIG-based systems remain highly vulnerable to voltage dips and grid faults, making the development of effective protection mechanisms an important research objective [6].

To improve the fault tolerance capability of hybrid renewable energy systems, this paper proposes a self-healing smart transmission and distribution framework incorporating a controllable crowbar protection scheme with hybrid PV-wind generation [7]. A fuzzy logic controller continuously supervises transmission line current and DC-link voltage to identify abnormal operating conditions and automatically activate the crowbar during fault events. The proposed protection strategy minimizes excessive fault current, safeguards the DFIG converter, and restores stable system operation immediately after fault clearance without requiring manual intervention [8].

The proposed framework is developed and validated using the MATLAB/Simulink environment under different fault conditions to evaluate its effectiveness in enhancing voltage stability, fault ride-through capability, and overall system reliability. The obtained simulation results demonstrate that the proposed intelligent protection approach provides improved transient performance and contributes to the development of resilient and reliable smart grid transmission and distribution systems [9].

2. Related Work

Recent advancements in smart grid technology have focused on improving the reliability, efficiency, and resilience of electrical power systems through intelligent monitoring, automation, and renewable energy integration. Several studies have reported that smart grids enable real-time fault

monitoring, adaptive energy management, and enhanced operational flexibility, thereby supporting the growing penetration of distributed energy resources [10]. Nevertheless, maintaining stable grid operation during severe fault conditions remains a significant challenge because renewable energy sources exhibit intermittent generation characteristics [11].

Hybrid photovoltaic (PV) and wind energy systems have been widely investigated to enhance renewable energy utilization and ensure continuous power generation. Recent research has demonstrated that hybrid configurations improve energy availability, reduce dependence on conventional power generation, and increase overall system efficiency [12]. However, voltage instability, transient disturbances, and power quality degradation continue to affect system performance under abnormal operating conditions [13].

To enhance the dynamic performance of renewable energy systems, intelligent control strategies based on fuzzy logic and adaptive optimization techniques have been extensively explored [14]. These approaches improve voltage regulation, reactive power support, and fault ride-through capability compared with conventional control methods. Furthermore, advanced protection strategies have been developed to safeguard Doubly-Fed Induction Generator (DFIG)-based wind energy systems during grid disturbances [15]. Although these methods improve converter protection and transient stability, most existing studies primarily emphasize energy management or converter control rather than integrating intelligent self-healing protection with controllable crowbar mechanisms [16].

Therefore, the development of an integrated self-healing smart transmission and distribution framework that combines hybrid PV–wind generation, fuzzy logic-based fault detection, and controllable crowbar protection remains an important research direction for improving grid stability, operational reliability, and fault resilience under dynamic operating conditions.

3. Mathematical Expressions

The proposed self-healing smart transmission and distribution system is mathematically formulated using the governing equations of the hybrid photovoltaic (PV)-wind energy conversion system, the Doubly-Fed Induction Generator (DFIG), and the controllable crowbar protection mechanism. These mathematical formulations describe the electrical characteristics of the proposed framework and support the evaluation of system performance under both normal and fault operating conditions.

The electrical power generated by the photovoltaic array is determined by

$$P_{PV} = V_{PV} I_{PV} \quad (1)$$

where P_{PV} represents the PV output power, V_{PV} denotes the output voltage, and I_{PV} represents the output current.

The output current of the photovoltaic array is expressed as

$$I = I_{ph} - I_o \left(e^{\frac{q(V+IR_s)}{nkT}} - 1 \right) \quad (2)$$

where I_{ph} is the photocurrent, I_o is the reverse saturation current, R_s is the series resistance, q is the electron charge, k is the Boltzmann constant, T is the operating temperature, and n is the diode ideality factor.

The mechanical power captured from the wind turbine is calculated as

$$P_{WT} = \frac{1}{2} \rho A C_p V^3 \quad (3)$$

where ρ denotes the air density, A is the rotor swept area, C_p is the power coefficient, and V is the wind velocity.

The tip-speed ratio governing wind turbine operation is represented as

$$\lambda = \frac{\omega R}{V} \quad (4)$$

where ω denotes the rotor angular speed, R represents the blade radius, and V is the wind speed.

The active power generated by the DFIG is expressed as

$$P = VI \cos \phi \quad (5)$$

where V represents the terminal voltage, I denotes the current, and ϕ is the power factor angle.

The reactive power supplied by the DFIG is represented by

$$Q = VI \sin \phi \quad (6)$$

where Q denotes the reactive power delivered to the grid.

The controllable crowbar protection circuit is activated whenever

$$I_r > I_{th} \quad (7)$$

where I_r denotes the rotor current and I_{th} represents the predefined protection threshold.

The DC-link voltage stability criterion is expressed as

$$V_{dc} > V_{dc}^{ref} \quad (8)$$

where V_{dc} is the measured DC-link voltage and V_{dc}^{ref} is the reference DC-link voltage used by the protection controller. These mathematical formulations provide the analytical basis for evaluating the effectiveness of the proposed self-healing protection strategy under different fault conditions.

4. Proposed Methodology

The proposed methodology presents an intelligent self-healing smart transmission and distribution framework by integrating hybrid photovoltaic (PV) and wind energy sources with a Doubly-Fed Induction Generator (DFIG) to enhance power system reliability during grid disturbances. As illustrated in Fig. 1, the photovoltaic array and wind energy conversion system jointly supply electrical power to the utility grid through power electronic converters and transformer units. The DFIG regulates active and reactive power, while the DC-link maintains stable power transfer between the rotor-side and grid-side converters, ensuring continuous operation under varying load conditions.

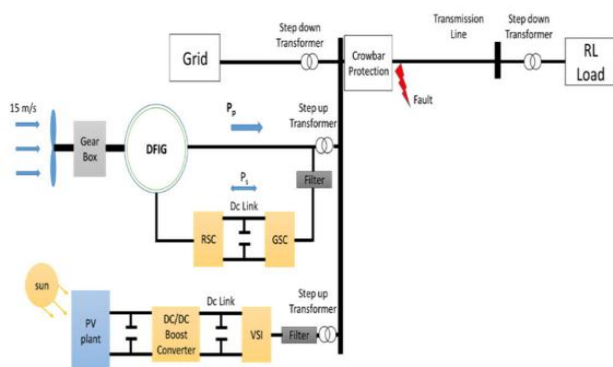


Figure 1: Proposed hybrid PV-wind system architecture

To improve fault tolerance, an intelligent fuzzy logic controller is incorporated into the proposed framework, as shown in Fig. 2. The controller continuously evaluates the system operating conditions using predefined fuzzy rules and generates an appropriate control signal for the controllable crowbar circuit. During abnormal operating conditions, the crowbar is automatically activated to suppress excessive rotor current, protect the DFIG converter, and improve fault ride-through capability, thereby maintaining voltage stability and reducing system disturbances.

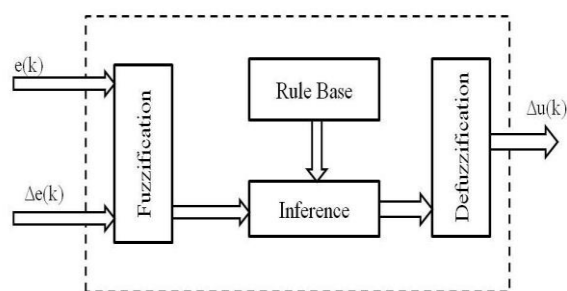


Figure 2: Fuzzy logic control framework

The complete system is implemented and validated in the MATLAB/Simulink environment, as presented in Fig. 3. The simulation model integrates the hybrid renewable energy sources, DFIG, fuzzy logic controller, and crowbar protection into a unified platform for performance evaluation under different fault conditions.

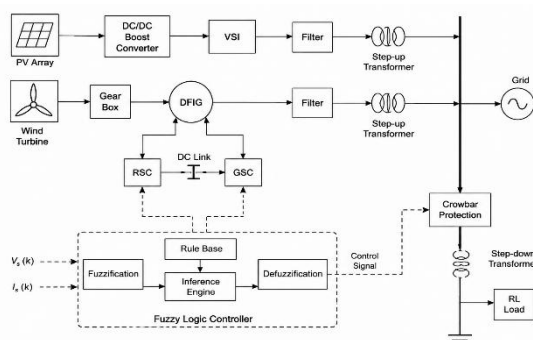


Figure 3: MATLAB/Simulink implementation of the proposed system

The principal simulation parameters adopted for system implementation are summarized in Table I.

Table I: Simulation Parameters

Parameter	Value
PV Rated Power	30 kW
DFIG Rated Power	1 MW
Grid Voltage	220 kV
Grid Frequency	50 Hz
DC-DC Converter	58 μ H, 2.2 mF
Load Rating	400 V, 60 kW

The selected parameters establish the operating environment for assessing the effectiveness of the proposed self-healing protection framework under different grid fault conditions.

5. Results and Discussion

The proposed self-healing hybrid photovoltaic (PV)-wind energy system was validated through MATLAB/Simulink under both normal and fault operating conditions to assess its dynamic performance and protection capability. The simulation results demonstrate the effectiveness of the proposed fuzzy logic-assisted crowbar strategy in maintaining system stability and ensuring reliable grid operation during transient disturbances.

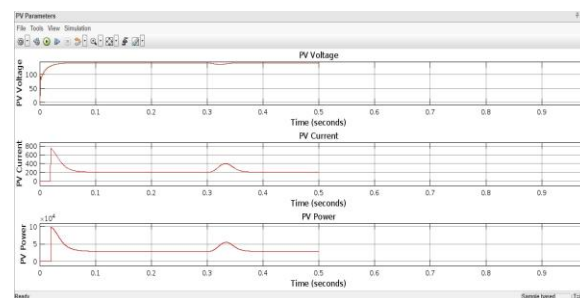


Figure 4: Dynamic response of the photovoltaic system

Figure 4 presents the voltage, current, and power characteristics of the photovoltaic array. The PV system rapidly reaches steady-state operation after initialization, while only minor transient variations are observed during the fault interval. The proposed control strategy effectively restores the operating condition, indicating stable renewable power generation.

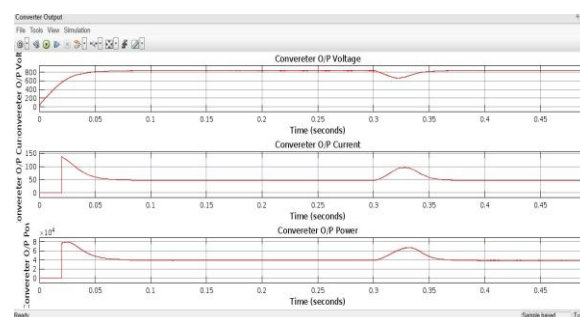


Figure 5: Performance characteristics of the DC-DC converter

Figure 5 illustrates the output voltage, current, and power of the DC-DC converter. The converter maintains regulated power transfer under normal operating conditions and exhibits rapid recovery following transient disturbances, thereby supporting continuous energy delivery to the grid.

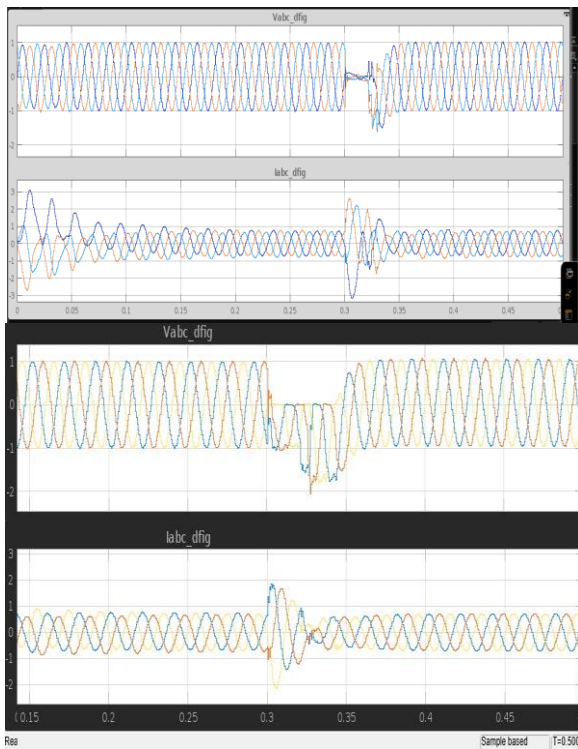


Figure 6: Dynamic response of the DFIG under fault conditions

As illustrated in Fig. 6, the DFIG voltage and current exhibit a noticeable transient variation during the fault interval, indicating the influence of the grid disturbance on the generator dynamics. Following the activation of the proposed fuzzy logic-assisted crowbar protection, the oscillatory behaviour is effectively attenuated, and both voltage and current gradually return to their steady-state operating conditions. This response demonstrates the capability of the proposed protection strategy to enhance transient stability while reducing electrical stress on the DFIG components.

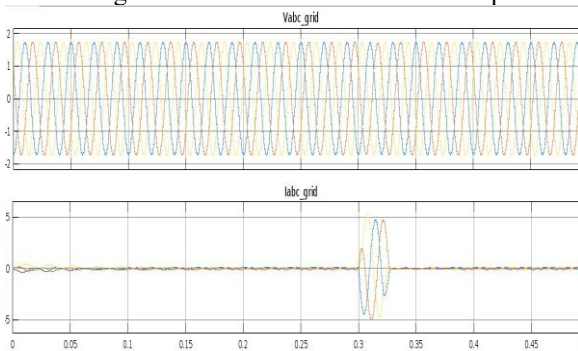


Figure 7: Grid voltage and current response during fault recovery

As depicted in Fig. 7, the three-phase grid voltage remains stable under normal operating conditions, while the grid current experiences a temporary disturbance during the fault interval. Following the operation of the proposed protection mechanism, the transient current oscillations are rapidly suppressed, enabling the system to regain stable operation within a short duration. The coordinated control of the DFIG and crowbar protection contributes to improved power quality, enhanced fault ride-through capability, and reliable grid operation.

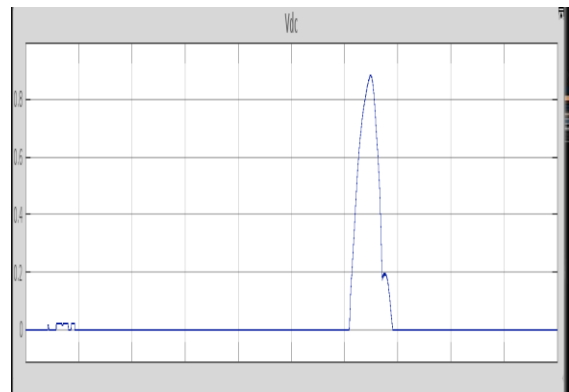


Figure 8: DC-link voltage response of the proposed system

As shown in Fig. 8, the DC-link voltage exhibits a temporary transient during the fault interval before rapidly returning to its steady-state operating condition. The proposed fuzzy logic-assisted crowbar protection effectively regulates the DC-link voltage, thereby maintaining stable power exchange between the renewable energy sources and the utility grid while improving the transient stability of the overall system.

Table II: Comparative performance analysis

Parameters	Peak overshoot		Settling time	
	Conventional	Proposed	Conventional	Proposed
DC link voltage	1220V	1160V	0.45s	0.37s
Stator current	2.2	1.9	0.45s	0.345s
Crowbar current	1100A	2300A	0.34s	0.33s
Rotor speed	1.4pu	1.12pu	0.44s	0.36s

The comparative evaluation confirms that the proposed fuzzy logic-based crowbar strategy enhances the dynamic performance of the hybrid renewable energy system when compared with the conventional protection approach. The simulation results demonstrate improvements in voltage regulation, transient stability, fault response, and overall system reliability, validating the effectiveness of the proposed framework for intelligent smart transmission and distribution applications.

6. Conclusion and Future Scope

The proposed self-healing hybrid photovoltaic (PV)-wind energy framework integrating a Doubly-Fed Induction Generator (DFIG), fuzzy logic controller, and controllable crowbar protection demonstrated improved dynamic performance under grid fault conditions. The simulation results verified enhanced voltage regulation, effective fault mitigation, and reliable system operation when compared with the conventional approach. Future research may investigate the integration of advanced artificial intelligence techniques, energy storage technologies, and real-time hardware validation to further improve the adaptability and practical implementation of intelligent smart grid systems.

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