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Evaluation of the Contingencies of Interconnecting Wind Production into an Existing Distribution Network

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***Abstract*—In recent years, the demand for renewable energy sources, particularly wind power, has increased significantly. In Portugal, government projections estimate a 10 GW increase in offshore wind capacity by 2030, tripling the current installed capacity. This expansion, alongside the repowering of existing onshore wind farms, will introduce substantial challenges for power networks. Some wind farms will connect to the transmission grid, while many others will be integrated into the distribution network, where infrastructure limitations could lead to operational constraints. Given the expected rise in power flow pressure, reinforcement of transmission and distribution networks will be required. Initially, the energy evacuation will rely on existing networks, which may face significant constraints under extreme load conditions. Therefore, contingency analysis, particularly under "n-1" scenarios, is crucial to assess grid resilience. This paper presents a real-case study analyzing the contingency impacts of integrating offshore and onshore wind farms into an existing 60 kV distribution network. The results highlight significant infrastructure vulnerabilities, principally line overloads in specific scenarios, emphasizing the urgent need for targeted network reinforcements, real-time monitoring systems, and dynamic optimization strategies to ensure stable wind power integration and prevent cascading failures.**

***Index Terms*—Contingency analysis, n-1 criterion, power distribution, wind energy integration, power system resilience.**

I. INTRODUCTION

Renewable energy sources, especially wind power, have experienced rapid growth, posing technical and operational challenges for electrical distribution networks originally designed for centralized generation. In Portugal, wind energy, particularly offshore, is projected to add an extra 10 GW of capacity by 2030. Additionally, existing onshore wind farms may experience turbine upgrades, further stressing distribution networks that frequently lack sufficient robustness and capacity.

Furthermore, integrating renewable sources effectively into distribution networks demands accurate forecasting methods. Recent comparative studies highlight the importance of aligning theoretical wind forecasts with actual generation data to identify discrepancies and enhance planning accuracy. Such analysis is essential to anticipate network stress and prevent contingencies caused by renewable power variability [1].

Recent international studies have addressed the integration of large-scale offshore wind into transmission networks. The North Sea Wind Power Hub project evaluated meshed and radial topologies, highlighting the role of hybrid interconnectors in enhancing system resilience and cost efficiency, as presented in [2]. Reference [3] compares electric and hydrogen-based transmission systems, showing that hybrid solutions can offer advantages depending on distance and scale. From a planning perspective, the study in [4] proposes a multi-objective transmission expansion model that balances cost, flexibility, and environmental impact. While these contributions focus on transmission-level integration, the present work complements them by analyzing the resilience of a real distribution network under contingency conditions resulting from wind power inte-

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gration.

An analysis is conducted on the behavior of a real 60 kV distribution network in Portugal, integrating multiple wind power producers. Although these producers have significant installed capacities, their scale typically does not justify direct connection to the transmission grid. Therefore, connecting wind and solar resources to distribution networks is often the most practical solution, promoting the increase of decentralized generation [5]. Distribution networks generally offer more accessible integration points due to their greater geographic coverage and adaptability for expansions and modifications [6], [7]. Nevertheless, such networks frequently face structural constraints arising from incremental expansions and the coexistence of various transmission line types. The network analyzed in this study integrates multiple wind farms that do not have the scale for direct connection to the transmission system, despite their high installed capacity. However, these networks frequently exhibit structural limitations resulting from incremental expansions, introducing different transmission line types. This study evaluates the resilience of such a network under extreme conditions, particularly focusing on "n-1" contingency scenarios.

This context sets the basis for a detailed contingency assessment of the existing 60 kV distribution grid, highlighting its exposure to failures under high renewable penetration. Decentralized generation is increasing, making the assessment of network resilience essential. The study specifically focuses on assessing network vulnerabilities through contingency analyses, emphasizing critical "n-1" scenarios derived from real operational data. In addiction, the nodal analysis methodology adopted in this work is particularly suitable for detailed contingency assessments at the distribution level, providing valuable insights into voltage stability and line loading in a real operational environment.

The following sections detail the methodology, including the power flow model, network constraints, and definition of the extreme operational scenarios considered [8]. Subsequently, simulation results are presented and analyzed to highlight potential network vulnerabilities and suggest necessary improvements for enhancing reliability and resilience.

II. METHODOLOGY

The resilience of a real 60 kV distribution network in Portugal was evaluated under extreme operational conditions (Fig. 1). Multiple wind farms with significant installed capacities were integrated into this existing network, where the direct connection to the transmission grid was not justified. The analysis evaluates network stability through contingency scenarios using the "n-1" criterion. The methodology includes developing a power flow model, defining realistic extreme scenarios of generation and load, and identifying critical contingencies based on actual operational data. The simulations were conducted using MATLAB tool to model the power flow equations and evaluate network resilience.

A power flow model was implemented using nodal analysis, considering active and reactive power balance at each bus. The network's admittance matrix was formulated to capture the relationships between buses and transmission elements. The simulations evaluated voltage stability and current loading across transmission lines. Contingency scenarios were tested using an iterative power flow solver, identifying voltage deviations and overload conditions.

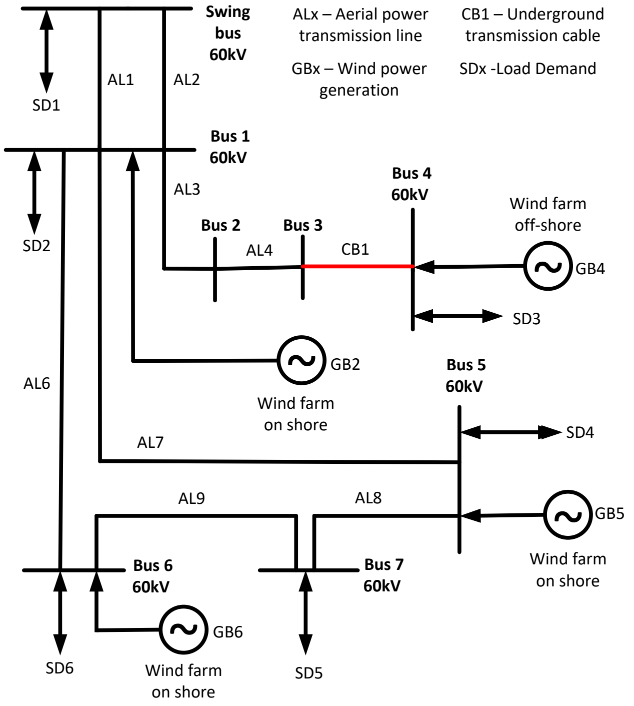

Fig. 1. Single-line diagram of the case study network, including injection and consumption points.

The reliability of power systems can be classified into different operational states, as illustrated in Fig. 2 [9], [10]. Under normal operating conditions, the system functions within safe margins. However, a disturbance such as an equipment failure or an unexpected generation drop can transition the network into an alert state ("n-1" condition). If the system cannot recover or further failures occur, it may escalate into an emergency state ("n-2" condition), leading to load loss and potential blackout. This study focuses on evaluating the system's transition from alert to emergency under different contingency scenarios.

The transition from an alert to an emergency state can occur rapidly, especially in distribution networks where automation at the 60 kV level is available but less developed at lower voltage levels (e.g., 30 kV and 15 kV). This lack of automation can lead to prolonged outages following major contingencies [11]. To assess these risks, this study simulates multiple extreme operational conditions, including peak load and high-generation scenarios, while evaluating system vulnerabilities.

A. Power Flow Model

The power flow equations were formulated using a nodal analysis approach (Fig. 3), defining injected currents at each

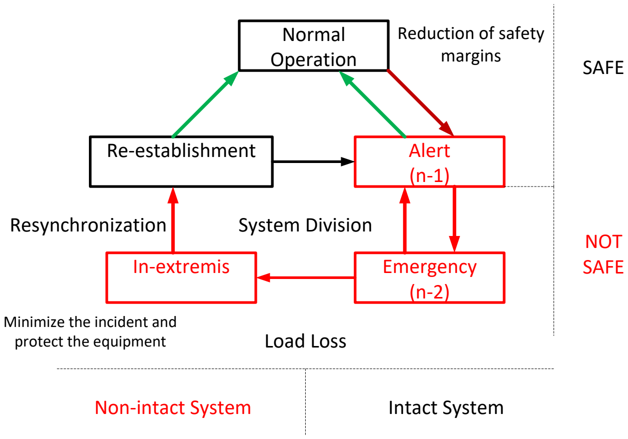

Fig. 2. Possible operational states of a power system.

network node [12]. Given the complexity and structure of the 60 kV distribution network under analysis, nodal representation was employed to effectively capture interactions between buses and to accurately identify network vulnerabilities during critical "n-1" contingency events.

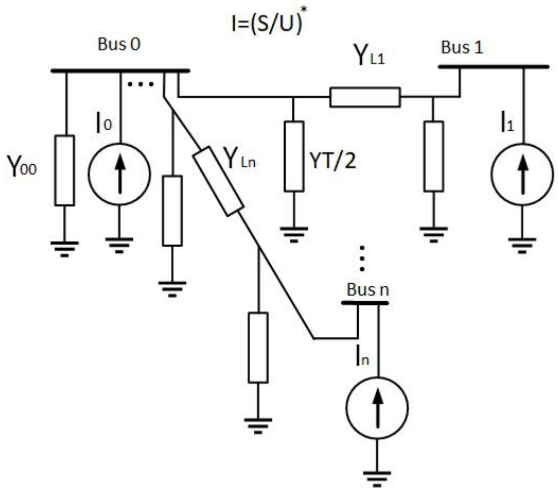

Fig. 3. Nodal representation of a power system, illustrating bus connections, admittance elements, and injected currents.

Node *0* serves as the reference node with a known voltage magnitude and phase angle. The mathematical model is represented by:

$$\begin{bmatrix} I_0 \\ \vdots \\ I_7 \end{bmatrix} = \begin{bmatrix} Y_{00} & \dots & Y_{07} \\ \vdots & \ddots & \vdots \\ Y_{70} & \dots & Y_{77} \end{bmatrix} \begin{bmatrix} U_0 \\ \vdots \\ U_7 \end{bmatrix} \tag{1}$$

This model is used to analyze how different network elements respond under normal and contingency conditions, helping to determine which lines or substations are at higher risk of failure.

Due to the network's topology, the admittance matrix $[Y]$ contains several null elements, reflecting the absence of direct connections between certain buses:

$$[Y] = \begin{bmatrix} Y_{00} & Y_{01} & 0 & 0 & 0 & 0 & 0 & 0 \\ Y_{10} & Y_{11} & Y_{12} & 0 & 0 & 0 & Y_{16} & 0 \\ 0 & Y_{21} & Y_{22} & Y_{23} & 0 & 0 & 0 & 0 \\ 0 & 0 & Y_{32} & Y_{33} & Y_{34} & 0 & 0 & 0 \\ 0 & 0 & 0 & Y_{43} & Y_{44} & Y_{45} & 0 & 0 \\ 0 & 0 & 0 & 0 & Y_{54} & Y_{55} & Y_{56} & 0 \\ 0 & Y_{61} & 0 & 0 & 0 & Y_{65} & Y_{66} & Y_{67} \\ 0 & 0 & 0 & 0 & 0 & 0 & Y_{76} & Y_{77} \end{bmatrix} \tag{2}$$

The power flow equations for active (P_i) and reactive (Q_i) power are expressed as:

$$P_i = U_i \sum_{j=0}^{7} U_j \left[G_{ij} \cos(\delta_i - \delta_j) + B_{ij} \sin(\delta_i - \delta_j) \right] \tag{3}$$

$$Q_i = U_i \sum_{j=0}^{7} U_j \left[G_{ij} \sin(\delta_i - \delta_j) - B_{ij} \cos(\delta_i - \delta_j) \right] \tag{4}$$

Here, G_{ij} and B_{ij} are respectively the longitudinal and transversal admittance elements between buses, while voltage magnitudes and angles are represented by U_i and δ_i.

Transmission lines were modeled using the π-model, and their parameters, including thermal limits, are detailed in Tables I and II, respectively.

TABLE I
ELECTRICAL PARAMETERS OF TRANSMISSION LINES

Line	**R (Ω/km)**	**R0 (Ω/km)**	**L (H/km)**	**L0 (H/km)**	**C (F/km)**	**C0 (F/km)**
AL1	0.059	0.273	5.83E-04	2.86E-03	2.01E-08	7.26E-09
AL2	0.059	0.273	5.83E-04	2.86E-03	2.01E-08	7.26E-09
AL3	0.154	0.356	1.18E-03	4.12E-03	9.69E-09	4.77E-09
AL4	0.125	0.198	1.21E-03	2.59E-03	4.14E-08	8.53E-08
CB1	0.06	0.3	3.50E-04	3.18E-04	2.50E-07	2.50E-07
AL6	0.118	0.332	1.13E-03	3.63E-03	1.03E-08	4.88E-09
AL7	0.059	0.279	6.11E-04	2.86E-03	1.93E-08	7.15E-09
AL8	0.118	0.332	1.13E-03	3.63E-03	1.03E-08	4.88E-09
AL9	0.059	0.279	6.11E-04	2.86E-03	1.93E-08	7.15E-09

TABLE II
THERMAL LIMITS AND LENGTH OF TRANSMISSION LINES

Line	**Length (km)**	**Summer Limit (A)**	**Winter Limit (A)**
AL1	6.7797	769	1089
AL2	6.6102	769	1089
AL3	3.4935	512	578
AL4	5.056	583	659
CB1	1	599	740
AL6	20.11	384	544
AL7	12.051	384	544
AL8	8.0085	384	544
AL9	2.7627	384	544

B. *Flowchart Representation of the Methodology*

To improve clarity and ensure methodological transparency, Fig. 4 presents a flowchart describing the structured process adopted in this study. The workflow begins with the definition of the distribution network's topology and characteristics, including buses, lines, and interconnection points. Subsequently, input data such as generation profiles from wind farms, load demands, and grid parameters are introduced.

A power flow model based on nodal analysis is then developed and used to simulate the steady-state operation of the network. Following this, contingency scenarios based on the "n-1" criterion are simulated, representing the failure of individual transmission lines under different operating conditions.

The next step involves evaluating whether the simulated contingencies lead to overloaded lines. If no overload is detected, the network is considered stable under that specific contingency. However, if overloads occur, a cascading failure analysis is triggered. This step evaluates the secondary effects resulting from the removal of the overloaded line(s), identifying whether additional lines become overloaded and whether the system transitions into an unstable or collapsed state.

Based on the severity of the impacts observed, mitigation strategies are considered. These may include reinforcing specific lines, modifying topologies, or introducing real-time control mechanisms. Finally, the results of the analysis guide a set of technical recommendations to improve the network's resilience and ensure secure integration of wind power under extreme operating conditions.

Figure 4 summarizes this structured methodology, designed to support resilience assessment under high renewable integration.

C. Network and Simulation Scenarios

The resilience of the network was tested by simulating seven extreme operational scenarios (SC1 to SC7), derived from real operational data. These scenarios include combinations of maximum and minimum load and generation conditions, as well as specific cases with isolated active generation units:

- **SC1:** Maximum generation, minimum load.
- **SC2:** Maximum generation, maximum load.
- **SC3:** Minimum generation, maximum load.
- **SC4:** Only generation at BUS2 active.
- **SC5:** Only generation at BUS5 active.
- **SC6:** Only generation at BUS4 active.
- **SC7:** Only generation at BUS6 active.

Tables III and IV present detailed generation and load values for each scenario. The analysis specifically evaluates compliance with the "n-1" contingency criterion, assessing whether the network maintains stability without requiring automatic disconnections or load shedding under critical conditions [13], [14].

III. Results and Discussion

The contingency analysis results provide insights into how the network transitions between operational states depicted in Figure 3. Initial simulations revealed that multiple transmission lines were operating near their thermal limits under normal conditions. When subjected to single-line failures ("n-1" contingencies), specific lines, such as AL7 and AL9,

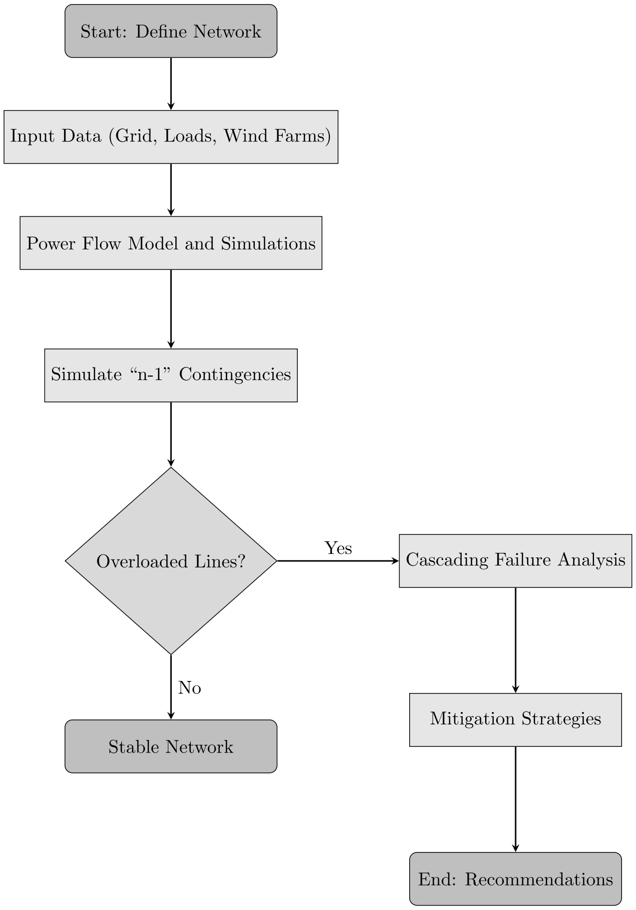

Fig. 4. Flowchart of the contingency analysis methodology.

TABLE III
Generation values for each scenario (kW, kVar)

Scenario	**GB2**	**GB4**	**GB5**	**GB6**
SC1	(-34560, 1470)	(-25163, -606)	(-36500, -80)	(-10830, 960)
SC2	(-34560, 1470)	(-25163, -606)	(-36500, -80)	(-10830, 960)
SC3	(0, 0)	(0, 0)	(0, 0)	(0, 0)
SC4	(-34560, 1470)	(0, 0)	(0, 0)	(0, 0)
SC5	(0, 0)	(0, 0)	(-36500, -80)	(0, 0)
SC6	(0, 0)	(-25163, -606)	(0, 0)	(0, 0)
SC7	(0, 0)	(0, 0)	(0, 0)	(-10830, 960)

TABLE IV
Consumption values for each scenario (kW, kVar)

Scenario	**SD2**	**SD3**	**SD4**	**SD5**	**SD6**
SC1	(0, 0)	(0, 0)	(0, 0)	(0, 0)	(0, 0)
SC2	(28590, 4720)	(17500, 270)	(9950, 130)	(21530, 6830)	(12140, 2280)
SC3	(28590, 4720)	(17500, 270)	(9950, 130)	(21530, 6830)	(12140, 2280)
SC4	(28590, 4720)	(17500, 270)	(9950, 130)	(21530, 6830)	(12140, 2280)
SC5	(28590, 4720)	(17500, 270)	(9950, 130)	(21530, 6830)	(12140, 2280)
SC6	(28590, 4720)	(17500, 270)	(9950, 130)	(21530, 6830)	(12140, 2280)
SC7	(28590, 4720)	(17500, 270)	(9950, 130)	(21530, 6830)	(12140, 2280)

experienced severe overloads, leading to potential network collapse, as seen in Table V.

Further analysis was conducted by removing overloaded lines to assess cascading failures. Table VI summarizes the new overloads observed when an initially overloaded line was removed. Removing a single overloaded line does not resolve the issue; instead, it amplifies system instability. The redistribution of power flow places excessive demand on the remaining lines, pushing them beyond thermal limits and ultimately causing a network blackout.

The contingency analysis reveals critical insights into the network's transition between operational states, as illustrated in Fig. 2. The following sections present key findings and their implications for grid stability and future planning.

A. "n-1" Contingency Analysis

The power flow analysis identified several critical vulnerabilities in the 60 kV distribution network under the simulated "n-1" contingency scenarios. Table V highlights specific transmission lines exceeding their thermal limits across different scenarios, demonstrating significant network constraints. Notably, line AL7 experienced overload conditions repeatedly, reflecting its vulnerability and highlighting a critical infrastructure limitation.

TABLE V
OVERLOADED LINES DETECTED IN CONTINGENCY SCENARIOS

Scenario	Overloaded Line	Max Current (A)	Limit (A)
SC3	AL1	1221.24	1089
SC3	AL2	1252.56	1089
SC3	AL7	755.41	544
SC4	AL7	775.07	544
SC5	AL8	756.78	544
SC6	AL7	762.18	544
SC7	AL9	831.88	544

Line AL7, identified as one of the oldest and most critical lines by the distribution operator, consistently exceeded its thermal capacity under various scenarios (SC3, SC4, SC6). Additionally, scenarios SC3, SC5, and SC7 revealed other critical lines (AL1, AL2, AL8, AL9) surpassing their thermal limits, indicating a broader infrastructure challenge.

The findings emphasize that integrating decentralized renewable generation requires careful and network-specific assessments. The observed overloads indicate the urgent need for specific infrastructure upgrades, such as reinforcing overloaded lines, implementing alternative routing paths to alleviate network pressure. Additionally, real-time monitoring systems should be deployed to proactively manage operational risks and maintain network stability under extreme conditions. The necessary modifications and reconfigurations will demand considerable investments, which must be strategically planned to maintain rigorous quality and service continuity standards.

B. Extended Contingency Analysis

Following the initial identification of overloaded lines in certain contingency scenarios, an additional set of simulations was performed by removing the overloaded lines to assess the cascading effects on the network. The objective was to determine whether removing a single overloaded line would stabilize the system or lead to further instability.

The analysis reveals that removing initially overloaded lines triggers new overloads elsewhere in the network, ultimately resulting in system-wide failure. This outcome highlights the network's limited redundancy, making it highly susceptible to cascading failures.

Table VI presents the scenarios where only one line was initially overloaded and the subsequent overloads that occurred after its removal, ultimately leading to network collapse.

TABLE VI
CASCADING FAILURES AFTER INITIAL OVERLOAD REMOVAL

Scen.	Removed Line	New Overloads	Max Current (A)
SC4	AL7	AL6, AL9	1087.81, 781.26
SC5	AL8	AL6, AL9	865.31, 555.74
SC6	AL7	AL6, AL9	1069.08, 761.81
SC7	AL9	AL7, AL8	854.99, 595.01

The results emphasize that removing a single overloaded line does not alleviate the problem but instead exacerbates system stress. The redistribution of power flow across the remaining lines increases their loading beyond thermal limits, ultimately leading to a system blackout.

C. Implications for Grid Planning and Reinforcement

The findings from this contingency analysis highlight several key aspects relevant for power system operators and planners:

- **Need for Targeted Network Reinforcements:** The network's inability to sustain single-line failures without cascading effects indicates a need for reinforcement of critical lines.
- **Real-Time Monitoring and Adaptive Protection:** Deploying automated monitoring and adaptive protection schemes could prevent progressive overload scenarios [15], [16].
- **Strategic Grid Expansion:** Future expansions must consider redundancy and resilience factors to prevent similar failures in high-renewable penetration scenarios.

These insights reinforce the necessity for continuous assessment and proactive infrastructure investments to ensure reliable wind energy integration into the existing power grid.

Furthermore, the recommendations were generated by identifying recurring overloads and cascading failures across multiple scenarios. Critical lines were identified based on the frequency and severity of their violations, supporting proposals for reinforcement and real-time control measures to mitigate risks under extreme operating conditions.

Finally, this analysis highlights persistent overloads on critical lines such as AL7 and AL9, suggesting immediate practical measures including targeted infrastructure upgrades to relieve operational tension. Additionally, enhancing real-time monitoring and deploying adaptive protection schemes could significantly reduce operational risks associated with cascading failures.

IV. CONCLUSION

A real-case 60 kV distribution network integrating wind power was analyzed, emphasizing the challenges posed by decentralized renewable generation. The findings reveal that existing networks require careful planning when interconnecting wind farms, as they often lack sufficient robustness to resist extreme scenarios.

Distribution networks are widely deployed across the terrain, making it economically viable to integrate renewable generation at 60 kV. However, the case study demonstrates that specific network components, such as line AL7, are highly susceptible to overloads under contingency conditions. Under extreme conditions, this line enters an alert "n-1" state. If the system transitions into an "n-2" state, it leads to supply failure and network collapse. Furthermore, the extended analysis further demonstrated that removing an overloaded line often leads to additional failures, culminating in cascading blackouts.

This study highlights the importance of reinforcing critical lines, improving grid monitoring, integrating forecasting algorithms to anticipate peak demand scenarios, and implementing dynamic grid reconfiguration techniques. Based on the findings, immediate recommendations for distribution network operators include prioritizing the upgrade of critical infrastructure (particularly lines AL6, AL7, AL8 and AL9), accelerating the deployment of real-time monitoring and adaptive protection systems. Such measures are essential to proactively manage extreme scenarios and ensure long-term stability and reliability in distribution networks with renewable energy sources. Future work should explore real-time control strategies and adaptive protection schemes to enhance network reliability and support large-scale renewable integration.

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