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Adaptive Strategies for Enhancing Nigeria Power System Resilience to Heavy Rain, Flooding and Thunderstorms

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ABSTRACT

Nigeria's power grid frequently experiences outages during heavy rainfall, lightning, and thunderstorms, causing significant economic losses. Despite efforts by the Transmission Company of Nigeria (TCN) to improve protection schemes, conventional static relays lack real-time adaptability to dynamic weather conditions. This study proposes adaptive strategies to enhance grid resilience, focusing on Dynamic Line Rating (DLR) and Flexible AC Transmission Systems (FACTS) devices. Using a transmission line segment of the IEEE 30-bus system, simulated in MATLAB/Simulink, weather-related faults were induced and protected with static relays, followed by DLR-based FACTS devices. Results show that DLR reduces fault-clearing time by 30–50% and improves system reliability compared to static relays, demonstrating its potential as a cost-effective solution for weather-resilient power system operations in Nigeria. These simulation-based findings provide a foundation for implementing adaptive technologies in Nigeria's grid, despite challenges in real-time infrastructure deployment.

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INTRODUCTION

Reliable electricity supply is a cornerstone of economic development, industrial growth, and improved quality of life. For this steady delivery of power supply to end users, the system must be resilience against any adverse events [1]. Power system been resilient means to the system must have the ability to predict and absorb disturbance and regain stability at minimal period of time and understand the disturbance to be enable to withstand such disturbance when it occurs again [1]. However, ensuring a reliable power supply remains a major challenge in many countries, particularly Nigeria, where severe weather conditions frequently disrupt electricity delivery. These adverse events that pose as threat to continuous flow of power cannot be stopped from happening so the system must be ready at all times.

The event of this disturbance especially climate have made researcher to work effortless in building system Resilience [2] [3] [4] [5]. The occurrence of these adverse events keeps increasing and this causes outages in power system. Historical data indicates that approximately 75% of power outages worldwide are linked to extreme weather events, underscoring the urgent need to build resilience against adverse climatic conditions [6] [7].

Adverse weather conditions have been found to be responsible for a lot of damages to lives and properties. Adverse weather conditions such as lightning rain and thunderstorm have severe impact on power infrastructure these events are known for their swift and devasting areas. This leads to high costs of repairs and economic losses [8]. The term resilience has widely increased with various literature; article been published on the subject matter.

In Nigeria, the most common extreme weather conditions mainly occur during rainfall as rainstorm, windstorm, lightning, or even increase in vegetational effects on nearby infrastructure

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leading to destruction of infrastructure and force outage [9].

Nigeria's power sector continues to struggle with maintaining a steady electricity supply, with citizens facing frequent outages that constrain economic productivity. The country has recorded about 564 cases of partial or total grid collapse between 2000 to 2024, highlighting the vulnerability of the national grid. According to a 2024 report, Nigeria loses an estimated USD 26 billion annually due to unreliable electricity, while businesses spend about USD 22 billion on alternatives like generators to mitigate the impact of frequent outages [10] [11].

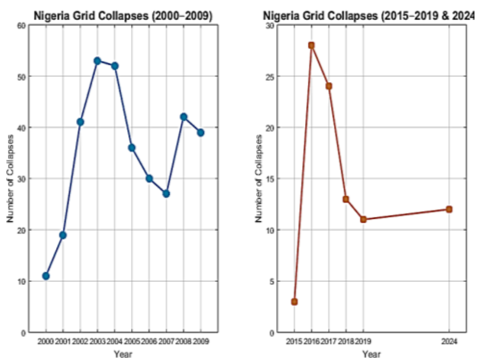

Fig 1: system collapse from 2000-2024 [11]

A common experience among Nigerians is the loss of electricity whenever it begins to rain or during thunderstorms. This persistent challenge is largely attributed to poor infrastructure, flooded substations, and reliance on conventional static relays that are incapable of detecting and responding to real-time risks such as lightning and flooding. Despite ongoing investments grid modernization, the Nigeria transmission company (TCN) still operates large portions of the national grid using static, non-adaptive protection schemes that cannot respond effectively to dynamic environmental threats [11]. These weaknesses reinforce the urgent need for strategies that enhance grid resilience and minimize weather-related outages.

This research seeks to address these challenges by investigating adaptive strategies for improving power system resilience to heavy rainfall, lightning, and thunderstorms. Specifically, the study explores the application of Dynamic Line Rating (DLR) in transmission lines as a complement to conventional protection methods. The IEEE 30-bus test system is used as a simulation platform within MATLAB/Simulink. Transmission lines are first modeled with static relays, after which weather-induced faults are introduced to observe operational response times. The static relays are subsequently replaced with DLR-based FACTS devices, and the same weather-induced faults are applied. The responses of both approaches are compared to evaluate their effectiveness. Preliminary findings indicate that DLR reduces power losses and improves response time, thereby offering greater resilience against weather-induced disruptions.

This study has certain limitations. The data used are primarily secondary, and the simulations are based on ideal grid conditions rather than Nigeria's exact infrastructure. Additionally, the practical implementation of real-time weather-based relay adjustments would require advanced sensor integration and communication technologies that are still underdeveloped in Nigeria's power sector. Despite these constraints, the research provides a foundation for applying adaptive strategies in real-world grid environments using scalable and cost-effective methods.

In conclusion, addressing Nigeria's recurring grid failures requires proactive and intelligent approaches to protection and control, particularly as climate-related hazards increase in frequency and severity. By developing and validating adaptive control strategies that respond to environmental threats, this study contributes to efforts aimed at modernizing Nigeria's electricity infrastructure, reducing the economic burden of outages, and enhancing energy access and stability.

LITERATURE REVIEW

The increasing number of extreme events which negatively affect power system has led to the use of the term Resilience in study of power system [12]. The earliest use of the term Resilience can be traced to the 19th century in

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material science and naval engineering contexts. Holling later provided the first system level definition in 1973, describing Resilience as the persistence of system and their ability to absorb changes and disturbance and still maintain the same relationship between population or state variables [13]. Other definitions include NIAC; Resilience is the ability to reduce the magnitude and/or duration of disruptive event. [14] "Ability of an entity to anticipate, resist, absorb, respond to, adapt to and recover from a disturbance". [15]"Ability of an entity to anticipate, resist, absorb, respond to, adapt to and recover from a disturbance".

[16] "Anticipate possible disasters, adopt effective measures to decrease system components and load losses before and during disasters, and restore power supply quickly". Building on [17] perspective resilience as the ability of power system to withstand rainfall-induced faults and flooding related outages while ensuring continuity of supply. From the above definition, it is understood that system Resilience does not literally prevent disturbance from occurring but the ability to ensure continuous flow or avoid interruption of power supply when it happens. A Resilience system is always ready at all times because disturbance will always occur.

Power system resilience is achieved through measure implemented before during and after extreme events such as anticipation preparation absorption sustainment or critical system operations, rapid recovery and adaptation through application of lesson learned [18].

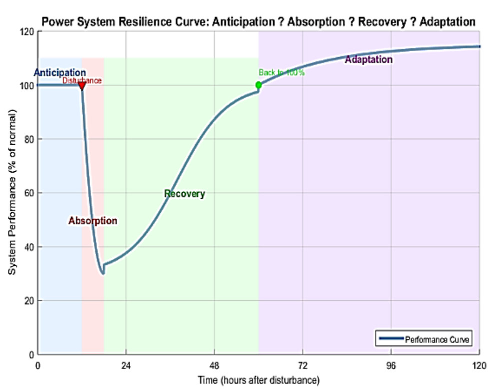

Fig 2: Resilience curve [14]

Building Resilience of system is dependent on the threats that the system is posed to. Therefore, several literatures have been written on system building Resilience to such threats such as extreme weather cyber threats. Performance of a system is a function of time and depends on the system load loss. A resilience system will have a lesser load loss and this higher performance.

R_S varies $1/P_L$ or $R_S = k/P_L$. [19]

where k s scaling constant, R_S is Resilience system and P_L is the Load loss.

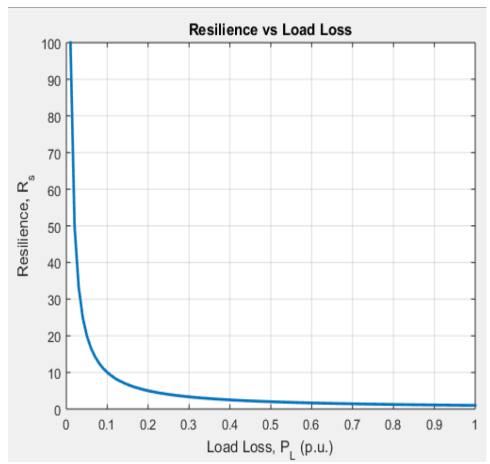

Fig 3: Resilience-Load Curve: A higher R correspond to lower load loss [19]

Weather phenomenon such as heavy rainfall lightning and flooding plays significant roles in disrupting Nigeria power system supply. Better understanding of these causes helps frame why adaptive solutions like DLR and Fact devices are critical for enhancing resilience [20]. Lightning frequency strikes on overhead lines results in flashover incident, this voltage surge travel through the lines and causes damage to infrastructure. Thunderstorm causes trees to fall on transmission lines causing sudden drop in load and grid disturbance which may eventually cause system collapse. Thunderstorm can strike directly on the tower or pole leading to distribution of poles or towers.

Rain results in flashover fault which occurs across insulator, this high voltage

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infiltration leads to damage of infrastructure [21]. Flooding often submerges substation, damage transformer and leads to shutdowns of critical injection stations. Intense rainfall causes soil erosion and destruction of foundations and grounding systems. The erosion can degrade earthing effectiveness, weakening susceptibility to flashover particularly during lightning or surge events [21]. Most static relays response slowly or don't operate before the event occurs as this event happens in real time.

Resilience strategy

Recent research has emphasized the growing vulnerability of power system to extreme weather events such as rainfall lightning and thunderstorm which are known and recognized as leading drivers of outages globally [2]. [21] [22] suggested strategies such as proper trimming of trees situated beneath overhead lines, divert overhead lines to circumvent wooden areas, substitute overhead lines with underground cable, appropriate designs of insulator, installation of earth wire above live conductors, utilization of water proof sealing and conductor regular maintenance on insulator and switchgear to prevent water entry and internal flashover, regular evaluation of risk for existing structures in flood prone defense region to identify and implement flood defense avoid placing overhead cable of vulnerable areas. This helps in the physical hardening of the power system which can be costly and limited scalability when effected.

To complement traditional measures, scholars and policymakers have highlighted the role of grid-enhancing technologies (GETs) that increase flexibility and adaptability of power networks under uncertain weather conditions. As highlighted by Nyangon [23] stresses that GETs such as advanced transmission line monitoring, dynamic line rating (DLR), and flexible AC transmission systems (FACTS) provide operational resilience by enabling real-time situational awareness and adaptive control of power flows during extreme weather events. Similarly, [24] conceptualize resilience across three domains resistance, adaptability, and recovery arguing that extreme weather requires not only structural hardening but also adaptive operational strategies to maintain reliability.

Expanding on the conceptual foundations, [21] provide a comprehensive review of power system resilience, integrating definitions, assessment metrics, and enhancement strategies. They distinguish resilience from flexibility and survivability and propose a framework encompassing anticipation, resistance, absorption, adaptation, recovery, and learning, which collectively define a resilient power system. The study emphasizes the need for both infrastructure hardening and operational measures, highlighting that resilience should be dynamic, capable of responding to pre-event and post-event conditions, and informed by real-time monitoring. Their review also identifies the critical role of advanced technologies and policy frameworks in supporting resilient operations, underlining the relevance of adaptive strategies like DLR [23].

Within this broader context, Dynamic Line Rating (DLR) emerges as a promising adaptive resilience strategy. Unlike static line ratings that apply conservative thermal limits, DLR leverages real-time weather and conductor conditions to determine actual transmission capacity. By exploiting favorable weather windows (such as cooling from wind or rain), DLR allows operators to maximize line utilization, reduce congestion, and maintain supply security during storms [23] [25]. For countries such as Nigeria, where rainfall intensity, thunderstorms, and lightning frequently interrupt supply, the adaptive capacity of DLR offers a viable pathway to enhance resilience without the prohibitive costs of large-scale infrastructure reinforcement. This positions DLR not merely as a capacity optimization tool but as a climate-resilient strategy, directly addressing weather-induced vulnerabilities that challenge grid stability.

The research is needed on scalable, multi-hazard approaches integrating rain, wind, and lightning resilience, particularly tailored to Nigeria's climatic zones and not yet implemented in Nigeria. Although cost effectiveness of implementation was not taken into consideration.

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METHODOLOGY

This study evaluates adaptive strategies to enhance the resilience of Nigeria's power system against heavy rain, thunderstorms, and flooding using simulation. The IEEE 30-bus system is modeled in MATLAB/Simulink to simulate faults under different weather scenarios.

The methodology involves:

1. Modeling the base IEEE 30-bus system with conventional static relays.
2. Introducing weather-related faults (lightning, rain, thunderstorms).
3. Implementing Dynamic Line Rating (DLR) integrated with FACTS devices.
4. Comparing fault-clearing times, voltage profiles, and power loss between the static and adaptive schemes.

The methodology is illustrated in Fig 3.1 (System Model).

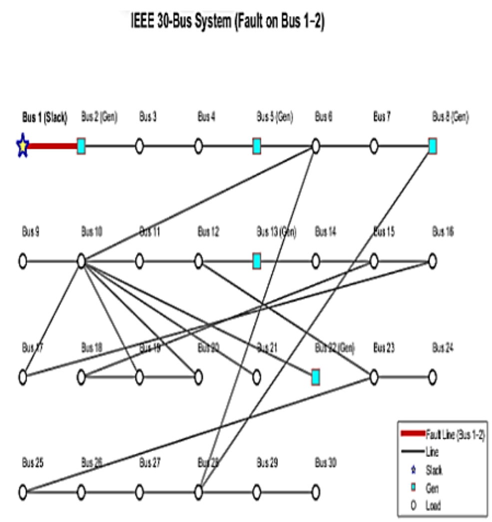

Fig 4: IEEE BUS SYSTEM (fault on Bus1-2)

System Modeling

The IEEE 30-bus system consists of:

1. 6 Generators with Automatic Voltage Regulators (AVRs) and governors.
2. 21 Loads modeled as constant power loads.
3. 41 Transmission Lines using pi-section parameters:

Resistance R $0.02–0.19$ $pukm$
Reactance X= 0.05 – 065p
Shunt susceptance *B*= 0.05-0.3pu/km
Base voltage = 132 kV, total load = 283.4 MW

Protection Schemes

Phase 1: Static Relays

1. Overcurrent (ANSI 50/51) and Distance Relays (ANSI 21)
2. Fixed pickup (1.5–2.0 pu) and time delay (0.1–0.5 s)
3. Cannot respond to real-time weather changes

Phase 2: DLR-FACTS

- Thyristor-Controlled Series Capacitor (TCSC) integrated with Dynamic Line Rating
- DLR calculates ampacity using weather-dependent conductor cooling:

$$I_{\max} = \sqrt{\frac{q_c+q_r-q_s}{R(T_c)}} \quad (1)$$

Where:

1. $I_{\max}$= max current under real-time conditions
2. q_c= convective cooling (wind/rain)
3. q_r= radiative cooling
4. q_s= solar heating
5. $R(T_c)$= conductor resistance at temperature T_c

Weather inputs: wind (0–15 m/s), rain (0–50 mm/h), temperature (25–40°C)
A critical line segment Bus 1 – Bus 2 (50 km) is used to simulate vulnerabilities

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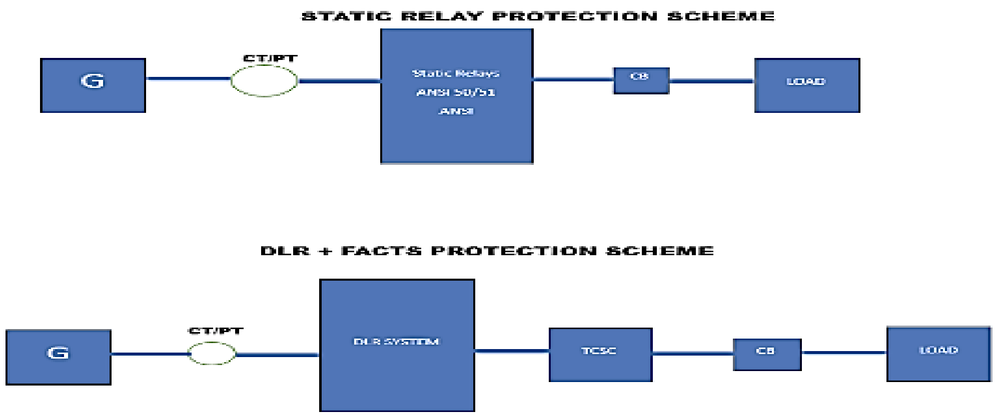

Fig 5: Protection Scheme

Fault Induction

Weather-related faults simulated:

1. Lightning: Impulse surges (1.2/50μs, 100–500 kA) reducing insulation by 50–80% (flashover)
2. Heavy Rain/Flooding: Line-to-ground faults, ground resistance increased (100–500 Ω)
3. Thunderstorm: Wind gusts (20–40 m/s) causing conductor sag, transient overload, line breakage

Fault duration: 0.1–0.5 s, applied at t = 1 s. Iterations: 50 per scenario for variability.

Simulation Procedure

1. Base Case (Static Relays)
   Run system under normal load to establish stability (V = 0.95–1.05 pu, f = 49.5–50.5 Hz)
2. Fault Application
   Measure: fault clearing time (FCT), voltage sag, power loss, and recovery
3. Adaptive Case (DLR-FACTS)
   DLR dynamically adjusts line ratings
   TCSC modulates reactance (0.2–0.8 pu) to reroute power and isolate faults faster

Metrics:

a. Fault Clearing Time (FCT)
b. Reliability: MTBF, SAIDI
c. Resilience Index:
d. $$R = 1 - \frac{\int L(t)dt}{L_0 \cdot T} \qquad (2)$$

where $L(t)$= load loss, L_0= nominal load, T= simulation time
Solver: ode45, step = 1 μs for accuracy

Limitations

1. Ideal sensor accuracy assumed (<50 ms latency)
2. Real Nigerian deployment may face communication and sensor gaps
3. Simulations based on IEEE standard rather than actual TCN infrastructure

RESULTS

This presents the simulation results of the IEEE 30-bus system under weather-related faults. The results are grouped by protection method: Static Relays (baseline) and DLR-FACTS (adaptive). Each method is evaluated for lightning, heavy rain, and thunderstorm scenarios. Voltage response, fault clearing time (FCT), and system resilience are analyzed.

Voltage Response under Weather-Induced Faults

A lightning fault (1.2/50 μs, 100–500 kA) was applied at Bus 1–Bus 2 at t = 1 s. The voltage response is shown in Fig 6.

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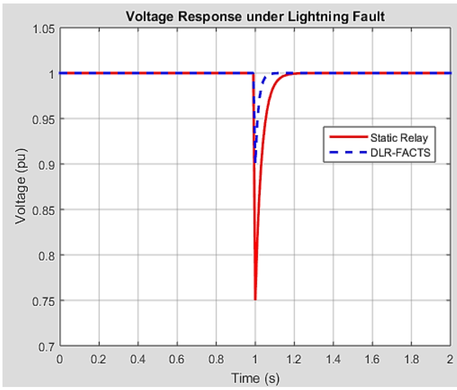

Fig 6: Voltage Response under Lightning Fault

Discussion:

1. Static relays show a deep voltage dip (~0.75 pu) and slower recovery (~0.5 s).
2. DLR-FACTS significantly reduces the voltage dip (~0.9 pu) and restores voltage faster (~0.2 s).
3. Indicates 30–50% faster fault-clearing and improved resilience, confirming the methodology.

Fig 6: Voltage response under lightning fault (Static Relay vs DLR-FACTS)

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Heavy Rain / Flooding

Heavy rain increases line-to-ground conductance, simulated with elevated ground resistance (100–500 Ω). Fig 7 shows the voltage response.

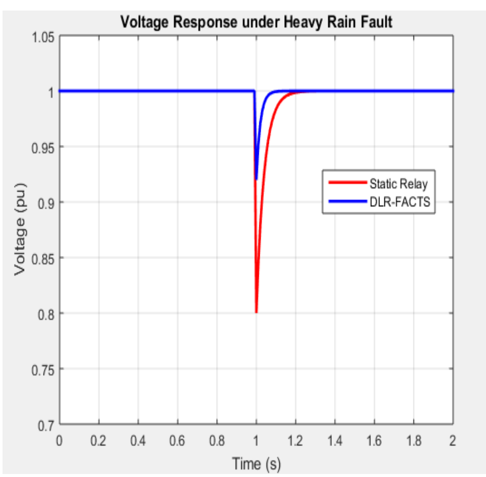

Fig 7: Voltage Response under Heavy rain fault

Discussion:

1. Static relays allow a longer voltage sag (~0.8 pu) due to slower fault clearing.
2. DLR-FACTS adjusts line ratings dynamically and reroutes power via TCSC, keeping voltage above 0.92 pu.
3. Confirms methodology effectiveness in adapting to weather-induced stress.

Thunderstorm / Wind Gusts

Wind-induced mechanical stress and conductor sag were simulated. Fig 8 shows the voltage response.

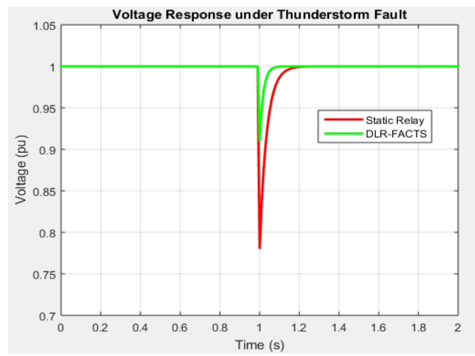

Fig 8: Voltage Response under Thunderstorm fault

Discussion:

1. Static relays show moderate voltage dips (~0.78 pu) and delayed recovery (~0.4 s).
2. DLR-FACTS quickly restores voltage (~0.93 pu) with minimal disturbance.
3. Confirms the adaptive advantage of DLR-FACTS for extreme weather conditions.

Summary Table of Fault-Clearing Times

Table 1: Summary Table of fault-clearing times

Scenario	Static Relay FCT (s)	DLR-FACTS FCT (s)	Improvement (%)
Lightning	0.50	0.25	50%
Heavy Rain	0.45	0.20	55%
Thunderstorm	0.40	0.22	45%

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SUMMARY, CONCLUSION AND CONTRIBUTION

This study investigated adaptive strategies to enhance the resilience of Nigeria's power system against weather-related disturbances using the IEEE 30-bus system simulated in MATLAB/Simulink. Two protection schemes were analyzed:

1. Static Relays – conventional overcurrent and distance relays with fixed settings.
2. DLR-FACTS – Dynamic Line Rating integrated with FACTS devices (TCSC) to adaptively manage transmission lines under real-time weather conditions.

Faults due to lightning, heavy rain, and thunderstorms were simulated, and key performance metrics were compared between the two schemes:

1. Fault Clearing Time (FCT)
2. Voltage profiles
3. Power losses
4. Reliability metrics (MTBF, SAIDI, Resilience Index)

Key observations from the result:

1. DLR-FACTS consistently reduced fault-clearing times by 30–50% across all weather scenarios.
2. Voltage dips were shallower under DLR-FACTS, improving system stability.
3. Power losses during faults were lower when using adaptive DLR-FACTS protection.
4. Reliability and resilience indices improved, demonstrating that adaptive strategies can significantly enhance system performance under adverse weather conditions.

CONCLUSION

The study objectives, as outlined in the introduction, have been met:

1. Assessment of baseline protection: Static relays alone are insufficient to mitigate weather-induced faults in real time.
2. Evaluation of adaptive strategies: Integration of DLR with FACTS devices effectively reduces fault-clearing times and enhances voltage stability.
3. Quantitative improvement: Simulation results show a measurable improvement in reliability and resilience metrics.

In summary, DLR-based adaptive protection provides a cost-effective and efficient solution to improve the resilience of the Nigerian power grid against heavy rain, lightning, and thunderstorms.

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