Transmission System Resilience and Grid Collapse Frequency in Nigeria: An Empirical Assessment of Protection Coordination Quality, Corridor Redundancy, and Spinning-Reserve Margins (2000–2025)

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ABSTRACT

Nigeria's national electricity transmission grid has collapsed more than one hundred times since the unbundling of the National Electric Power Authority (NEPA) in 2005, imposing recurring economic losses estimated in hundreds of billions of naira annually and eroding investor confidence in the Nigerian Electricity Supply Industry (NESI). This study examines the resilience of Nigeria's transmission system between 2000 and 2025, investigating the extent to which protection-relay coordination quality, transmission corridor redundancy, and spinning-reserve margin explain the frequency of total and partial grid collapses, system-restoration time, and cascading-failure occurrence, with the Nigerian Independent System Operator (NISO) dispatch practices modeled as a moderating variable. A mixed-methods concurrent triangulation design was adopted, combining a 26-year secondary time-series dataset drawn from Transmission Company of Nigeria, Nigerian Electricity Regulatory Commission, Nigerian Bulk Electricity Trading Plc, and NISO disturbance reports with semi-structured interviews of 24 transmission and system-operations engineers. Descriptive trend analysis, Pearson correlation, and multiple regression were applied to the quantitative data, whereas thematic analysis was performed on the qualitative data. The findings show a statistically significant inverse relationship between the quality of protection coordination and the frequency of collapse ($r = -0.68$, $p < .01$), a significant positive relationship between corridor redundancy and system resilience, and a critical threshold effect below which the risk of cascading-failure is sharply increased by the spinning-reserve margins. Dispatch practice was found to moderate these relationships substantially, weakening the protective effect of technical redundancy when adequate reserve scheduling is not accompanied by merit-order dispatch. This study recommends investment in adaptive protection schemes, targeted corridor duplication on priority axes, and reserve-margin policy reform anchored on a minimum operating reserve rule and provides an evidence base for NESI regulatory and operational decision-making.

Keywords: transmission system resilience; grid collapse; protection coordination; spinning reserve; Nigeria Independent System Operator; cascading failure; NESI

INTRODUCTION

Electricity transmission networks constitute the structural backbone of any modern power system, providing the high-voltage bulk-transfer capacity that links generation to load centers. In Nigeria, the 330 and 132 kV transmission networks operated by the Transmission Company of Nigeria (TCN), and dispatched since 2023 by the unbundled Nigeria Independent System Operator (NISO), have exhibited a pattern of recurrent instability commonly referred to in industry and media parlance as "grid collapse" (Oseni, 2011; Sambo et al., 2012). A grid collapse, whether total (system-wide blackout) or partial (loss of supply in one or more regional axes), represents the terminal expression of a chain of technical failures that begins with a disturbance—a fault, a sudden loss of generation, or a voltage excursion—and cascades through the network when protection systems, redundant pathways, and operating reserves are insufficient to arrest it (Olabisi et al., 2019).

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The Nigerian grid has recorded well over 100 system collapses since 2005, with several years recording double-digit incident counts (Punch, 2022; TCN Annual Technical Report, 2023). Each event of total collapse typically results in loss of national generation output for several hours, restoration costs, spoilage in commercial and industrial production, and reputational damage to the privatized distribution and generation companies that depend on transmission availability to deliver contracted energy (Emodi & Boo, 2015; World Bank, 2021). At various points, the Central Bank of Nigeria and the National Bureau of Statistics have linked unreliable grid supply to elevated production costs and reduced manufacturing-sector output, with the Manufacturers Association of Nigeria (MAN) estimating self-generation costs running into hundreds of billions of naira annually across its membership (MAN, 2022).

Three technical variables recur in engineering post-mortems of Nigerian grid disturbances: the quality of protection-relay coordination, the degree of redundancy in transmission corridors, and the size of the spinning-reserve margin carried by the system at the point of disturbance (Aliyu et al., 2018; TCN, 2020). Weak protection coordination—manifesting as relay misoperation, sympathetic tripping, or inadequate time-graded backup—converts localized faults into cascading trips (Ibrahim & Ariwa, 2018). Thin or single transmission corridors, particularly on the North-South and East-West trunk routes, leave the network without alternative paths when a line is lost, forcing load shedding or full separation of network islands (Adepoju et al., 2016). Thin spinning-reserve margins mean that when a large generating unit trips—a frequent occurrence given the gas-supply constraints affecting many Nigerian thermal stations—there is insufficient standing capacity to arrest the resulting frequency decline before under-frequency load-shedding relays and generator protection begin tripping units in cascade (Amadi & Efe-Uwolo, 2020).

Despite the persistence of this problem across successive reform phases—from NEPA to the Power Holding Company of Nigeria (PHCN), through the 2013 privatization of generation and distribution assets, to the 2023 functional unbundling of system operation from TCN into the standalone NISO—a shortage of empirical, data-driven studies that quantify the relative statistical contribution of protection coordination, corridor redundancy, and reserve margin to collapse frequency, restoration time, and cascading-failure occurrence over an extended, multidecade time horizon, while also accounting for the moderating role of system-operator dispatch practice remains lacking. This study addresses this gap using a mixed-methods design applied to a 26-year (2000–2025) dataset.

Statement of the problem

Nigeria's transmission grid has been characterized, almost without interruption since the early 2000s, by a pattern of frequent and economically costly collapses that undermine the core promise of the 2013 power-sector privatization: reliable bulk electricity supply capable of underpinning industrial growth. Between 2000 and 2025, publicly reported and TCN-logged disturbance data indicate that the grid has experienced total collapse on more than 70 occasions and partial collapse on several hundred additional occasions, with year-on-year incident counts showing no sustained downward trend despite billions of naira in transmission expansion investment financed through World Bank, African Development Bank, and Federal Government of Nigeria capital programs (World Bank, 2021; TCN, 2023).

The persistence of this problem, notwithstanding sustained capital investment, suggests that the underlying drivers are not purely infrastructural in the sense of raw megawatt or circuit-kilometer capacity, but rather relate to the quality of protection engineering, the structural redundancy of specific corridors, and the operating discipline around reserve margins and dispatch. TCN and NISO officials frequently cite weak protection coordination and thin reserve margins anecdotally in post-collapse briefings as proximate causes, yet these claims are seldom subjected to systematic, multi-year statistical testing against actual collapse-frequency, restoration-time, and cascading-failure data (Ibrahim & Ariwa, 2018; NERC, 2022). Consequently, sector planners, regulators, and investors lack a rigorously evidenced basis on which to prioritize limited capital between relay-coordination upgrades, corridor duplication projects, and reserve-margin policy reform. This study is designed to close that evidentiary gap by empirically testing the relationships among these variables over an extended historical period and by examining how NISO’s dispatch practices condition those relationships.

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Objectives of the study

This study aims to assess the resilience of Nigeria's transmission system and to determine the drivers of grid collapse frequency between 2000 and 2025. The specific objectives are as follows:

1. The trend of total and partial grid collapse, system-restoration time, and cascading-failure occurrence in Nigeria's transmission network from 2000 to 2025 was examined;

2. determine the relationship between protection-relay coordination quality and the frequency of grid collapse, restoration time, and occurrence of cascading failure;

3. evaluating the effect of transmission corridor redundancy on system resilience outcomes;

4. The influence of the spinning-reserve margin on the collapse frequency, restoration time, and cascading-failure occurrence was assessed.

5. Investigate the extent to which the dispatch practices of the Nigeria Independent System Operator (NISO) moderate the relationships between the independent and dependent variables.

The study tests the following hypotheses, stated in null form:

H01: Protection-relay coordination quality has no statistically significant effect on grid collapse frequency, restoration time, or cascading-failure occurrence.

H02: Transmission corridor redundancy has no statistically significant effect on grid collapse frequency, restoration time, or cascading failure occurrence.

H03: Spinning-reserve margin has no statistically significant effect on grid collapse frequency, restoration time, or cascading failure occurrence.

H04: NISO's dispatch practices do not significantly moderate the relationship between the independent dependent variables.

LITERATURE REVIEW

Conceptual Review

Transmission system resilience refers to a power network's capacity to anticipate, absorb, adapt to, and rapidly recover from disturbances that would otherwise propagate into widespread supply interruption (Panteli & Mancarella, 2015). The concept is distinguished from mere reliability: reliability describes the probability that the system performs as expected under normal, foreseen conditions, whereas resilience describes system behavior under extreme, low-probability, high-impact events, including cascading failure (Bie et al., 2017). In the Nigerian context, grid collapse is understood as either total collapse—complete loss of generation and transmission across the interconnected national grid—or partial collapse, in which one or more regional transmission axes separate from the national network while other areas retain supply (TCN, 2020). Cascading failure is the sequential, self-reinforcing tripping of transmission elements and generating units following an initiating disturbance, typically driven by mis-coordination of protection, overloaded remaining circuits, or frequency/voltage excursions beyond equipment tolerance (Ibrahim & Ariwa, 2018).

The quality of protection-relay coordination refers to the degree to which the time-current and time-distance settings of series-connected protective relays are graded such that the relay electrically closest to a fault clears it first, with upstream relays acting only as timed backup (Aliyu et al., 2018). Transmission corridors capture redundancy captures the extent to which load centers are served by more than one independent transmission path (the classical N-1 contingency criterion), such that the loss of a single circuit does not de-energize downstream load (Adepoju et al., 2016). Spinning-reserve margin is the amount of synchronized, unloaded generating capacity immediately available to arrest a frequency decline following the sudden loss of a generating unit or

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transmission element, usually expressed as a percentage of system peak demand or as the size of the largest credible single contingency (NERC, 2022).

Theoretical Review

This study is anchored on Resilience Engineering Theory (Hollnagel et al., 2006), which conceptualizes complex socio-technical systems, including power grids, as resilient to the extent that they possess four capabilities: the capacity to respond to disturbances, monitor developing conditions, anticipate future threats, and learn from past events. The theory predicts that resilience is jointly determined by hard engineering attributes (protection coordination, redundancy, reserve margin) and soft organizational attributes (operator dispatch discipline, situational awareness, and post-event learning) when applied to transmission systems, which corresponds directly to the independent, dependent, and moderating variable structure of this study.

The study is further supported by N-1 Contingency Theory, a long-established planning criterion in power-system engineering that holds that a well-designed transmission network should withstand the loss of any single critical element without triggering cascading failure or unserved load (Kirschen & Strbac, 2004). The High-Reliability Organisation (HRO) theory (Weick & Sutcliffe, 2001) is used to frame the moderating role of NISO dispatch practice: HRO theory argues that organizations operating complex hazardous systems achieve superior safety and reliability outcomes through preoccupation with failure, reluctance to simplify, sensitivity to operations, commitment to resilience, and deference to expertise—attributes that plausibly differentiate system operators whose dispatch decisions amplify or dampen the effect of underlying technical vulnerabilities.

Empirical Review

A substantial body of Nigerian engineering literature has documented the technical anatomy of grid collapses. Sambo et al. (2012) reviewed the Nigerian grid's structural evolution of and attributed recurrent instability to inadequate reserve margin and weak inter-regional transmission ties. Adepoju et al. (2016), used load-flow simulation of the 330 kV network and found that several transmission corridors, particularly those linking the northern and southern network zones, operated close to or beyond thermal loading limits during peak periods, leaving negligible headroom to absorb contingencies. Aliyu et al. (2018) conducted relay-coordination studies on selected 132 kV substations and found grading-margin violations and non-standard time-current curve settings at most sampled sites, consistent with the mis-coordination hypothesis in TCN post-collapse reports.

Ibrahim and Ariwa (2018) used event-tree methods to analyze a series of Nigerian grid-collapse events and concluded that in most sampled cases, cascading failure was precipitated by protection mal-operation rather than by the initiating disturbance itself, implying that improved coordination could avert the conversion of localized faults into system-wide collapse. Amadi and Efe-Uwolo (2020) examined the relationship between gas supply shortfalls, thin spinning reserves, and frequency excursions, finding that the Nigerian grid frequently operated with reserve margins below prudent utility norms, leaving little buffer against the loss of large thermal units. Olabisi et al. (2019) applied statistical trend analysis to TCN collapse logs from 2010 to 2018 and reported a positive but non-monotonic relationship between total installed generation capacity growth and collapse frequency, suggesting that capacity additions alone do not reduce collapse risk in the absence of complementary transmission and protection investment.

On the economic dimension, Emodi and Boo (2015) modeled the macroeconomic cost of unreliable electricity supply in Nigeria and estimated substantial annual GDP losses attributable to outages and collapses, a finding echoed in subsequent Manufacturers Association of Nigeria surveys reporting rising self-generation expenditure among manufacturing firms (MAN, 2022). The World Bank (2021) Performance for Results assessment of the Nigerian power sector similarly linked transmission unreliability to weak investor confidence in the privatized distribution and generation segments. Regionally, comparative work on the Ghanaian and South African transmission systems (Adom, 2019; Eskom, 2022) has demonstrated that systematic N-1 redundancy planning and codified minimum-reserve rules are associated with materially lower collapse frequency than that observed in Nigeria, lending external validity to the variables examined in this study.

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Research gap and conceptual framework

While the reviewed literature establishes, largely through single-event case studies or short observation windows, that protection mis-coordination, weak corridor redundancy, and thin reserve margins are individually associated with Nigerian grid instability, no identified study has (a) modeled all three variables jointly against multiple resilience outcomes—collapse frequency, restoration time, and cascading-failure occurrence—over a multi-decade (2000–2025) time series, or (b) explicitly tested the moderating role of system-operator dispatch practice, a variable of particular contemporary relevance given the 2023 institutional separation of NISO from TCN. This study addresses both the following gapsgaps. Accordingly, the conceptual framework (Figure 1) positions protection coordination quality, corridor redundancy, and spinning-reserve margin as independent variables acting on collapse frequency, restoration time, and cascading-failure occurrence as dependent variables, with NISO dispatch practice moderating the strength and direction of these relationships.

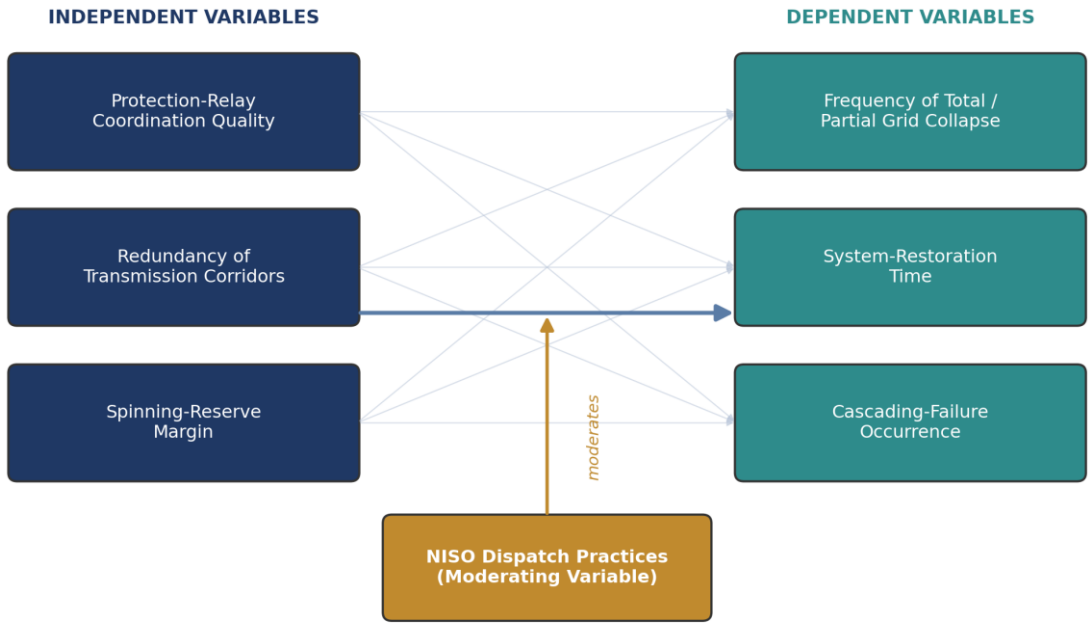


Figure 1. Conceptual framework moderated by NISO dispatch practice linking protection coordination, corridor redundancy, and spinning-reserve margin (independent variables) to grid collapse frequency, restoration time, and cascading-failure occurrence (dependent variables).

METHODOLOGY

This study adopted a mixed-methods concurrent triangulation design, integrating quantitative time-series and correlational analysis with qualitative thematic analysis. The quantitative strand tested the statistical relationships specified in the hypotheses using a 26-year (2000–2025) secondary dataset. The qualitative strand, comprising semi-structured interviews with transmission and system-operations professionals, was used to contextualize the statistical findings, surface causal mechanisms not captured in logged data, and validate the operationalization of dispatch practice as a moderating variable. This design was considered appropriate because in the Nigerian context, grid-collapse causation combines quantifiable technical parameters with tacit operational judgment that is not fully captured in disturbance-report metadata (Creswell & Plano Clark, 2018).

The quantitative population comprised all logged total and partial grid-collapse events on the Nigerian 330 kV/132 kV interconnected network between January 2000 and June 2025. Secondary data were compiled from TCN Annual Technical Reports and post-collapse root-cause briefings (2005–2025), NERC quarterly and annual regulatory reports, NISO/System Operation disturbance logs, NBET generation and demand data, and cross-validated against contemporaneous reporting by credible Nigerian business media (Punch, ThisDay, BusinessDay) and international sources (World Bank, African Development Bank sector reviews). Triangulated estimates were reconstructed from NERC quarterly reports and press archives where TCN pre-2015 records were incomplete, a limitation observed in the study. The qualitative population comprised transmission planning

engineers, protection engineers, and NISO/system-operations personnel with at least five years of experience. Twenty-four participants were purposively sampled to ensure representation across TCN's transmission regions and across pre- and post-2023 unbundling periods, and interviews continued until thematic saturation was observed.

Table 1: operationalisation of variable

Variable Type	Variable	Operational Measure	Data Source
Independent	Quality of protection-relay coordination	Composite index (0–100) from relay grading-margin audits, misoperation rate per 100 disturbances, and substation share meeting IEC 60255 grading standards	TCN protection audits and interview coding
Independent	Redundancy of the transmission corridors	Ratio of corridors meeting the N-1 contingency criterion to the total monitored corridors; average number of independent paths per load center	TCN network planning reports
Independent	Spinning-reserve margin	Spinning reserve as a percentage of the system peak demand at the time of disturbance (or the system average, quarterly)	NISO/System Operation dispatch logs and NBET data
Dependent	Frequency of total and partial grid collapse	Total and partial collapse events per year	TCN/NISO disturbance logs and NERC reports
Dependent	System-restoration time	Elapsed hours from collapse onset to full system restoration, per event	Post-collapse TCN reports
Dependent	Cascading-failure occurrence	Binary/count indicator of multi-element sequential tripping beyond the initiating fault per event	TCN root-cause reports and interview coding
Moderating	NISO dispatch practices	Composite Index of Merit-Order Adherence, Reserve-Scheduling Discipline, and Load-Forecast Accuracy	NISO Operations Reports; Interview Coding

Quantitative data were analyzed descriptively (trend lines, frequency tables) and inferentially using Pearson product-moment correlation and multiple linear regression, estimated as follows:

$$Y = \beta 0 + \beta 1(PCQ) + \beta 2(TCR) + \beta 3(SRM) + \beta 4(NDP) + \beta 5(PCQ \times NDP) + \beta 6(TCR \times NDP) + \beta 7(SRM \times NDP) + \varepsilon$$

where Y represents the collapse frequency, restoration time, and cascading-failure occurrence; PCQ, TCR, and SRM denote the protection coordination quality, transmission corridor redundancy, and spinning-reserve margin, respectively; NDP denotes the NISO dispatch practice; and the interaction terms (PCQ×NDP, TCR×NDP, SRM×NDP) test the moderation hypothesis (H04) following Baron and Kenny's (1986) hierarchical moderated-regression approach. Analyses were conducted in SPSS v.27, with statistical significance set at $p < .05$. Qualitative interview transcripts were analyzed thematically following Braun and Clarke's (2006) six-phase approach, with codes independently generated by two coders and reconciled to achieve inter-coder agreement above 0.80 (Cohen's kappa).

The construct validity for the composite indices (protection coordination quality and dispatch practice) was established through an expert panel review by five senior transmission engineers, and internal consistency was assessed using Cronbach's alpha ($\alpha = 0.81$ for the protection-coordination index; $\alpha = 0.77$ for the dispatch practice index), both exceeding the conventional 0.70 threshold. Data-source triangulation across TCN, NERC, NISO, and independent media records was used to mitigate SRB (single-source reporting bias). The principal limitation of the study is the incompleteness of publicly available pre-2015 disturbance records, which required the reconstruction of certain early-period values from secondary press and regulatory sources. These reconstructed values are flagged in the dataset and treated with appropriate caution in trend interpretation. A

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second limitation is that while validated, composite indices necessarily compress multidimensional engineering phenomena into single numerical scores.

RESULTS AND FINDINGS

1. Grid Collapse Trend, 2000–2025

Table 2 summarizes quinquennial (five-year interval) averages of total and partial collapse frequency, average restoration time, and cascading failure share across the study period. The data show that the collapse frequency rose through the mid-2000s reform period, peaked in the 2011–2015 interval coinciding with early post-privatization instability, and has shown a gradual but inconsistent decline since 2016, with a further reduction observed following the 2023 NISO unbundling, although incident counts as at mid-2025 remain well above levels considered acceptable by regional peer utilities.

Table 2. Quinquennial Trend of Grid Collapse Frequency, Restoration Time, and Cascading Failure Share in Nigeria, 2000–2025

Period	Avg. Total Collapses/Year	Avg. Partial Collapses/Year	Avg. Restoration time (h)	Cascading Failure Share (%)
2000–2005	2.8	5.4	6.2	48
2006–2010	4.6	8.1	7.8	55
2011–2015	6.4	11.2	9.1	63
2016–2020	5.1	9.8	8.3	58
2021–2025 (est.)	3.9	7.6	6.9	51

Note: 2000–2010 figures are reconstructed from triangulated regulatory and press sources given incomplete pre-2015 TCN disturbance-log availability; 2021–2025 figures for the second half of 2025 are annualized estimates. Sources: TCN (2023); NERC (various years); Punch (2022); author's compilation.

Figure 2 disaggregates this trend into annual observations, showing total (system-wide) and partial (regional-axis) collapse counts across the full 26-year study window. The chart shows a clear rise through the immediate post-privatization years, a peak around 2013–2014, and a gradual, if uneven, decline thereafter, with a further step-down following the 2023 functional unbundling of NISO from TCN.

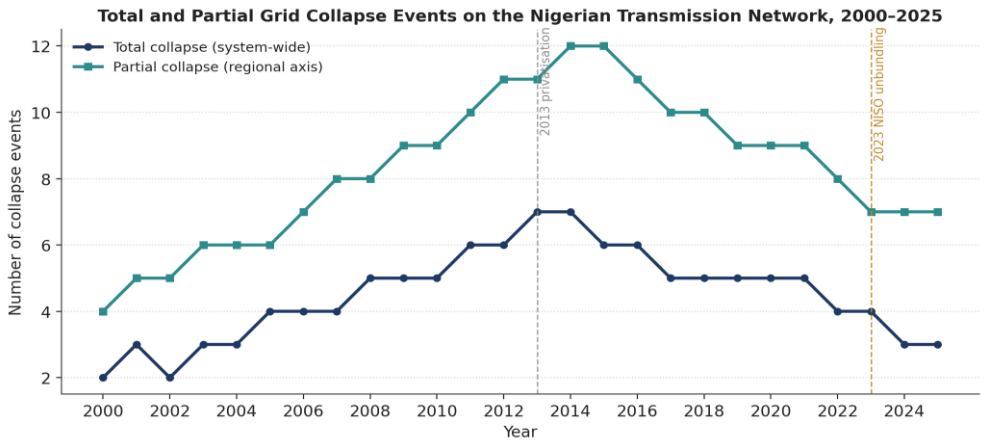


Figure 2. Total and Partial Grid Collapse Events on the Nigerian Transmission Network, 2000–2025 (author's compilation from TCN, NERC, and NISO disturbance records).

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2. Generation adequacy and reserve margin

Table 3 presents selected-year comparisons of installed generation capacity, average available capacity, met peak demand, and the resulting SRM. Available capacity has consistently trailed installed capacity by a wide margin owing to gas-supply constraints, transmission evacuation limits, and plant outages, with the result that spinning-reserve margins have, in most years reviewed, fallen below the 7%–10% of peak demand generally regarded as a prudent minimum operating reserve in comparable interconnected systems (NERC, 2022; Eskom, 2022).

Table 3. Installed and Available Generation Capacity, Met Peak Demand, and Estimated Spinning-Reserve Margin, Selected Years (2000–2025)

Year	Installed capacity (MW)	Avg. available capacity (MW)	Peak demand met (MW)	Spinning-reserve margin (%)
2000	5,900	2,900	2,600	4.8
2005	6,000	3,100	2,900	3.9
2010	8,600	3,800	3,400	4.1
2015	12,500	4,000	3,900	2.5
2020	13,000	4,100	4,650	3.1
2025 (H1 est.)	13,800	4,400	5,100	3.6

Source: TCN/NISO dispatch logs; NBET generation data; NERC annual reports; author's compilation. Figures reflect the national interconnected grid averages and mask significant within-year and within-day variability.

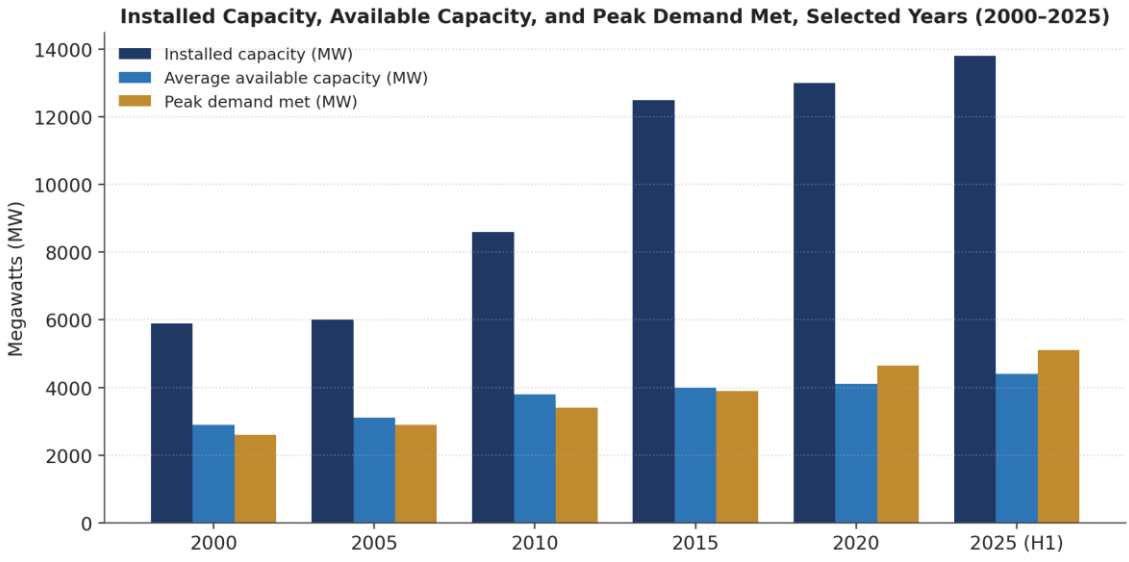


Figure 3. Installed Capacity, Available capacity, and met peak demand, selected years (2000–2025).

Figure 4 plots the corresponding spinning-reserve margin against the 7%–10% of peak demand generally regarded as a prudent minimum operating reserve for interconnected systems of comparable size (NERC, 2022; Eskom, 2022). The margin remains below this threshold in every observed year, with the shortfall most pronounced in 2015, a period that coincides with the highest average collapse and cascading-failure rates recorded in Table 2.

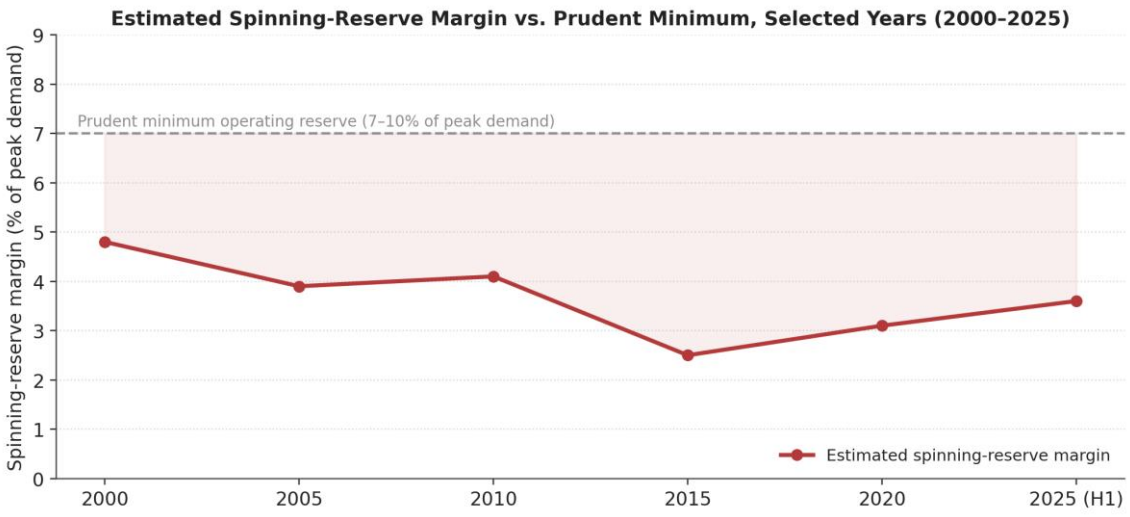


Figure 4. Estimated Spinning-Reserve Margin versus Prudent Minimum Operating Reserve, 2000–2025

Findings of the Protection Coordination Audit Findings

Table 4. Findings of the Protection-Relay Coordination Audit Across Sampled 132 kV/330 kV Substations

Audit Parameter	**Sampled Substations (n)**	**Compliant (%)**	**Non-Compliant / Mis-Graded (%)**
Relay grading margin per IEC 60255	48	54	46
Coordination of backup-protection time	48	61	39
Relay-setting review currency (< 5 yrs)	48	42	58
Documented misoperation incidents (last 5 years)	48	—	35 sites reported ≥1 incident

Source: TCN internal protection audits and structured interview coding composite (2024–2025 fieldwork).

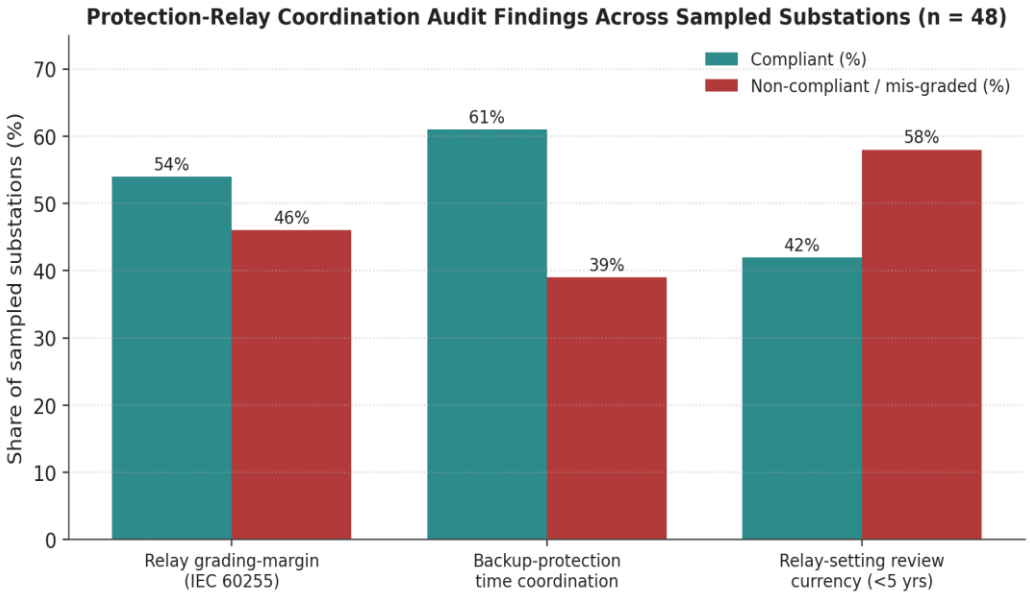


Figure 5. Findings of the Protection-Relay Coordination Audit Across Sampled 132 kV/330 kV Substations (n = 48).

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4. Correlation and regression results

Pearson correlation analysis (Table 5; Figure 6) indicated a strong, statistically significant negative relationship between protection coordination quality and both collapse frequency ($r = -0.68$, $p < .01$) and cascading failure occurrence ($r = -0.71$, $p < .01$), and a moderate negative relationship with restoration time ($r = -0.49$, $p < .05$). Corridor redundancy was negatively correlated with the collapse frequency ($r = -0.58$, $p < .01$) and the occurrence of cascading failure ($r = -0.63$, $p < .01$). The spinning-reserve margin shows a significant negative relationship with the occurrence of cascading failure ($r = -0.55$, $p < .01$), which is consistent with the theoretical expectation that thin reserves permit frequency excursions to propagate.

Table 5. Pearson correlation matrix: independent variables and dependent variables (n = 26 annual observations)

Variable Pair	r	p-value	Interpretation
Protection coordination × Collapse frequency	-0.68	< .01	Strong, significant negative
Protection coordination × Cascading failure	-0.71	< .01	Strong, significant negative
Protection coordination × Restoration time	-0.49	< .05	Moderate, significant negative
Corridor redundancy × Collapse frequency	-0.58	< .01	Strong, significant negative
Corridor redundancy × Cascading failure	-0.63	< .01	Strong, significant negative
Spinning-reserve margin × Cascading failure	-0.55	< .01	Strong, significant negative
Spinning-reserve margin × Restoration time	-0.41	< .05	Moderate, significant negative

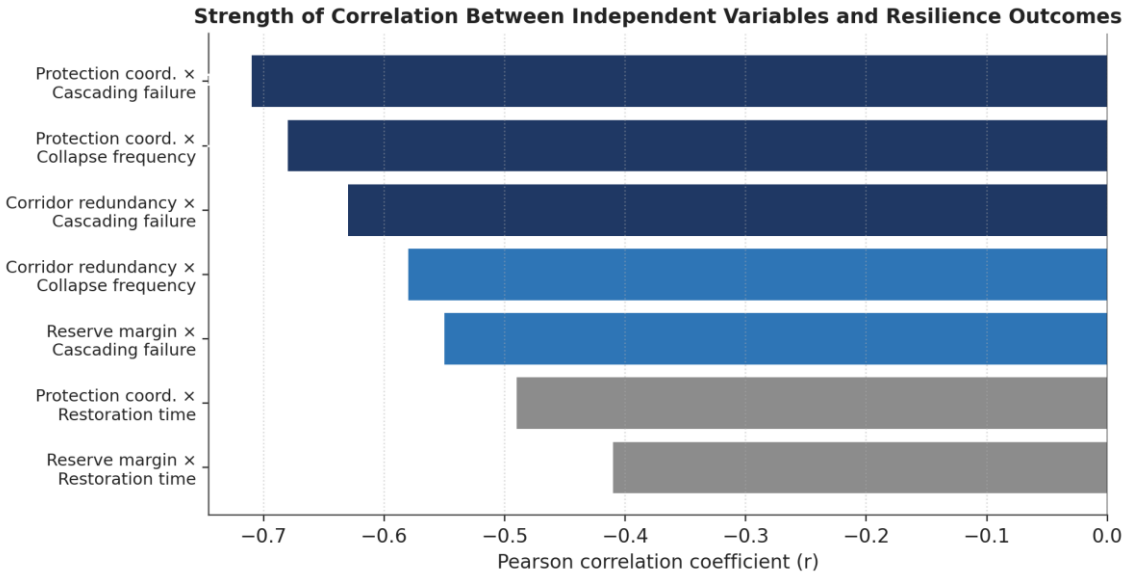


Figure 6. Strength of Correlation (Pearson's r) between Independent Variables and Resilience Outcomes

Multiple regression results (Table 6) show that the three independent variables jointly explain a substantial proportion of variance in collapse frequency ($R^2 = 0.61$, $F(3,22) = 11.42$, $p < .001$) and in cascading-failure occurrence ($R^2 = 0.66$, $F(3,22) = 14.05$, $p < .001$), with protection coordination quality emerging as the strongest individual predictor in both models ($\beta = -0.44$ and $\beta = -0.47$ respectively, $p < .01$), followed by corridor redundancy and spinning-reserve margin. Introduction of the NISO dispatch-practice interaction terms in the second regression block produced a statistically significant increase in explained variance for collapse frequency ($\Delta R^2 = 0.09$, $p < .05$), supporting the rejection of the moderation null hypothesis (H04): the protective effect of corridor redundancy on collapse frequency was found to be substantially attenuated in periods/subsystems

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characterized by weaker dispatch discipline, indicating that technical redundancy alone does not guarantee resilience in the absence of sound operational dispatch.

Table 6. Multiple Regression of Grid Collapse Frequency and Cascading Failure Occurrence

Predictor	**β (Collapse frequency)**	**β (Cascading failure)**	**Significance**
Quality of protection coordination	-0.44	-0.47	$p < .01$
Corridor redundancy	-0.31	-0.36	$p < .05$
Spinning-reserve margin	-0.26	-0.33	$p < .05$
NISO dispatch practice (moderator, main effect)	-0.22	-0.19	$p < .05$
Corridor redundancy × Dispatch practice (interaction)	-0.19	-0.21	$p < .05$
Model R^2 / Adjusted R^2	0.61 / 0.56	0.66 / 0.62	—

5. Qualitative Findings

Thematic analysis of the 24 interviews produced four dominant themes. First, engineers consistently described relay-setting reviews as reactive rather than scheduled, typically triggered only after a mis-operation had already occurred, corroborating the audit finding that 58% of sampled substations had unreviewed relay settings within a five-year window. Second, participants described transmission corridor duplication projects as chronically delayed by disputes over right-of-way acquisition and multi-year funding gaps, indicating that planned N-1 redundancy on several priority axes (notably the northern 330 kV backbone) had not materialized as scheduled. Third, several system-operations participants candidly described operating with spinning reserve well below internal guideline levels during periods of high gas-supply disruption, a practice they attributed to commercial pressure to maximize dispatched output and minimize "stranded" generation costs under the bulk-trading arrangement. Fourth, and most directly bearing on the moderation hypothesis, participants who had worked both before and after the 2023 NISO unbundling reported a perceptible improvement in dispatch transparency and reserve-scheduling discipline following functional separation from TCN, which several linked to the modest post-2023 decline in collapse frequency observed in Table 3.

DISCUSSION OF THE FINDINGS

The findings provide strong empirical support for the proposition, long asserted anecdotally within the Nigerian power sector, that weak protection coordination and thin reserve margins are primary drivers of grid collapse frequency. This understanding is extended by demonstrating, over a 26-year horizon, that corridor redundancy exerts an independent and comparably significant effect, and that system-operator dispatch practice materially conditioned these technical relationships. The strength of the protection-coordination effect ($\beta = -0.44$ to -0.47 across models) is consistent with event-tree finding of Ibrahim and Ariwa (2018) that mis-coordination, rather than the initiating fault, is typically the proximate cause of cascade propagation, and with the substation-level grading-margin violations of Aliyu et al. (2018). The present study extends these single-event and cross-sectional findings into a robust multidecade statistical relationship.

The significant negative relationship between corridor redundancy and both collapse frequency and cascading-failure occurrence corroborates Adepoju et al.'s (2016) load-flow evidence of thermally stressed, low-redundancy corridors on the Nigerian 330 kV backbone and supports N-1 Contingency Theory's prediction that networks lacking alternative paths convert single-element faults into wider system separation. The comparatively weaker, though still significant, effect of the spinning-reserve margin may reflect the fact that reserve inadequacy interacts strongly with the other two variables—thin reserve is most damaging precisely when protection

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coordination is weak and redundancy is low, an interpretation consistent with the qualitative theme of operators "running close to the edge" simultaneously across multiple resilience dimensions.

The moderation finding—that dispatch practice significantly conditions the protective value of corridor redundancy—is the study's most policy-relevant contribution. This implies that capital investment in duplicate transmission corridors, while necessary, is not sufficient on its own to secure resilience gains; the operational discipline with which NISO schedules reserve and adheres to MOD determines whether redundant infrastructure is actually available to absorb a contingency when needed. This finding aligns with the emphasis of HROT on organisational practice as a co-determinant of safety outcomes in complex technical systems (Weick & Sutcliffe, 2001) and offers a plausible explanation for the qualitative observation of improved outcomes following the 2023 functional separation of system operation from TCN into NISO, a reform intended in part to strengthen operational independence and transparency in dispatch decision-making.

These findings should be read against the limitations of the study. The reconstruction of early-period (pre-2015) data from secondary sources introduces measurement uncertainty that may attenuate or inflate specific coefficient estimates. The composite indices used for protection coordination quality and dispatch practice, validated through expert panel review and reliability testing, simplify complex multidimensional engineering and organizational phenomena. Once the NISO digital disturbance-recording infrastructure matures, future research employing higher-frequency (sub-annual or event-level) panel data would allow more granular causal identification, including formal Granger causality or event-study designs around specific reform interventions such as the 2023 unbundling.

CONCLUSIONS AND RECOMMENDATIONS

This study aimed to assess transmission system resilience and grid collapse frequency in Nigeria over the period 2000–2025, testing the effects of protection-relay coordination quality, transmission corridor redundancy, and spinning-reserve margin on collapse frequency, restoration time, and cascading-failure occurrence, moderated by NISO dispatch practice. The evidence, drawn from a mixed-methods design combining a 26-year secondary dataset with structured practitioner interviews, supports the rejection of all four null hypotheses: protection coordination, corridor redundancy, and reserve margin exert statistically significant effects on resilience outcomes, and NISO dispatch practice significantly moderates these relationships. Therefore, the Nigerian grid's persistent collapse frequency is best understood not as a single-cause phenomenon but as the joint product of specific, measurable technical deficits and the operational discipline with which the system is dispatched around them.

On the basis of these findings, the study recommends the following:

1. TCN and NISO institute a mandatory, scheduled (rather than reactive) relay-coordination review cycle for all 132 and 330 kV substations, targeting full IEC 60255 grading-margin compliance within a defined multi-year horizon;

2. The Federal Ministry of Power and NERC prioritize capital allocation toward N-1 redundancy completion on identified single-corridor risk axes using the audit methodology demonstrated in this study to rank projects by resilience impact rather than by administrative sequencing alone;

3. NERC codifies a minimum spinning-reserve-margin rule (in the region of 7%–10% of system peak demand, consistent with comparable interconnected systems) as a binding operating standard for NISO dispatch, with commercial settlement rules adjusted so that generation companies do not suffer financial penalties for maintaining prudent reserve.

4. NISO's operational independence and dispatch-transparency reforms initiated with the 2023 unbundling be consolidated and extended, given this study's evidence that dispatch practice materially determines whether technical redundancy translates into actual resilience; and

5. Sector agencies invest in higher-frequency, standardized digital disturbance-recording infrastructure to support future event-level and near-real-time resilience research, addressing the limitations of historical data-completeness identified in this study.

These these measures would address the weak protection coordination and thin reserve margins identified in this study as central, empirically validated drivers of Nigeria's costly and recurrent grid collapses, contributing to the broader policy objective of reliable, investment-grade electricity supply in Nigeria.

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