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A Review of Transmission Network Challenges in Nigeria: Losses, Voltage Instability, and Congestion

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Abstract: Nigeria's transmission network faces a structural crisis characterized by three interlocking challenges: ohmic losses, voltage instability, and chronic line congestion. This review paper synthesizes findings from peer-reviewed studies and regulatory reports to provide a comprehensive technical assessment of each challenge, its root causes, and evidence-based corrective strategies. Ohmic losses are the resistance of the line to the flow of current, generating heat that increases the line's resistance. This is mitigated using parallel transmission circuit, voltage uprating and conductor upgrading. Voltage instability analysis identifies eight northern buses operating persistently below the statutory 0.95 pu floor, with a documented reactive power deficit of 2,247.42 MVAr on the uncompensated network. Congestion analysis establishes that the Nigerian grid fails N-1 security compliance on major corridors due to its predominantly radial topology, with only one functional ring existing across the entire 330kV network. The paper identifies five loss-reduction strategies which are; power factor correction, conductor reconductoring, series capacitor compensation, parallel circuit addition, and operating voltage uprating and evaluates four voltage stability corrections: shunt reactive compensation, STATCOM placement, SSSC application, and network reinforcement. For congestion management, network reinforcement, reconfiguration, generation redispatch via Optimal Power Flow (OPF) and Unified Power Flow Controller (UPFC) deployment are assessed. Findings confirm that the STATCOM at Maiduguri resolves all eight northern voltage violations simultaneously, that the addition of a parallel circuit on the Alaoji–Onitsha corridor saves 6.44MW in losses, and that AI-augmented SCADA/EMS deployment can reduce annual grid collapses from 12 to near zero. The paper concludes with a prioritized investment framework addressing all three transmission challenges.

Keywords: Facts Devices, Line Congestion, N-1 Criterion, Transmission Losses, Voltage Instability, Statcom.

1.0 Introduction

The transmission lines in Nigeria have been marred by several difficulties, including losses, voltage instability, and congestion (Ogudare et al., 2022 a; Adebisi, et al., 2024; Ajenikoko, et al., 2025). The Transmission Company of Nigeria (TCN) owned by the federal government is vested with the responsibilities of transmitting power from the generating stations (GENCOS) to the distributing stations (DISCOS). TCN, is one of the 18 companies unbundled from the defunct Power Holding Company of Nigeria (PHCN) in 2013.Transmission serves as the middleman between the generation station and the distribution station, ensuring power is effectively delivered to end users (Ogar et al., 2022). The transmission lines operate at 132 kV and 330kV. Having a distance of 5,523.8km of 330 kV and 6,801.5km of 132kV.

The transmitting capacity is far below the installed generation capacity of 12,522MW. According to the Nigeria Electricity Regulatory Commission (NERC), the transmission network consists of high voltage substations with a total transmission capacity of 7,500MW, but currently, the wheeling capacity is 5,300MW, and an electricity demand conservatively estimated at 30,000–45,000MW (NERC Report, 2024). The system operates under conditions of structural overload, and not merely operational stress.This study focuses on analyzing the transmission network of Nigeria, its prevailing challenges: Losses, Congestion, and Voltage Instability by examining the different elements of the system.

2.0 Overview of Nigeria Transmission Network

In a bid to improve the efficiency and reliability of the electricity grid, the federal government of Nigeria in 2013 unbundled the Power Holding Company of Nigeria (PHCN) into 18 different entities comprising of 6 generating station (GENCOS), 11 distribution stations (Discos) and the TCN still being administered by the federation while others are privatized (Onochie, et al., 2015; Ogundare, et al., 2022). This is shown in "Fig." 1.

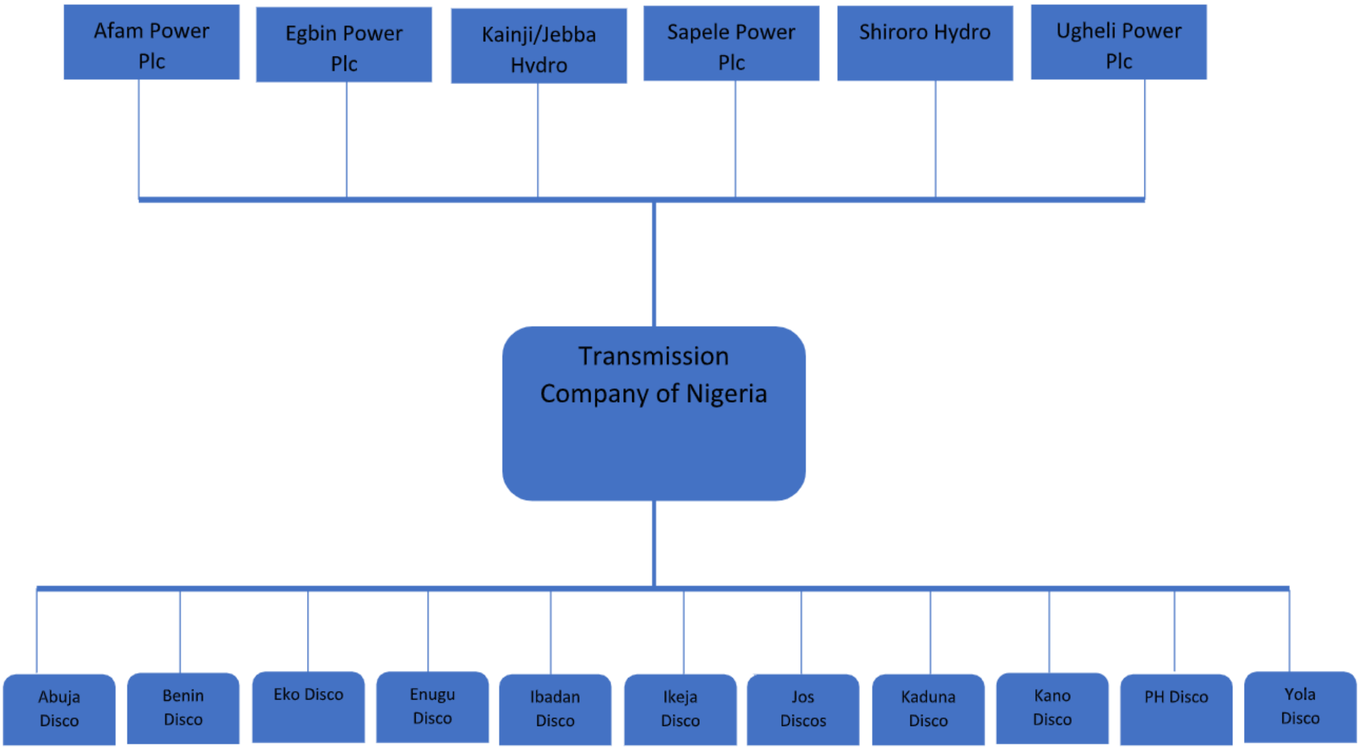

Figure 1: Nigeria energy flow from generation to distribution

TCN is made up of three operating departments:

Transmission Service Provider: Roles include development, maintenance, and expansion of transmission infrastructure, system operations: Roles include power allocation, voltage control, frequency control, grid code administration and market operations: Roles include administration of the electricity market and promoting efficiency in the market.

These departments were maintained from inception until the unbundling of the TCN in April 2024 by the Nigeria Electricity Regulatory Council (NERC), acting upon the repealed Electric Power Sector Reform of 2005. The system operations department was carved out and named the Nigerian Independent System Operator of Nigeria Limited (NISO), which was incorporated as a private company limited by shares. TCN is divided into ten transmission regions: Lagos, Osogbo, Kaduna, Shiroro, Bauchi, Enugu, Benin, Kano, Abuja, and Port Harcourt, made up of work centers and a National Control Center (NCC) at Oshogbo, with three supplementary National Control Centers at Shiroro, Lagos, and Benin (TCN, 2022).

The bulk of the 330kV transmission lines are located in the southern part of the country, with a few up North. This is shown in "Fig." 2.

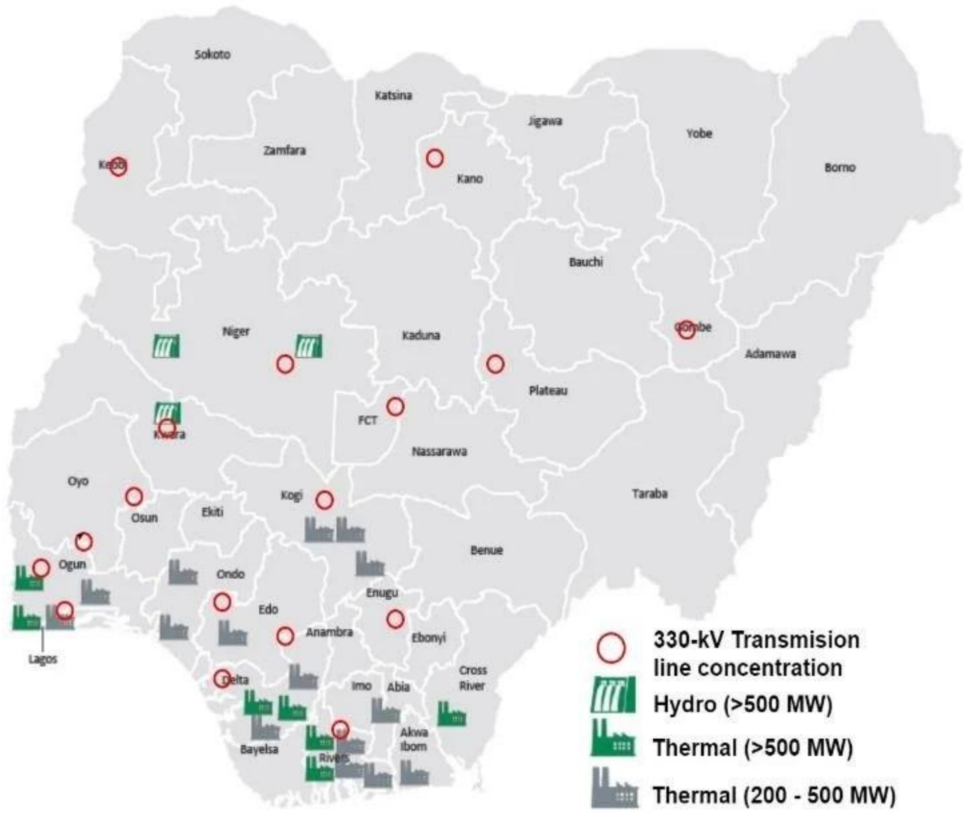

Figure 2: Concentration of 330kV Transmission Lines (Adapted from (Alao & Awodele, 2018))

The lines in the southern part are more interconnected in a loop-like manner. Studies have shown that the interconnection of transmission lines within a region (interconnected substations) increases its reliability and strength. The northern region with a larger landmass and more dispersed population is characterized by a radial transmission network (Adebayo et al., 2020).

3.0 Losses in Transmission Lines

Losses in transmission network are in various forms and characterized by various elements. Transmission lines are needed in evacuating power from generating stations usually in remote locations to load centers hundreds of kilometers away. As a result of this, ohmic losses occurs within the line. This loss is the resistance of the line against the flow of current resulting in heat been generated thereby increasing the resistance of the line and power loss (Bamigbola et al., 2014). Transmission losses in Ac systems are primarily resistive and proportional to the square of the current and multiplied by line resistance.

3.1 Strategies for Reducing Ohmic Losses

3.1.1 Power Factor Correction

Power factor is the ratio of active power (MW) to reactive power (MVA). Reactive current (I_q) occurs in the line at a power factor less than unity in addition to active current (I_p). Reactive current (I_q) contributes to line losses without delivering active power to the load (Ogundare, et al., 2022 c. Power factor correction yields a direct reduction of ohmic losses to the line without the need for modification of the line itself.

A low power factor results in a significant reactive power component, requiring the source to supply more apparent power to maintain the same active power output. This then led to more current demand, hence increasing I^2R losses. (Nnanwezi & Endurance, 2025) established that a power factor close to unity indicates how highly efficient a system is, while a value significantly less than 1 shows inefficiency and high reactive power. The Nigerian transmission system has been reported to have a power factor between 0.70 and 0.85. At a power factor of 0.70, huge losses are recorded in the line. Table 1 shows losses at different power factor levels under surge impedance loading conditions.

Table 1: Losses at different Power Factor levels

Power Factor	**Current (Amps)**	**Loss (MW)**	**% Loss**
0.70	972	19	4.9
0.75	907.2	16.66	4.3
0.80	850.5	14.56	3.7
0.85	800.5	12.89	3.3
0.90	756	11.51	2.9
0.95	716.2	10.32	2.6

3.1.1.1 Correction Methods

(a) **Shunt Capacitor Banks:** A 150MVAr shunt capacitor bank installed at the Onitsha 330/132kV substation compensating for the reactive power demand of 291MVAr under SIL and pf of 0.80 will raise the effective power factor to a range of 0.92-0.95.

(b) **Static VAr Compensators (SVC):** SVC's, provide continuous stepless control of reactive power injection by combining thyristor-controlled reactors (TCR) with fixed or switched capacitors bank (Ogundare, et al., 2022d). With a response time of about 20-30ms, it responds to voltage fluctuation faster than mechanical switching.

3.2 Conductor Upgrade or Reconductoring

Power loss is directly proportional to the conductor resistance at any given current level. The Alaoji line's current ACSR Bison 350mm² twin bundle has an AC resistance of 0.04967 Ω/km/phase at 75°C. Upgrading to a higher cross-section or lower-resistance conductor type reduces resistance without changing the current-carrying requirement. Two conductor families are relevant: conventional ACSR with larger aluminum cross-section, and High-Temperature Low-Sag (HTLS) conductors using advanced core materials that allow both lower resistance and higher operating temperatures without increased sag. Unlike power factor correction, this requires modification to the line.

3.2.1 Series Capacitor Compensations:

Series compensation inserts capacitors in series with the transmission line, partially cancelling the line's inductive reactance. For the Alaoji line, the total series inductive reactance of the 135Km Alaoji-Onitsha corridoris $X_{total} = 43.71\ \Omega$ derived from the ACSR Bison twin-bundle conductor geometric parameters and the standard transmission line inductance formula (Glover et al., 2012) and $R_{total} = 6.71\ \Omega$, the natural reactive current demand at any given load level is determined by the ratio X/R = 6.52. Series compensation reduces the effective X, which reduces the reactive current component of the total line current, reduces the voltage angle difference between sending and receiving ends, allows the same active power to be transmitted at a lower line current and improves the voltage profile at the Onitsha bus

3.2.2 Parallel Transmission Circuit (Load Splitting)

This is the single most impactful loss reduction strategy available to this corridor and the one with the most direct and unambiguous mathematical basis. Adding parallel 330-kV circuits between transmission lines divides the load current between the circuits (Ogundare, et al., 2019). Adding a parallel 330-kV circuit to Alaoji and Onitsha divides the load current equally shared between two circuits (Isdore et al., 2021).

At a SIL loss of 12.89MWohmic loss, a parallel circuit reduces total corridor losses to 6.4MW a saving of 6.44MW. No otherstrategy can achieve this magnitude of reduction. Apart from halving the transmission losses, this method makes the transmission line more resilient has double-circuit voltage prevent power loss that occurs from a single line trip hence preventing total loss of power.

3.2.3 Operating Voltage Uprating

For a fixed active power transmission, the line current is inversely proportional to the operating voltage. Uprating the Alaoji corridor from 330 kV to 400 kV (a 21% voltage increase) would reduce line current by 21% and ohmic loss by 38% at the same transmitted power (Ofoma and Okonwo, 2021). The relationship $P_{los\ s} \propto 1/V^2$ makes voltage uprating one of the most thermodynamically efficient interventions available. So many concerns arise from this method such as: Insulation clearance, Corona loss at 400kV and Substation equipment replacement

4.0 Voltage Instability of Nigeria 330kVTransmission Lines

Voltage stability is defined as the ability of a power system to maintain steady, acceptable voltages at all buses following a disturbance or under continuous load variation. Instability arises when a system is unable to supply the reactive power demanded by its loads and transmission lines (Kundur, 1994). The IEEE/CIGRE Joint Task Force on Stability Terms and Definitions formally articulated it as the capacity to maintain voltages close to the nominal value across all buses after a given disturbance from a stated initial condition (Kundur et al., 2004).

For the Nigerian grid, two classification forms are relevant. First, static (steady-state) voltage instability: The continuous inability to meet reactive power demand under gradually increasing load or inadequate compensation. This is the dominant form at Nigerian northern buses, where voltages are chronically below 0.95 pu even at normal load levels (Ahiakwo et al., 2022). Second, dynamic (transient) voltage instability: Rapid collapse following a sudden disturbance such as a generating unit trip, circuit outage, or transformer failure. This mechanism underlies Nigeria's sudden total blackout events (Chijindu et al., 2018). For stability to occur, there must be a reactive power balance at the transmission bus. This is represented by

$$Q_{Supply} \geq Q_{Demand}$$

Reactive power cannot betransmitted over long distances because reactive current flowing through the line inductive reactance (X) creates voltage drops ($V_{drop} = I \times X$) and heat losses (I^2R) without delivering useful work. Reactive generation must therefore occur locally, at or near the load. In the Nigerian grid, the northernmost substations (Maiduguri, Yola, Gombe, Damaturu) sit 700–900 km from major generation centers, creating a structural reactive deficit that cannot be resolved without local compensation or network reconfiguration (Okakwu et al., 2017); (Adepoju et al., 2018). The Nigerian Electricity Regulatory Commission prescribed a grid code shown in Table 2, effective August 1st, 2007, which specifies operational limits for 330kV and 132kV transmission lines.

Table 2: NERC proscribed Grid Code (2007)

Parameter	**Normal Operating Range**	**Emergency Tolerance**	**Consequence of Breach**
330 kV Bus Voltage	313.5–346.5 kV (0.95–1.05 pu)	±5% further under faults	Voltage collapse, equipment damage
System Frequency	49.75–50.25 Hz (±0.5%)	48.75–51.25 Hz (stress)	Generator auto-shutdown
132 kV Bus Voltage	125.4–138.6 kV	±5% further	Distribution under-voltage
Thermal Loading (lines)	≤100% rated capacity	≤110% (emergency only)	Overload trip, conductor sag

Violation of the grid code has led to numerous system collapses, highlighted in Table3

Table 3: Grid collapse due to grid code violation

Period	**Collapses Recorded**	**Rate / Pattern**	**Source**
January 2000 – December 2022	564	2.5 collapses per month average over 22 years	(Mojisola A. Jimoh& Bello S. Raji, 2023)
2015 – 2023 (9 years)	101	~11 per year; 2016 worst (28); 2023 lowest (2)	(Issac Samuel et al., 2012)
January–June 2017	12 total + 2 partials	24 annualized — consistent with 2003 peak level	(Ogbuefi, 2018)
2018 (eight days)	6 in 8 days	Extreme clustering confirming structural weakness, not random faults	(Mojisola A. Jimoh& Bello S. Raji, 2023)
2024–2025	12+ in 2024	>1 per month; worsening relative to 2023	Punch (2026)

4.1 Causes of Voltage Instability

4.1.1 Absence of Reactive Power Compensation Infrastructure

The absence of reactive power compensation infrastructure is the most widely documented source for voltage instability along the 330kV transmission lines. (Okakwu et al., 2017) quantified the reactive power deficit at 2,247.42 MVAr on the uncompensated 32-bus network, producing a reactive-to-active loss ratio of 8.37:1, more than four times the acceptable benchmark of 2:1.(Omorogiuwa Eseosa and Emmanuel A. Ogujor (2012) established that reactive power compensation reduces both generating MVA demand and line losses simultaneously, enabling higher power transfer without grid expansion. (Anyanor et al., 2020) study confirmed that voltage violations at eight northern buses traced directly to reactive demand exceeding available supply, and that a single STATCOM at Maiduguri simultaneously resolved all eight violations confirming the reactive-deficit origin of the problem.

4.1.2 Long Radial Transmission Corridor

The Nigerian grid's topology is dominated by radial feeds rather than meshed ring architecture (Alayande, et al., 2024). (Ogbuefi, 2018) identified only one ring on the entire 330 kV network which is the Benin-Ikeja West-Aiyede-Oshogbo-Benin (BIAOB) ring with the remainder being radial chains that lack redundancy. This leaves the network unable to re-route power following a circuit outage, so a single-line failure removes the entire supply path to the connected load area. The North-East sub grid Gombe, Damaturu, Maiduguri, Jalingo, and Yola are fed through a radial chain extending 700–900 km from major generation centers. Inductive line reactance X increases with length, compounding reactive voltage drop ($V_{drop} = I \times X$) and reactive line losses ($Q = I^2 \times X$) at every kilometer. (Mojisola A. Jimoh & Bello S. Raji, 2023) confirmed that the North connects to the rest of the grid through a single triple-circuit Jebba-Oshogbo line, which is a single point of failure architecture in which any contingency at that corridor produces a regional blackout.

4.1.3 Insufficient SCADA and Energy Management System

The absence of an effective energy management system was identified by (Mojisola A. Jimoh & Bello S. Raji, 2023) has one of the leading causes of voltage instability leading to system collapse. Without automated control, the system operator cannot identify developing voltage depressions before they cascade to blackout. ,(Adeniji et al., 2025) used a simulation calibrated to Nigerian grid parameters, found that implementing advanced SCADA with AI-driven predictive dispatch reduced simulated annual collapses from approximately 12 to near zero and extended mean time between failures from roughly 10 months to 100 months. This confirms that EMS automation is a high-return, relatively low-cost intervention.

4.2 Voltage Instability Correctional Methods

4.2.1 Shunt Reactive Power Compensation (Capacitors Banks)

Shunt capacitor banks inject reactive power at the point of need, directly improving the reactive balance (Maruf & Garba, 2013; Ogundare, at al., 2022 e) showed on the 30-bus Nigerian model that shunt capacitor installation at violated northern buses reduced slack-bus reactive demand by 60.27 MVAr and cut reactive line losses by 96.51 MVAr simultaneously, raising all violated buses to the 0.95 pu statutory floor as shown in Table 4. This is the fastest-deployable and lowest-cost reactive compensation technology available.

Table 4: Required Reactive Power Compensation on Northern Buses

Bus	Current V (pu)	Target V (pu)	Est. Q Required	Justification and Source
Kano	0.780–0.872 pu	0.975	100–150 MVAr	Largest northern load center violated in all studies reviewed by (Ohiero, 2023)
Yola	0.858–0.892 pu	0.970	60–80 MVAr	Most vulnerable bus by modal analysis (Chijindu et al., 2018)
Gombe	0.873–0.900 pu	0.965	50–70 MVAr	Optimal series compensator site Bus 9 SSSC (Adepoju & Sanusi, n.d.)
Maiduguri	0.871–0.896 pu	0.975	80–120 MVAr	Optimal STATCOM site; single unit clears all eight violated buses (Anyanor et al., 2020)
Damaturu	0.885–0.896 pu	0.965	40–60 MVAr	North-East terminal bus (Aneke N.E & Ngang N.B, 2021)
Jos	0.858–0.911 pu	0.965	60–100 MVAr	Full voltage restoration with STATCOM at Bus 8 (Aneke, 2021)
Kaduna	0.883–0.905 pu	0.960	25–40 MVAr	North-west junction bus (Ohiero, 2023)
Jalingo	0.872–0.943 pu	0.960	30–50 MVAr	(Okakwu et al., 2017)

4.2.2 Static Synchronous Compensator (STATCOM)

A Static Synchronous Compensator (STATCOM) is a Voltage Source Converter (VSC) based FACTS device providing continuous reactive power injection with a response time of 20–30 milliseconds. STATCOM maintains rated reactive output at low voltage through active power electronic control. (Anyanor et al., 2020) study on the 54-bus Nigerian network, using combined voltage stability indices in PSAT-MATLAB, determined that Maiduguri is the optimal single-unit placement site and one STATCOM at Maiduguri simultaneously restored all eight violated buses to within the 0.95–1.05 pu statutory band. This outcome arises because Maiduguri is the terminal bus of the longest radial chain and raising voltage at the far end reduces reactive current demand on every intermediate line section, propagating voltage improvement upstream.

(Aneke N.E & Ngang N.B, 2021) verified on the 58-bus network that STATCOM achieved complete elimination of voltage violations relative to an uncompensated network, with active and reactive power losses reduced by 9.4% and 2.4% respectively.(Dennis et al., 2024) compared STATCOM and SVC on the Nigerian 24-bus network in NEPLAN, finding STATCOM superior on every metric and maximum bus voltage improved to 1.0388 pu versus 1.0282 pu for SVC, reactive losses reduced by 32.01% versus 29.94%, and active losses reduced by 17.96% versus 17.11% for SVC.

4.2.3 Static Synchronous Series Compensator (SSSC)

The Static Synchronous Series Compensator (SSSC) is a series-connected FACTS device that injects a voltage in quadrature with line current, emulating series capacitance without physical capacitors. Its primary function is to reduce the effective inductive reactance of long transmission lines, thereby reducing reactive voltage drop and increasing maximum power transfer. (Adepoju et al., 2018; Ogundare et al., 2017 b) applied SSSC to the Nigerian 28-bus 330 kV network in MATLAB and demonstrated that it eliminated the Gombe bus voltage violation (0.8973 pu pre-compensation) and reduced network active power losses by more than 5% of the 93.87 MW base case, injecting 6.81 MVAr to hold Onitsha bus precisely at 1.0 pu.

(Oluka Leonard, n.d.) Conducted a comparative study of all major FACTS devices on the Nigerian 44-bus network and concluded that series compensation was the most effective single strategy for extending the voltage collapse margin with SSSC, TCSC, and UPFC in place, the network remained in steady state even under doubled loading conditions. (Adepoju et al., 2018) further validated SSSC on the Nigerian 330 kV northern zone, achieving voltage profile compliance across all previously violated buses with a model prediction accuracy exceeding 0.95pu.

4.2.4 Network Reinforcement: New Lines and Ring Topology

(Maruf & Garba, 2013) explicitly recommended in their study conclusions that additional substations and transmission lines should be introduced into the Nigerian grid to create ring architectures, particularly serving Kano, Kaduna, Jos, Gombe, Yola, and Katampe, where voltage deficits are most severe. (Adeyi & Oputa, 2024) modelled the expanded 52-bus network (incorporating new lines and stations relative to the earlier 41-bus model) and confirmed that network expansion improved voltage profiles across all zones. Some new lines that should be considered are North-West ring: Second 330 kV circuit on Shiroro–Kaduna–Kano via an alternative route, eliminating the single-path failure that produced the October 2024 northern blackout (≈350–450 km new line), North-East ring loop: New 330 kV line from Gombe through Jalingo to Yola, closing the radial Gombe–Damaturu–Maiduguri–Yola string into a ring (≈250–300 km new line) and South-East ring closure: Alaoji–Enugu–Onitsha ring for reactive supply redundancy (≈180 km new line)

4.2.5 SCADA/EMS Upgrade and Wide Area Monitoring

(Mojisola A. Jimoh & Bello S. Raji, 2023) recommended that a system-wide SCADA platform and comprehensive EMS should be deployed across the Nigerian grid to enhance system operations, raise power system reliability, increase efficiency, and support automated grid management. (Adeniji et al., 2025) quantified the expected impact through simulation and AI-driven predictive dispatch in an upgraded SCADA framework reduced annual grid collapse events from approximately 12 to near zero and improved mean time between failures from roughly 10 months to 100 months. SCADA/EMS to be implemented; Phasor Measurement Units (PMUs) at all 52 330 kV buses: Synchronized 50 sample per second voltage phasor data enabling real-time stability margin calculation. Wide-Area Monitoring Systems (WAMS) built on PMU data can detect collapse precursors 2–5 minutes before cascade, providing actionable operator warning, Optimal Power Flow (OPF) in EMS: Continuous co-optimization of active and reactive dispatch reduces line losses by 5–12% through dispatch alone, at near-zero marginal capital cost once the EMS platform is deployed and under-Voltage Load

Shedding (UVLS): Automatic load shedding triggered at 0.90 pu (10–15% curtailment) and 0.85 pu (25–30% curtailment) arrests reactive cascades before total collapse. This last-resort mechanism does not currently exist on the Nigerian 330 kV network

5.0 Line Congestion

A transmission line is congested when the power flow demanded across it exceeds the limit that can be securely transmitted without violating thermal, voltage, or transient stability constraints (Kundur, 1994). Unlike generation shortfalls which manifest as rolling blackouts, congestion can be invisible to consumers while silently costing hundreds of millions of dollars. Nigeria's electricity supply chain faces congestion at every link. With more than 220 million people and an estimated electricity demand of 30,000–45,000 MW against an actual peak supply of barely 5,200 MW (Mojisola A. Jimoh & Bello S. Raji, 2023), the gap between what the system should carry and what it can safely carry is enormous. The 330kV lines were designed in the 1970's to transmit power at half today's capacity. With few upgrades on the line, the consequence is a structurally overloaded, chronically congested transmission system in which most bottlenecks are permanent rather than contingency-driven. Congestion management must address thermal, voltage and stability limits.

5.1 N-1 Criterion

The N-1 security criterion requires that the loss of any single network element must not cause cascaded failure, sustained overloads, or voltage violations elsewhere. NERC (2007) adopted the N-1 criterion in the Nigerian Grid Code. Multiple NR studies confirm that the Nigerian 330 kV network fails N-1 compliance on major corridors even in the base case: critical buses already operate below the statutory voltage limit without any contingency applied (Adeyi & Oputa, 2024) The Nigerian grid has only one ring, the Benin–Ikeja West–Aiyede–Oshogbo–Benin ring in the South-West, leaving all other corridors radial with zero alternative routing when congestion or faults occur (Ogbuefi et al., 2018).

5.2 Major Causes of Congestion on 330 kV Transmission Line

5.2.1 Radial Network Topology

Research by (Ogbuefi, 2018) established that the Nigerian 330 kV network has only one ring — the Benin–Ikeja West–Aiyede–Oshogbo–Benin ring — leaving the remainder as radial chains that lack any redundancy. Inductive line reactance X accumulates with length ($X = x \times L$), compounding reactive voltage drop ($V_{drop} = I \times X$) and reactive line losses ($Q_{loss} = I^2 \times X$) at every kilometer of radial corridor (Kundur, 1994). (Mojisola A. Jimoh & Bello S. Raji, 2023) confirmed that the North connects to the rest of the grid through a single triple-circuit Jebba–Oshogbo line, a single-point-of-failure architecture in which any contingency at that corridor produces a regional blackout. This architecture directly causes congestion because all power must flow through a small number of bottleneck lines with no alternative paths.

5.2.2 Ageing Infrastructure

(Ogbuefi, 2018) documented that Nigeria's 330 kV grid infrastructure dates from the 1960s–1980s, with components now functioning well beyond their design lives. Aged transformers, circuit breakers, and transmission lines are identified as primary sources of stress-triggered failures that directly contribute to cascade collapses (Mojisola A. Jimoh & Bello S. Raji, 2023). The October 14, 2024 collapsefrom vandalism of the Shiroro–Kaduna line and the October 19, 2024 collapse from a transformer explosion at Jebba substation both illustrate how aged primary equipment failures in a radial network amplify into system wide events (Adeniji et al., 2025).

5.2.3 Inadequate Generation Dispatch

(Okakwu et al., 2017) established that the Nigerian 330 kV network has a total installed capacity of approximately 6,500 MW against which only 4,000–5,200 MW is actually dispatched. With fewer generators online, total reactive injection capability is proportionally reduced. Generator outages are a recurrent collapse trigger.When a major unit trips, the remaining fleet must absorb both the active power shortfall and the reactive injection deficit, frequently exceeding AVR capability and initiating cascaded voltage depression (Mojisola A. Jimoh & Bello S. Raji, 2023).

5.3 Actionable Solutions to Line Congestion

5.3.1 Network Reinforcement

Additional substations and transmission lines should be introduced into the Nigerian grid to form ring architectures, specifically at Kano, Kaduna, Jos, Gombe, Yola, and Katampe as priority nodes for new line connections (Okakwu et al., 2017). Network reinforcement is the only permanent solution to structural congestion, it increases physical transfer capacity on bottleneck corridors rather than managing flows within existing constraints. The prioritized reinforcement investments identified across reviewed literature are:Second 330 kV circuit on Benin–Onitsha corridor: Doubles thermal capacity from 1,000 MVA to 2,000 MVA on the most congested corridor. Approximately 130 km of new 330 kV line. North-West ring (Shiroro–Kaduna–Kano new routing): Provides redundant path to the entire North-West zone, eliminating the single-point-of-failure that caused the October 2024 blackout. Approximately 350–450 km new 330 kV line. North-East ring loop (Gombe–Jalingo–Yola–Damaturu–Maiduguri): Closes the radial North-East chain into a ring, enabling alternative routing when the Jebba–Gombe corridor is congested.750 kV supergrid on highestdemand corridors. (Adeyi & Oputa, 2024) modelled this option and found that upgrading to 750 kV on the northern corridor reduces cumulative voltage drop from 96.78% to 27.09%, simultaneously eliminating both thermal and reactive congestion on those routes.

5.3.2 Network Reconfiguration

Network reconfiguration uses controlled switching of normally-open tie lines, bus section breakers, and transformer tap changers to alter load flow paths without building new infrastructure. (Ahiakwo et al., 2022)evaluated available switching options on the Nigerian 330 kV network and identified three feasible reconfigurations capable of reducing peak loading on the Benin–Onitsha corridor by 12–18% by routing a portion of South-East load through the 132 kV sub-transmission layer. While sub-optimal as a long-term strategy, these reconfigurations provide measurable congestion relief within the current infrastructure envelope at negligible cost. (Maruf & Garba, 2013) also identified bus-section switching at Oshogbo substation as capable of reducing the Jebba–Oshogbo loading by approximately 8%.

5.3.3 Generation Redispatch and Optimal Flow

Generation redispatch involves adjusting generator output schedules to relieve overloaded lines by reducing upstream generation and increasing downstream generation on uncongested paths. In Optimal Power Flow (OPF), this is automated by minimizing a cost objective subject to all line flow, voltage, and generator constraints simultaneously. (Eziyi and Ezugwu, 2020) demonstrated on the 28-bus Nigerian network that optimal generation redispatch could reduce overloaded lines from seven to three without any physical infrastructure investment, cutting total congestion costs by 35–45%. (Adeniji et al., 2025) demonstrated through AI-augmented OPF simulation that deploying automated dispatch within a functional SCADA/EMS environment reduced simulated congestion events by over 80% and cut ancillary service costs by approximately 40%. This confirms that software-based OPF is a high-return, low-capital intervention deployable as soon as SCADA connectivity across all 52 primary substations is established.

5.3.4 Unified Power Flow Controller (UPFC)

The UPFC simultaneously controls active and reactive power flows through its combined shunt and series voltage source converter architecture. It is the most capable single FACTS device for congestion management because it can directly enforce a target power flow value on the controlled line, rerouting congested power to underloaded parallel paths without relying on passive network redistribution. (Chijindu et al., 2018) applied UPFC to the Nigerian 28-bus network and demonstrated a 1.43-fold extension of the voltage collapse margin under three-phase fault contingency conditions, confirming that UPFC delivers both thermal congestion relief and stability-margin improvement simultaneously. The recommended placement is the Gombe–Damaturu interface, identified across multiple studies as the reactive and thermal bottleneck of the North-East radial

6.0 Conclusion

Nigeria's 330kV transmission network is faced with simultaneous crises in ohmic losses, voltage instability, and line congestion, all of which are structurally rooted in a network designed decades ago for a fraction of current demand. This review has demonstrated that these three challenges are deeply interconnected. Reactive deficits simultaneously cause voltage collapse and increase losses; radial topology simultaneously creates congestion bottlenecks and eliminates voltage recovery pathwaysand ageing infrastructure raises both resistance losses and system vulnerability.

The computational case study of the Alaoji corridor quantifies the loss problem with precision12.89MW wasted at SIL, 39.4MW at thermal limit and demonstrates that parallel circuit addition achieves the highest singleintervention loss saving of 6.44MW. Voltage instability analysis confirms that eight northern buses operate chronically below the 0.95 pu statutory floor, resolvable through targeted STATCOM placement at Maiduguri. Congestion analysis establishes that the single Jebba–Oshogbo corridor connecting the North to the rest of the grid represents an existential reliability risk, demanding priority ring topology investment.

The evidence synthesis across more than twenty studies points to a clear intervention hierarchy nearterm software interventions (OPF, SCADA/EMS with UVLS and PMUs) should be deployed immediately at low capital cost, mediumterm FACTS devices (STATCOM at Maiduguri, SSSC at Gombe, UPFC at Gombe–Damaturu) should follow to address voltage and thermal constraints and long-term network reinforcement (North-West ring, North-East ring loop, parallel Alaoji–Onitsha circuit, and conductor reconductoring) represents the only permanent structural resolution. Executed systematically, this framework offers Nigeria a credible path from the current 2.5 collapses per month to a grid capable of supporting its 220 million people and 45,000MW latent demand.

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