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Research Article

Mitigating Power Losses in Nigeria's Power Transmission System: Analysing Challenges and Exploring Solutions

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Abstract

This study offers a unique perspective on the challenges and potential solutions for mitigating power losses in Nigeria's power transmission system. While numerous technical strategies are available, their practical application within the specific context of Nigeria remains underexplored. The analysis focuses on the country's transmission grid, highlighting the critical elements and their impact on power efficiency. The study identifies significant causes of power losses, such as resistive, over-excitation, under-excitation, and coronal losses. It explores the technological and policy interventions needed to address these issues. However, it is crucial to emphasise that these interventions must be part of a comprehensive approach. Through detailed case studies of Lagos, Abuja, Kano, and Port Harcourt, the research presents best practices, including innovative grid technologies, infrastructure upgrades, community engagement, and regulatory reforms. The findings underscore the complexity of the issue and the crucial need for a comprehensive approach that combines technological advancements and effective policy frameworks to enhance the reliability and efficiency of Nigeria's power transmission system. This comprehensive approach ensures that all aspects of the problem are considered and addressed, leading to more effective solutions.

Keywords: Power Transmission System; Power Loss Mitigation; Smart Grid Technologies; Regulatory Reforms; Infrastructure Upgrades

Introduction

The urgency of mitigating power losses in Nigeria's power transmission systems, a topic that has not been extensively explored, underscores the significance of this study. We examine the challenges of minimising power losses in the Nigerian National Transmission Grid by studying different vital elements of the system. Although many documents available on specific topics have revealed many helpful technical strategies, little information is available on how to translate these strategies into practical work in the scope of a country's particular settings, or even the local level, or what technical and non-technical resources, infrastructure, and conditions are needed, and how this could be practically planned. In addition, research on what has been done, focusing on an individual system, highlighting the influence of actual applications on the technical background of power losses, showing changes in the power system to minimise the power loss, to create a guide when proposing, or even thinking about planning a future expansion of the power system, is still minimal. "Mitigating Power Losses in the Nigerian National Grid: Analysing Challenges and Exploring Solutions" highlights the significance of internal power loss, describes and analyses the research and development strategies put forward to deal with the problem, and then discusses the challenges of mitigating power losses in the Nigerian power transmission system. The high performance of power grids depends on providing reliable power without compromising power quality and ensuring minimal losses. Nevertheless, the impact of power loss can be seen in almost every existing transmission infrastructure worldwide, significantly burdening the national grid. The literature has a lot to say about power losses and different techniques that can be employed to mitigate them and improve the overall efficiency and quality of transmission systems. Our research provides practical insights and recommendations that can guide future planning and expansion of power systems, making it a valuable resource for policymakers, engineers, and researchers in the field.

Overview of Nigeria's Power Transmission System

The Transmission Company of Nigeria (TCN), which has existed for some time, has become the owner and operator of the National Integrated Power Project. Nigeria currently has over 50 power-generating stations within the NPC. Delays in executing the feasibility study and manpower early in the ongoing reform program also cost TCN insufficient knowledge of revenue flows from power customers (Sule, 2023). Furthermore, based on the Transmission Grid Code Guideline for Development, System Planning, and Reserved Services for the Nigerian Power Sector, a comprehensive package of induction training would be availed to current and new individuals employed within the outfit to pass through this channel by the NBET in Nigeria (Remy & Chattopadhyay, 2021). The System Maintenance and Evaluation framework introduced the power system load forecast methodologies and a specification of the power system to be contracted for the supply process in Nigeria (Ogar et al., 2022). Nigeria's transmission system is the conduit of the electric power supply chain, where electric power is transferred from generating stations to local power distribution networks within the country. Generating stations create electric power, and distribution systems deliver electric power directly to consumers, regarded as final product delivery points. The capacity of the Nigerian power transmission network experienced outstanding expansion when the 132/33kV-1, 2, & 3 were commissioned in 1968 and 1974, respectively, in Aba, Abia State, Plateau, and Ondo State. However, the transmission capacities of the Nigerian transmission systems over time from 1974 to 2014 have remained below capacity at an average Spare Transmission Capacity of 10% (Adebayo et al., 2024).

Understanding the Nigerian Power Transmission System is crucial for anyone concerned with the efficient distribution of electricity nationwide. With a deep comprehension of this complex network, one can navigate the intricacies of power transmission and contribute to advancing Nigeria's energy sector. A comprehensive understanding of the Nigerian Power Transmission System requires an in-depth exploration of its infrastructure, operations, and challenges. By delving into this system's key components and mechanisms, one can gain insights into its functioning and identify potential areas for improvement. Moreover, understanding the Nigerian Power Transmission System enables stakeholders to make informed decisions, implement effective strategies, and collaborate towards a reliable and sustainable power supply.

Analysis of Nigeria's Transmission System

Overview

Figure 1 illustrates Nigeria's power transmission system, highlighting the nationwide 330 kV and 132 kV circuits and substations. The map provides a comprehensive view of the geographical distribution and connectivity of high-voltage transmission lines and substations essential for power distribution and grid stability.

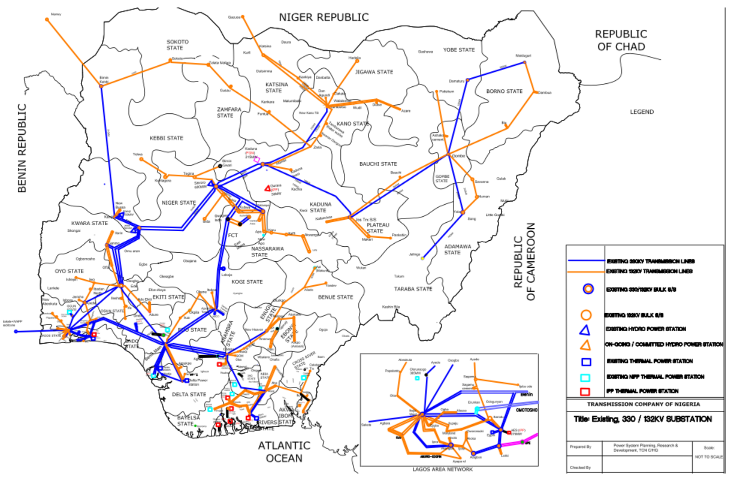

Figure 1: The transmission system in Nigeria comprises 330 kV and 132 kV circuits and substations

Key Components of the Transmission System

1. ***330 kV Circuits:***
    a. Represented by the bold blue lines, the 330 kV circuits form the backbone of the national grid. These high-voltage lines are crucial for long-distance transmission, reducing power losses over extensive distances.

b. The 330 kV lines connect major power-generating stations to regional substations, facilitating the bulk transfer of electricity.

2. ***132 kV Circuits:***

a. As indicated by the orange lines, the 132 kV circuits serve as regional distribution lines. They remove power from the 330 kV lines at substations to deliver electricity to local distribution networks.

b. These lines ensure that power reaches more localised areas, supporting consumers' final leg of electricity distribution.

3. ***Substations:***

a. Marked by various symbols, substations are critical nodes in the transmission network where voltage is transformed between high and lower levels.

b. Substations are also points of control and protection, managing the flow of electricity and safeguarding the grid from faults and overloads.

Geographic Distribution

1. ***Southern Region:***

a. The southern part of Nigeria, including Lagos, Port Harcourt, and Benin, shows a dense network of 330 kV and 132 kV lines. This region has a high concentration of industrial and urban centres, necessitating robust transmission infrastructure.

b. The coastal proximity and industrial activities demand substantial power, leading to a more intricate and extensive network.

2. ***Northern Region:***

a. The northern region has fewer 330 kV lines, indicating a less dense population and industrial presence than the south.

b. Cities like Kano and Kaduna are major nodes connecting the northern grid to the southern power sources.

3. ***Central Region:***

a. Abuja, the capital city, serves as a significant hub in central Nigeria, with multiple 330 kV and 132 kV lines converging to ensure reliable power supply to government and administrative functions.

b. The central region's grid connects northern and southern networks, which is pivotal in balancing the national grid.

Challenges and Considerations

1. ***Infrastructure Upgrades:***

a. Many transmission lines and substations are ageing and require upgrades to handle increasing power demands and improve reliability.

b. Investments in modernising infrastructure with advanced technologies such as High-Temperature Low-Sag (HTLS) conductors and smart grid solutions are essential.

2. ***Power Loss Mitigation:***

a. The map highlights potential areas where power losses can occur due to the long-distance transmission and the state of existing infrastructure.

b. Implementing loss reduction strategies, including improved maintenance and the use of superconducting materials, can enhance efficiency.

3. ***Regional Disparities:***

a. There is a noticeable disparity in the density and quality of the transmission network between the north and south. Efforts to balance this, including new transmission projects and regional development initiatives, are crucial.

4. ***Security and Vandalism:***

a. Protecting the transmission infrastructure from vandalism and theft, especially in remote areas, is critical for maintaining a stable power supply.

As depicted in Figure 1, Nigeria's transmission system underscores the complexity and scale of managing a national grid across diverse regions. Addressing the challenges through strategic upgrades, policy reforms, and technological innovations will be vital to improving the reliability and efficiency of Nigeria's power transmission system.

Understanding Power Losses in Transmission Systems

There are numerous causes of power losses in the power network. In order to understand power losses and how they can be mitigated, it is crucial to delineate the sources of the power losses (Kuchanskyy **&** Zaitsev, 2020). There are two **primary** sources of power losses. The first source of power loss is I2R, where I refers to the current while R refers to the effective resistance offered by the conducting path of the electric power. Effective resistance is the sum of the resistance caused by the forces of the operation of the materials and spurious resistance (Blinov et al., 2020). The causes of the effective resistance, which are factors contributing to power losses, are:

Causes of Over-Excitation: If over-excitation (i.e., too much reactive power) is allowed in the transmission system, oscillation is expected because the system becomes operationally unstable (Shi et al., 2021).

Causes of Under-Excitation: Under-excitation results from high transmission lines due to low electrical power demand. It leads to low reactive power running through the transmission lines. The magnitude of power loss depends on the excess reactive power flowing on the transmission lines. Reactive power drives the voltage profile in the transmission line. Currently, under-excitation reduces the dielectric losses in Nigeria's power transmission system. In some developed countries, excess generation capacity relative to power traffic commonly causes the voltages to run high while low reactive power flows on the transmission lines (Van et al., 2020).

The second significant source of power losses is the coronal losses. Generally, coronal losses, also known as the corona effect, arise at high voltages of alternating electric currents through the ambient air **(Adebayo et al., 2020**). Thus, gas mixtures are partially ionised, and a portion of the energy of the electric field is spent on that, affecting system losses. Although these coronal losses may affect power losses somewhat, they must be considered to highlight effects that may not be associated with usual I2R losses.

Other factors contributing to power losses include several types of resistance within the electrical infrastructure. The resistance of line conductors, which carry electricity across long distances, is a significant source of power loss. Similarly, the resistance within transmission line conductors also contributes to these losses. Distribution network conductors, which distribute power locally, have a resistance that leads to energy dissipation. Additionally, the transposition of distribution network circuits, which involves rearranging the conductors to balance the load, can introduce resistance that affects power efficiency. Transformers adjust voltage levels for transmission and distribution and also have inherent resistance that causes power losses. Service conductors, which connect the main distribution lines to individual consumers, add another resistance layer. The resistance of the connecting wires within the system further contributes to power losses. Lastly, the resistance of various electrical equipment used throughout the transmission and distribution process also plays a role in the overall power losses experienced in the system.

Causes of Power Losses

The priority focus in EPOSS is on max-imm particle swarm optimisation/successive linear programming, which minimises total production and losses using different initial condition generations (Shiru et al., 2020). A closer look at Nigeria's University of Lagos and Benin City zones shows they have a higher share of the total national power system. The Lagos zone is peopled with a large industrial base, and several industries are also located on the Benin axis, so these zones are often faced with greater load demands (Olajide & Lawanson, 2022). Igarashi et al. then argue that a high voltage push of over 400kV is required in Africa, especially Nigeria, to optimise energy and reduce losses (Ojekunle et al., 2020). This study delves into the analysis of causes of power losses within the transmission system, which was used to focus on the analysis of the causes of power losses in the transmission system to lay the foundation for analysing how the challenges and possible solutions to mitigate these losses (Odukoya & Ifarajinmi, 2021).

Causes of Power Losses: According to Article 2 of the EPOSS Regulation (TCN, 2014), a distinction is made between technical losses, which are inherent in the transmission system and occur when the transmission network suffers energy dissipation due to the inherent properties of electrical devices, and non-technical losses, which are related to energy theft or illegal connections to the network. Bignasco et al. (2015) estimate that reducing non-technical losses may lead to a potential 15% reduction in the entire non-OECD country, while using high-voltage superconducting power metal oxide semiconductor systems (HVDC) transmission cuts total losses by 50% due to reduced technical and non-technical losses, as the HVDC transmission system has fewer components adapted to the system and shorter lines.

Impact of Power Losses

Based on the analysis carried out, it was observed that the impact associated with the transmission power losses experienced by the Nigerian power transmission system significantly affects transmission system capacity, leading to higher network losses, economic implications of losses, inefficiency, and a reduction in perceived value quality and measurement of service (Komolafe & Udofia, 2020). Given the impact of high power losses, the transmission sector must be economically regulated (Adams et al., 2020). Regulators must anticipate future investment in transmission expansion programs by identifying and reducing the anticipated increase in future power losses. This would encourage the adoption of more proactive and preventive loss reduction measures within the sector rather than the implementation of corrective loss reduction measures, which are generally reactive (Mukhtar et al., 2021). Regulatory amendments and policies that encourage the injection of adequate resources into eliminating the leading causes of technical, non-technical, and commercial losses due to power theft must be implemented in the sector (Fasina et al., 2021). The transmission system is considered the nerve line of power systems. It forms the quantum leap between self-sufficiency and procuring power from a nearby distribution system or an external generation source (Adebayo et al., 2019). As such, any amount of power loss occurring in the system can be assumed to severely impact the quality of the power transmitted through it. A drop in the quality of the transmitted power would subsequently lead to an increase in the inability of the distribution system and load to convert the power into usable energy (Mukhtar, 2018). It can be assumed that losses occurring in the Nigerian power transmission have equally converted the expected quality of energy received by end-users to an unusable conversion of power received from the generation source.

Challenges in Mitigating Power Losses in Nigeria's Transmission System

Operationally, it would be necessary to introduce policies that discourage deliberate theft of conductors and equipment and persuade farmers and companies to desist from 'accidentally' hitting or destroying conductive and structural poles and transformers (Ramirez-Bettoni & Nemeth, 2023). According to the author, phase identification in under-energised EHV systems has yet to be developed, except in developed electrical transmission systems. Eligible customers (and individuals, since power consumption is generally assumed to be through electrical meters) should be charged for subsidised power/energy consumption rather than paying lump sums or being overcharged (Stephen & Iglesias, 2023). Moreover, the absence or non-maintenance of local substations at or close to the locations of high power demand would exacerbate the problem of increased power losses in a rapidly growing demand environment, affecting the electrical grid's revenue.

Large and heavy metal enclosures, durable against natural corrosion, bad weather, and rodents/animals, must house such systems/switchyards. They are mostly imported, even via air freight, to where electrical substations have been developed in remote and rural grids/subsystems (Adebayo et al., 2022). Upgrades usually cost approximately 40% more than the original or previous equivalent equipment but should become standard as costs gradually decrease (Liu et al., 2021). Pneumatically operated HCBs could last years, even with non-regular maintenance, despite the existing tendency to have all switching equipment manually operated. Mitigating power losses in Nigeria's transmission system is complex due to infrastructure, operational requirements, and enormous costs.

Investing in technologies like FACTS or HTLS tends to counter the local initiatives for grassroots power generation, including in places where the grid is already stable. RFIDs are challenging to implement as transformers handling considerable power are vulnerable to this relatively safe 'attack' (Uzelac et al., 2020). It is evident that uprating the lines (whether or not there is land for this), yard coil equipment, and generally bearings, besides introducing a general multi-level maintenance policy to maintain the transmission system in top working conditions, would involve huge costs. Introducing original suppressors would likely involve an inappropriate substitution of the original with later suppressors. Cutting the shield wire and leaving it on the ground where it cannot collide with people and animals would be best in such rural districts, a practice already used in grids in developed countries. Challenges in mitigating power losses in Nigeria's transmission system emerge when one seeks to solve a technical issue, hoping to improve the state of things. Identifying these challenges is essential to address them. Because of the complex nature of the infrastructure and operational requirements to mitigate power losses in Nigeria's power transmission system, an attempt is made to identify these challenges and the various possible solutions.

Table 1: Summarising the challenges in mitigating power losses in Nigeria's Transmission System, with the possible location

Category	*Challenges*	*Possible Location Example*
Technological	Obsolete infrastructure (e.g., outdated transmission lines and equipment)	Lagos, Ibadan
	Frequent high-voltage breakdowns	Benin City, Port Harcourt
	Lack of maintenance and upgrades	Kaduna, Kano
	Inefficiency in transmission designs and materials	Abuja, Enugu
	Inadequate use of advanced technologies (e.g., superconducting materials, FACTS, HTLS)	Lagos, Abuja
	Technical limitations in phase identification and high VF/low VF management	Onitsha, Sokoto
	Challenges in implementing smart grid technologies and power electronics	Lagos, Port Harcourt
Policy/Regulatory	Inadequate regulatory frameworks and policy implementation	National, affecting all states
	Conflicts between federal and state-level regulations	National, conflicts in states like Lagos
	Insufficient enforcement against power theft and illegal connections	Rural areas, urban fringes
	Lack of investment incentives for upgrading and maintaining infrastructure	Nationwide
	Ineffective governance and oversight in the power sector	National, affecting major cities
Economic	High costs of upgrading and maintaining transmission infrastructure	Lagos, Abuja
	Economic losses due to high power loss rates and inefficiencies	Nationwide
	Limited funding for advanced research and development in power technologies	Nationwide
	Financial implications of implementing new technologies and maintaining existing ones	Nationwide
Operational	Inadequate manpower and technical expertise in managing and operating the transmission system	Rural areas, regional grids
	- Vandalism and theft of transmission infrastructure components	Rural areas, Lagos suburbs

- Environmental challenges such as bush, swamp, and urban sprawl affecting transmission paths	Niger Delta region, Northern Nigeria
- Poor performance of grid systems due to lack of localised substations and maintenance	Onitsha, Aba
- Operational inefficiencies such as inadequate phase identification and reactive power management	Nationwide, especially in growing urban areas

This table highlights the challenges in mitigating power losses in Nigeria's transmission system and provides location-specific examples of where these challenges are prevalent.

Infrastructure Challenges

The increasing loss of power in our transmission infrastructure system has become a great concern to power generation and distribution companies (Adoghe et al., 2023). Power network phenomena that result in electrical energy losses are numerous, but significant among them are issues relating to generation availability (power production), systems stability, default exposure, combustion, insulation, lightning effects in thunderstorms, conductor inductive effect, reactor leakage from the management system, switching rechargeable battery, capacitor management for short circuits, and battery status management of electrical energy supply system of power transmission lines (Babatunde et al., 2023). Nepal's transmission line system, grid, and substations where power is evacuated are the primary physical or structural impediments leading to power losses in power transmission lines. Other indices include power production (generation), power evacuation systems and lines, wheeling of power (transmission), and improvement of operating setups, which experts verified (Ajibola et al., 2021). All these hindrances contribute to weaknesses that allow power to escape and accumulate losses in the transmission system. It is appalling and worrisome to hear that Nigeria's electrical power companies are losing 47 per cent of their electricity supply. This is called the 'peak generation' of 5,323 megawatts (MW) in October 2018, following the fall of 3,529 MW due to pipeline vandalism. Due to the power losses, N13.404 billion was lost. In February, the peak power fell by 1 63 MW to 35.51 MW and N5.520 billion. This power outage lasted about three to four weeks and was perpetuating, leading to power losses. Nigeria's power transmission infrastructure faces numerous challenges, including obsolete infrastructure, vandalism, lack of investment, inadequate capacities, and the absence or poor implementation of technology (Amadi & Ekeng, 2024).

Obsolete transmission equipment has become a significant cause of power loss due to frequent high-voltage breakdowns. Nigeria's transmission towers and lines have lacked regular maintenance, painting, or replacement, often leaving parts of the transmission power system in less than satisfactory conditions. Since Nigeria's transmission lines run through various environmental conditions of the bush, swamp, and urban sprawl, the isolated conditions of the transmission infrastructural path have been ideal environments for thieves vandals targeting dangerous pilfering of installed power infrastructures seeking metals from wires, rods, insulators, turbines, engines, shooting sticks, cooking stoves, and other appliances. These destructive events of infrastructure capacity have led to increased transmission disturbance, resulting in power reduction. The structural capacity of the Nigerian power transmission system in acting against power losses is frustrating, and measures can be adopted to redress the situation.

Operational Challenges

The source of power loss and system instability in Nigeria's power transmission system is widespread, and the operations' shortcomings sometimes reflect the problem's commercial and technical aspects. These are related to policy, system standard/procedure, and equipment's working efficiency, manpower, and safety requirements.

Limitations of the Study: In the work, sector-based future forecasts are not executed, depending on onsite assessments of load configuration and the demand's annual growth rate.

Managerial Problem: The managerial problem in the operation happens regularly with the management of manpower according to energy propagation. The coal supply is challenging to manage and depends upon the conditions and security position. Relaxation in overloading is another problem in line with the protection issue, which increases the probability of failure in relays. The configuration of the network for voltage correction is also a problem.

Scheduled outages: This is another common phenomenon that minimises the chance of forced outages. According to this, a few substations have to take short shutdowns, two out of schedule and two apart out of schedule at an equal time, to maintain the hardening of the mechanical loads, with two series reactors in each transmission system phase-wise. A step voltage drop has almost started and should be completed early.

Planning for AA—Maintenance: This is another pervasive problem when the line has to be shut down for planned or forced maintenance activity, which further increases the probability.

Inadequate Loadability is the most common problem. As per the considered network, Table 2.2—Loadability analysis and congestion can be maintained for the operation control centre as loss parameters and equivalent capacity are very close to each other, reflecting the loads in terms. That is why there are periodic shutdown events.

Technical Challenges: Major hurdles in improving or updating the systems to mitigate the power loss and reduce the losses include power factor correction, voltage improvement, series or shunt compensation, transmission network shaping and expansion, etc. Some technical issues are prevalent in transmission system-related substations, regulators, etc., reflecting common problems. Power flow analysis and operation also highlight the congested centre, losses vs flow, voltage profile, and feasibility of new power entrants, which are widespread problems.

In today's world, economics and energy requirements depend significantly on factors such as the direct transfer of energy and interfaces depending upon the economies. The primary source of charge/revenue generation in electricity transport is a commercial d-, depending upon the system's preference. For particular networks, the system operator has to trace and minimise the input after performing d and interchanged work. In an analogical power transmission system, "nettles" performance mitigation is based on the capital distribution between two series pass production sources.

Exploring Solutions to Mitigate Power Losses

Introduction and context. This part of the report focuses on establishing potential solutions to mitigate the profligate degeneration of energy within Nigeria's transmission system. To achieve this aim, the focus shifted away from power losses in general to measures within transmission systems, not minding high VF (voltage frequency) or low VF (voltage frequency) that will be practicalised or configuration that has been deployed in the Nigerian electricity grid (Mohammed et al., 2020). Moreover, it also encourages the appropriate on-lining of new assets in grid systems. Mitigating the poor performance of grid systems depends on the accuracy of solutions applied to the grey areas of challenge. It is important to note that just as the transmission system is divided into subsystems, the identification of constraints is also divided into technological and policy interventions. Accordingly, it is expedient for both categories of views to be presented in the same order as before (Adebanji et al., 2022).

Mitigating Power Losses in Nigeria's Power Transmission System: Expert Solutions This section focuses on establishing potential solutions to reduce the profligate degeneration of energy within Nigeria's transmission system. The solutions fall within two broad categories: technological and policy/regulatory interventions. The organisation of the solutions for consideration emerges in this order. Several areas are defined as potential research focuses for improved design of technological components, control systems, and models. Research is needed to recommend policy reforms to share some barriers among grid facilities and sectors (Komolafe & Udofia, 2020). The number of recommendations is pre-determined as the solution to these areas will enhance the overall performance of the Nigerian power transmission system, if not solve it completely. Technological solutions may include grid infrastructure advancements, implementation of innovative grid technologies, and improvement of maintenance practices. Research in these areas can help design more efficient and resilient power systems (Edomah et al., 2021). Policy reforms could focus on incentivising investment in new technologies, enforcing stricter regulations against power theft, and fostering better collaboration between stakeholders in the power sector (Dahunsi et al., 2021).

Technological Solutions

Innovative and technological solutions promise to mitigate power losses in the transmission system. Some technologies have already been developed or are being developed. Among the technological solutions, developing high-temperature nanomaterials for implementation in modern electrical systems to increase their load-carrying capability, particularly overhead high-voltage transmission lines, promises to be one of the most effective for these power system components (Hassan, 2020). Moreover, the development of new materials and advanced transmission designs, including superconducting materials to increase the capacity of transmission, retaining less power in the form of heat dissipation (losses), and evacuated cable tunnels to dissipate heat, is a more sustainable solution for transmitting alternating and direct current electricity over and across the transmission system (Chen et al., 2021). Additionally, transformers with solid insulation, mobile dryer transformers, insulation level upgrades, and power electronics in the transmission system are effective measures to counteract the power loss problem in transmission systems (Pandey, 2022). Power loss in a power system is an old problem that has grown with real-time power demand growth and is not simple to solve under voltage and power parameters. Implementing a flywheel with power electronics in a transmission system is a technical solution whose decommissioning overcomes power downtime outages (MacManus-Driscoll & Wimbush, 2021). These technological solutions promise reduced power dissipation and shall be adopted to boost system robustness.

Policy and Regulatory Interventions

The broader regulatory environment for service providers and electricity market participants is essential, and the trends observed in the system losses may indicate the overall weaknesses or robustness of the institutional framework (OBAFEMI, 2021). In other words, the Nigerian Transmission Loss Level (NTLL) may be an indirect and top-level measure of the country's institutional strength. Therefore, top-level institutions must support and facilitate structural and systemic interventions to tackle and mitigate systemic constraints with the most significant potential for bolstering the increment of institutional and economy-wide robustness (MUZALIA, 2021). Addressing the policy and regulatory challenges before considering any technical solutions is essential in designing loss responses. Understanding the governance and regulatory barriers to system-wide loss mitigation is critical. Although several theoretical accounts of the political economy of regulation exist in the literature, the peculiarities of the Nigerian regulatory context of the transmission company need to be thoroughly investigated (Leite et al., 2020). Internationally, the political economy of transmission system governance and regulation resonates with the Nigerian electricity system's regulatory framework features. Understanding the political and economic features of the Nigerian power sector regulatory environment may provide a better perspective on the regulatory strategies most viable in supporting transmission loss mitigation in the country.

Policy and regulatory interventions reside at the core of addressing power loss challenges. The Nigerian power sector is characterised by severe governance and regulatory challenges, especially at the state and local levels. The sector also faces legal and regulatory conflicts between the federal power sector regulator and state-level institutions, leading to a shallow level of policy implementation (Adebayo et al.). Therefore, strategic governance and improved regulatory frameworks may contribute to addressing the constraints in the electricity system by improving financial and technical performance, incentivising further investments in the system, and increasing the reliability of the electricity market.

Case Studies and Best Practices with Examples for the Challenges and Mitigation of Power Losses in Nigeria's Transmission System

Case Study 1: Lagos - Implementation of Smart Grid Technologies

Challenge: As Nigeria's commercial hub, Lagos faces significant power losses due to outdated infrastructure and high demand.

Best Practice**:** Introduction of smart grid technologies.

Implementation:

1. ***Advanced Metering Infrastructure (AMI):*** It has been deployed across various parts of Lagos and allows real-time monitoring and management of electricity usage, which helps reduce non-technical losses like electricity theft.
2. ***Real-Time Monitoring:*** Sensors and smart meters installed throughout the grid allow quick detection and response to faults or inefficiencies.
3. ***Demand Response Programs:*** Programs that encourage consumers to reduce or shift their power use during peak periods, decreasing the load on the transmission system.

Example: In Victoria Island, the implementation of AMI reduced electricity theft by 30% within the first year, leading to more accurate billing and higher revenue for power companies.

Outcome: A reduction in power losses and improved reliability of the power supply. Enhanced consumer engagement and satisfaction due to transparent billing and better service.

Case Study 2: Abuja - Upgrading Transmission Infrastructure

Challenge: Rapid urbanisation in Abuja has outpaced the capacity of its ageing transmission infrastructure, causing significant power losses and frequent outages.

Best Practice: Upgrading and modernising the transmission infrastructure.

Implementation:

1. ***Reconductoring Projects*:** Replacement of old conductors with new, higher-capacity ones to reduce resistive losses.
2. ***High-Temperature Low-Sag (HTLS) Conductors:*** Installation of HTLS conductors to carry more current without excessive sagging.
3. ***New Substations:*** Construction of new substations to decentralise the load and improve grid stability.

Example: In the Gwarinpa area, introducing HTLS conductors and new substations resulted in a 20% reduction in transmission losses and significantly fewer outages.

Outcome: A noticeable decrease in transmission losses and improved stability and reliability of the power supply in Abuja.

Case Study 3: Kano - Addressing Vandalism and Theft

Challenge: Vandalism and theft of transmission infrastructure are persistent problems in Kano, leading to increased power losses and service disruptions.

Best Practice: Community engagement and security enhancements.

Implementation:

1. ***Community Policing:*** Collaboration with local communities to report suspicious activities and protect infrastructure. Awareness programs about the importance of power infrastructure.
2. ***Physical Security Measures:*** Installation of surveillance cameras, fencing around critical infrastructure, and hiring security personnel.
3. ***Legal Framework:*** Strengthen laws and regulations to impose stricter penalties for vandalism and theft and ensure rigorous enforcement.

Example: In the Nassarawa area, community policing and physical security measures reduced incidents of vandalism and theft by 50% within six months.

Outcome: A significant reduction in vandalism and theft, leading to fewer interruptions and losses in the power transmission system.

Case Study 4: Port Harcourt - Regulatory and Policy Reforms

Challenge: Port Harcourt, an industrial hub, suffers from regulatory and policy issues that lead to inefficiencies and power losses in the transmission system.

Best Practice: Implementing comprehensive regulatory and policy reforms.

Implementation:

1. ***Policy Incentives*:** Introducing incentives for private investment in transmission infrastructure, such as tax breaks and subsidies.

2. ***Regulatory Reforms:*** Streamlining the regulatory framework to reduce bureaucratic hurdles and enhance coordination between federal and state agencies.
3. ***Performance-Based Regulation:*** Implementing regulations that tie utility performance to incentives, encouraging companies to reduce losses and improve service quality.

Example: In the Trans-Amadi Industrial Layout, regulatory reforms and policy incentives attracted private investments, which upgraded transmission lines and substations, resulting in a 25% decrease in power losses.

Outcome: Increased investment in transmission infrastructure, improved regulatory oversight, and enhanced coordination among stakeholders, leading to a reduction in power losses and improved grid reliability.

The challenges facing Nigeria's power transmission system are diverse, involving technological, regulatory, economic, and operational issues. However, through targeted interventions and best practices, significant progress can be made in mitigating power losses. The Lagos, Abuja, Kano, and Port Harcourt case studies demonstrate that a combination of smart technologies, infrastructure upgrades, community engagement, and policy reforms can effectively address these challenges, leading to a more efficient and reliable power transmission system in Nigeria.

Recommendations

To ensure synergy in the overall configuration of the power system, a practical and pragmatic dispatch policy needs to be evolved. Such a policy should not only provide direction for the utilities to maintain a meaningful strategic plan but also provide guidelines for a viable economic solution to the power loss, leading to the efficient functioning of the utilities. The planner may think of having a control strategy by applying innovative devices and technologies to mitigate the surges in the transmission lines. The strategies for reducing fault current intensity, preventing voltage collapse, and reducing corona losses need to be developed to ensure voltage stability enhancement and loss minimisation for the systemic operation of the power grids. Looking towards the Internet of Things (IoT) technologies, Smarty's concept for integrated operation and comprehensive planning in reducing power losses in the power transmission system is also urgently needed.

Conclusion

The challenges of power losses in a power transmission system are addressed in this paper in the context of Nigeria. Tackling the multiplicity of these challenges can contribute to the development and stability of power system operations and the grid. In this context, quick identification, diagnosis, and upgrading of multi-stage loads are promising for reducing corona losses. In addition, the anticipation and prevention of voltage collapse have become an urgent requirement in the present paper. It is also indicated that transmission lines provide a low impedance path over which short circuits can transform directly to the ground, thus necessitating an enhanced technique to spot and arrest the transmission line faults and lower the fault current flow. In this connection, load flow improvement has been observed as a potent way to minimise the transmission line fault, but it will require a high degree of planning and system studies.

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