

ADVANCED POWER TRANSMISSION TECHNIQUES FOR REDUCING LOSSES IN LONG-DISTANCE POWER TRANSFER

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ABSTRACT

Power losses in long-distance transmission remain a major challenge for efficient electricity delivery, especially in developing countries like Nigeria. These losses, caused by technical inefficiencies and outdated infrastructure, result in high operational costs, reduced utility revenue, and limited energy access. This study explores advanced transmission techniques—such as High Voltage Direct Current (HVDC), Flexible AC Transmission Systems (FACTS), High-Temperature Low-Sag (HTLS) conductors, and Dynamic Line Rating (DLR)—to reduce losses and improve grid reliability. Focusing on the Nigerian power system, the research highlights the economic, social, and environmental impacts of transmission inefficiencies. It demonstrates that adopting modern technologies, coupled with policy reform and strategic investment, can significantly reduce losses, enhance grid performance, and support national development goals.

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INTRODUCTION

Electricity plays a pivotal role in modern life, supporting essential services, economic development, and technological advancement. However, delivering electricity efficiently from generation centers to end users remains a technical challenge—especially in countries with expansive geographies or inadequate infrastructure. (Chineke, & Igwiro, 2008). Power transmission over long distances is particularly prone to inefficiencies caused by technical losses, environmental conditions, and infrastructural constraints. In the 21st century, improving the efficiency of long-distance power transfer has become increasingly critical due to growing energy demands, integration of renewable energy sources, and the urgent need to reduce greenhouse gas emissions.

In countries such as Nigeria, where power generation is often centralized, electricity must be transported across hundreds of kilometers to reach urban and rural demand centers. This long-distance transmission is marred by substantial technical losses, which in some cases can account for more than 20% of generated electricity. (Ibrahim, Shaari, & Mohd. 2021). These losses not only reduce the availability of power to end users but also increase the cost of electricity and the burden on existing infrastructure. Without effective strategies to mitigate these transmission losses, national development goals and efforts to provide universal access to electricity will remain compromised.

Advanced power transmission techniques offer promising solutions to this challenge. Innovations such as High Voltage Direct Current (HVDC) systems, Flexible Alternating Current Transmission Systems (FACTS), and the use of High-Temperature Low-Sag (HTLS) conductors are transforming how power is transmitted over long distances (Santos, Gough, Fitiwi, Silva, Shafie-Khah, & Catalão, 2021). These technologies help reduce resistive losses, improve voltage stability, and allow greater control over power flow in the grid. Moreover, modern grid management tools—such as Phasor Measurement Units (PMUs) and Supervisory Control and Data Acquisition (SCADA) systems—enhance operational efficiency by enabling real-time monitoring and adaptive control of transmission networks. The efficient transmission of electric power over long distances has been a subject of engineering concern since the inception of centralized power systems in the late 19th century. (Domínguez, Escobar, & Gallego, 2017). Traditional Alternating Current (AC) systems, while efficient for moderate distances and local distribution, face significant technical challenges when scaled for high-voltage, long-distance transmission. Among these challenges are resistive losses (I^2R), reactive power losses due to system inductance and capacitance, voltage instability, and limited controllability over power flows.

In the context of developing nations, these challenges are exacerbated by aging infrastructure, suboptimal grid planning, low investment in transmission upgrades, and weak enforcement of maintenance practices. For example, Nigeria's power transmission network operates significantly below optimal performance levels. The national grid is often overloaded, resulting in frequent voltage fluctuations, equipment failure, and large-scale blackouts. Compounding these problems is the fact that Nigeria generates a significant portion of its electricity in the southern part of the country, while the bulk of demand comes from the north, necessitating long-distance transmission.

The integration of modern transmission technologies can drastically improve grid performance. HVDC transmission, for instance, offers 30–40% lower losses compared to AC systems over

long distances, particularly in cross-country or submarine cable applications. (Liu, Zhang, Cheng, Liu Zhang, & Zhang, 2021) FACTS devices such as STATCOMs and SVCs enhance dynamic voltage control and stability. HTLS conductors allow higher current-carrying capacity with reduced sagging and thermal stress. Moreover, the implementation of Wide Area Monitoring Systems (WAMS), PMUs, and SCADA systems allows transmission system operators to respond proactively to grid disturbances, thereby preventing cascading failures.

Globally, countries like China, India, and Brazil have embraced these innovations with remarkable success. China, for example, has invested heavily in HVDC projects to transport hydropower from the west to its highly industrialized east coast. Similarly, India's adoption of FACTS technologies has helped stabilize its transmission network and accommodate growing renewable energy penetration. (Roldán, Nieta, García-Bertrand, & Mínguez, 2018) These international examples provide valuable insights for nations like Nigeria seeking to modernize their transmission infrastructure and reduce energy losses. Despite ongoing reforms in the Nigerian power sector, one of the most persistent and costly challenges remains the high level of technical losses in the transmission network. These losses are primarily due to outdated infrastructure, poor grid planning, inadequate maintenance, and inefficient long-distance power transfer. In many cases, electricity generated from gas-powered stations or hydroelectric dams must travel over 400 km to reach major load centers, leading to significant voltage drops and energy dissipation. These losses not only compromise service reliability and quality but also drive up operational costs for utilities and end users.

Currently, the average transmission loss in Nigeria ranges between 7–10%, with actual figures potentially higher in rural and under-monitored areas. This inefficiency represents a major drain on the power sector's limited financial resources and hampers efforts to meet national electrification targets. Furthermore, the lack of real-time monitoring and automation within the transmission network limits the system's ability to respond to dynamic load changes, equipment failure, or grid instability—making it vulnerable to blackouts. (Teimourzadeh & Aminifar, 2015) While some policy measures and infrastructure investments have been introduced, they are often hampered by insufficient funding, lack of technical capacity, and institutional inertia. The failure to adopt advanced power transmission techniques continues to delay the realization of a resilient and efficient power system. Thus, it becomes imperative to explore viable technological interventions that can reduce long-distance transmission losses and improve overall power delivery efficiency.

Concept of Power Transmission

Power transmission is a fundamental aspect of electrical engineering and energy infrastructure. It involves the bulk movement of electrical energy from generating stations to substations near populated areas where electricity is distributed to consumers. (Ploussard, Olmos, & Ramos, 2019) In modern power systems, power transmission plays a vital role in ensuring a stable, efficient, and reliable supply of electricity across vast geographical regions. This section explores the concept, purpose, components, and classifications of power transmission, providing the foundational understanding required to appreciate the challenges and advancements in this field.

Power transmission refers to the process of transporting electrical energy from the point of generation (such as thermal, hydro, or renewable power plants) to the point of distribution or consumption through high-voltage transmission lines. Unlike power distribution, which deals with delivering electricity at lower voltages directly to consumers, transmission focuses on moving large quantities of electrical energy over long distances using high voltages to reduce

energy losses. (Wang, Geng, & Jiang, 2019) According to the **International Electrotechnical Commission (IEC)** and other standard bodies, transmission systems are defined by their voltage levels, typically ranging from **69 kV to over 765 kV** in high-voltage and extra-high-voltage applications. The power transmission system serves several critical functions in the electrical power infrastructure:

Linking Generation to Load Centers

Power plants are often located far from areas of high electricity demand due to geographic or environmental considerations. Transmission lines bridge this gap by efficiently transporting energy from these remote generation sources to urban, industrial, and rural load centers.

Enhancing System Reliability and Stability

An interconnected transmission network enables electricity to flow through multiple routes, providing redundancy and enhancing the reliability of the power system. If one route fails, others can compensate, reducing the risk of blackouts.

Facilitating Economic Dispatch

Transmission allows for the optimal dispatch of power from the lowest-cost generating units, regardless of their location. This reduces overall generation costs and enhances economic efficiency in power markets.

The Nigerian Power Transmission Context

Nigeria's power transmission sector faces unique challenges that exacerbate the issues of power losses. The Transmission Company of Nigeria (TCN) operates a radial network with limited redundancy, making it vulnerable to faults and outages. The existing transmission lines have a wheeling capacity of about 7,500 MW, while the actual demand often exceeds this capacity. This mismatch leads to overloading and increased losses.

Nigeria, Africa's most populous nation and largest economy, faces a persistent and complex challenge in the form of an unreliable and inefficient power sector. (Ayokunle O. 2015) Despite having an installed generation capacity of over 12,000 MW, actual power delivered to end-users is often less than 4,000 MW, primarily due to limitations in the transmission and distribution infrastructure. The transmission network is a critical link in the electricity supply chain, bridging the gap between generation and end-user consumption. However, in Nigeria, this link is marked by aging infrastructure, technical losses, limited coverage, and frequent system collapses. This section explores the structure, challenges, and reform efforts in the Nigerian power transmission sector, highlighting the urgent need for modernization through advanced transmission technologies.

Structure of the Nigerian Power Transmission System

The power transmission sector in Nigeria is operated by the Transmission Company of Nigeria (TCN), a government-owned entity responsible for electricity bulk transmission, grid operations, and system stability. TCN emerged from the unbundling of the defunct National Electric Power Authority (NEPA) and was formally incorporated in 2005 under the Electric Power Sector Reform (EPSR) Act. Nigeria's transmission network consists of both 330 kV and 132 kV transmission lines:

- 330 kV lines connect major generation stations to regional substations and serve as the main backbone of the national grid.
- 132 kV lines serve as sub-transmission routes, linking regional substations to distribution companies (DisCos).

The country's transmission grid forms a radial and looped network connecting the six geopolitical zones and major urban centers. However, it lacks redundancy in many parts, resulting in vulnerabilities and frequent system disturbances. Transmission Infrastructure Overview is slated below

- **Total line length:** Over 20,000 km (330 kV and 132 kV combined)
- **Substations:** Over 800 transmission substations
- **Wheeling capacity:** Currently estimated at ~8,100 MW (as of 2024), though often underutilized due to constraints
- **Coverage:** Many rural and semi-urban areas remain unconnected to the national grid

Factors Contributing to Power Losses in Long-Distance Transmission

Power losses in long-distance transmission refer to the portion of electrical energy generated that is dissipated or wasted as electricity travels from power plants to end users through transmission lines. These losses are a major concern for electrical utilities and governments, as they directly affect the efficiency, reliability, and cost of electricity supply. (Keiner, Walter, & Bogdanov 2025) In many countries, particularly those with aging infrastructure or vast geographical areas, transmission losses significantly reduce the amount of usable power delivered to consumers.

The power transmission process involves high-voltage lines, substations, transformers, and other equipment that together make up the transmission grid. Despite technological advancements, the very act of transmitting power over hundreds of kilometers leads to unavoidable energy losses due to the physical and electrical characteristics of the system. These losses are generally classified as **technical losses**, which are inherent in the system, and **non-technical losses**, which result from human factors such as theft or meter tampering. This section focuses exclusively on **technical losses**, as they are directly related to the physical and engineering design of the transmission system.

Resistive (I^2R) Losses: One of the primary sources of power loss in transmission lines is resistive losses, which occur due to the inherent resistance of the conductors. As current flows through the transmission lines, a portion of the electrical energy is converted into heat, leading to energy dissipation. (Al-Hamouz, 2019) These losses increase with the length of the transmission line and the amount of current flowing through it.

Reactive Power Losses: Transmission lines exhibit inductive and capacitive properties, leading to the generation of reactive power. While reactive power does not perform any useful work, it is essential for maintaining voltage levels within the system. (Anumaka, 2012) However, the presence of reactive power can lead to voltage drops and increased losses, particularly over long distances. Managing reactive power is crucial for minimizing these losses and ensuring the stability of the power system.

Corona Effect: At high voltages, the electric field around the conductors can ionize the surrounding air, leading to the formation of a corona discharge. (Bamigbola, Ali, Oke 2014) This phenomenon results in energy loss in the form of electromagnetic radiation and ozone

generation. The severity of the corona effect increases with the voltage level and the physical condition of the conductors.

Ferranti Effect: The Ferranti effect occurs when a long transmission line, especially one operating under light load conditions, exhibits a rise in voltage at the receiving end. (Ngasop, David, Djalo, 2020) This phenomenon is due to the line's capacitance and can lead to overvoltage conditions, potentially damaging equipment and increasing losses. Mitigating the Ferranti effect involves careful line design and the use of reactive power compensation devices.

Advanced Techniques for Reducing Transmission Losses

Transmission losses are an inherent challenge in the delivery of electrical power, particularly over long distances. These losses not only reduce system efficiency but also increase the operational costs of power utilities. (Godslove I., 2020) As global energy demands rise and power systems expand to integrate renewable energy sources and serve remote areas, minimizing these losses becomes imperative. In this context, several advanced techniques and technologies have been developed to mitigate technical transmission losses. This section provides a detailed examination of such advanced techniques, including their principles of operation, advantages, applications, and relevance in improving power transmission efficiency—particularly in developing countries such as Nigeria.

High Voltage Direct Current (HVDC) Systems: HVDC technology offers a significant advantage over traditional alternating current (AC) systems for long-distance power transmission. (Wang, Redfern, 2010) By converting AC to DC for transmission and then back to AC at the receiving end, HVDC systems minimize resistive losses and allow for more efficient power transfer over long distances. Additionally, HVDC systems can stabilize the grid by providing better control over power flow and enhancing system reliability.

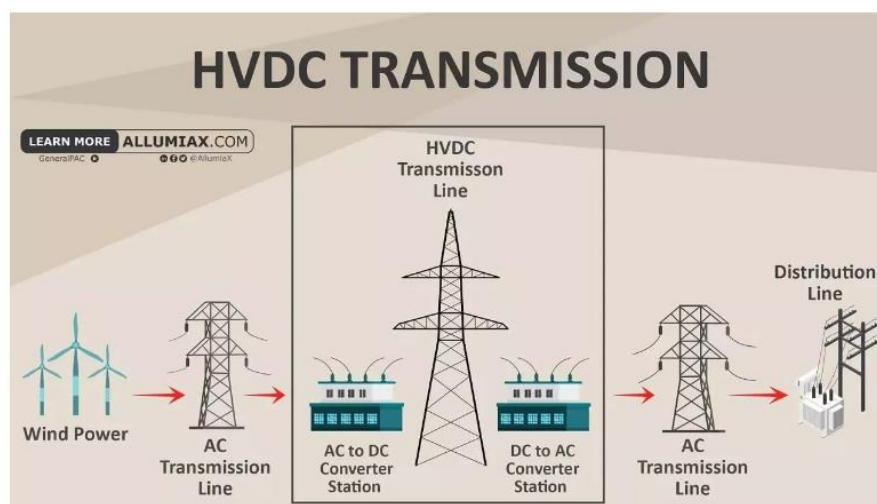


Fig. 1: High Voltage Direct Current (HVDC) Systems

Source: <https://www.allumiax.com/blog/high-voltage-direct-current-hvdc-transmission>

HVDC Transmission system is the combination AC and DC system, first the generated AC voltage is converted into DC at the transmission end, when it reaches the receiving end DC is inverted to AC for distribution purposes. (Marene, Inmaculada, Oihane, Abarrategui, & Iturregi 2014) So, in order to carry out this operating, we need conversion devices at both ends of

transmission line. However, HVDC Transmission is economical only for long distance transmission; overhead lines having a length more than 600km and underground cables of length more than 50km. Further we are going to discuss components, working, classification, comparison with HVAC system, advantages & disadvantages of a HVDC Transmission system.

Flexible AC Transmission Systems (FACTS): FACTS devices are used to enhance the controllability and stability of AC transmission systems. (Ban, Salem, Swadi, Senjyu, Kamarol, & Motahhir. 2024) They can regulate voltage, control power flow, and improve system stability, thereby reducing losses and preventing cascading failures. Common FACTS devices include Static Var Compensators (SVCs), Thyristor-Controlled Series Capacitors (TCSCs), and Unified Power Flow Controllers (UPFCs).

High-Temperature Low-Sag (HTLS) Conductors: HTLS conductors are designed to operate at higher temperatures than conventional conductors, allowing for increased current capacity without excessive sagging. (Riba, Bogarra, Gómez-Paul, Moreno-Eguilaz, 2020) This capability enables the transmission of more power through existing lines, reducing the need for new infrastructure and minimizing losses associated with overloading.

Superconducting Cables: Superconducting cables operate without electrical resistance when cooled to cryogenic temperatures, effectively eliminating resistive losses. (Bruzek, Allais, D. Dickson, Lallouet, Allweins, Marzahn 2015) While the technology is still in the developmental stage and faces challenges related to cost and cooling requirements, superconducting cables hold promise for future high-efficiency transmission systems.

Advanced Monitoring and Control Systems: The integration of advanced monitoring and control systems, such as Supervisory Control and Data Acquisition (SCADA) systems and Phasor Measurement Units (PMUs), allows for real-time monitoring of transmission networks. (Manbachi, Farhangi, Palizban, Arzanpour, 2017) These systems enable operators to detect and respond to issues promptly, optimizing power flow and reducing losses.

Economic Implications of Power Losses

Electric power is a critical driver of economic growth, industrialization, and improved quality of life. Efficient power transmission ensures that electricity generated at power plants reaches consumers in sufficient quantity and quality. (Ibrahim, Kwenejo, Bansal, Njoroge, Venkatta, Naidoo 2023) However, **power losses**—especially during transmission and distribution—can significantly undermine this process. These losses, if left unchecked, have far-reaching economic implications at both micro and macro levels. They affect electricity pricing, investment flows, productivity, industrial competitiveness, and national development goals. This section explores the direct and indirect economic impacts of power losses, with a focus on developing countries like Nigeria.

Increased Cost of Electricity Generation: One of the most immediate economic effects of power losses is the need to generate more electricity than is ultimately consumed. For example, if 10% of electricity is lost during transmission and distribution, utilities must generate 110 MW to deliver 100 MW to consumers.

Reduced Revenue for Utilities: Power losses directly reduce the amount of energy that utilities can bill for. In a country where losses may exceed 30% (as is sometimes the case in Nigeria), this represents a massive revenue leakage.

Reduced Industrial Competitiveness: **Industries rely on reliable and affordable electricity. High power losses translate into higher energy costs, frequent outages and Increased reliance on expensive backup generators**

Reduced Productivity and GDP Growth: Power outages and voltage instability caused by transmission inefficiencies disrupt production and service delivery across the economy. According to the World Bank, power shortages can reduce a country's GDP by 2–5% annually, especially in economies where power supply is already constrained.

Loss of Investor Confidence: Investors view reliable infrastructure as a key factor in assessing a country's business environment. Persistent transmission losses and related inefficiencies deter foreign direct investment (FDI) and Delay energy sector privatization efforts.

Table: Social, Environmental, and Economic Implications of Power Losses

Category	Aspect	Implication	Examples
Social and Environmental Spillovers	Energy Poverty	- Increased electricity costs reduce affordability and access - Off-grid or underpowered households - High energy costs passed to consumers	- 85+ million Nigerians lack grid access - Long load shedding hours in rural and urban areas
	Environmental Impact	- Increased fuel consumption - Higher GHG emissions - Greater local pollution - Environmental degradation	- SO_x, NO_x emissions - Undermines Nigeria's climate commitments - Risk of international penalties for non-compliance
Multiplier Effects on the Economy	Revenue Decline	- Lower industrial output = reduced tax contributions	- Industries affected by unstable power - Less revenue for government services
	Unemployment	- Loss of jobs in energy-dependent sectors	- Factory closures due to power shortages
	Foreign Exchange Loss	- High production costs reduce export competitiveness	- Loss of market share for Nigerian-made goods
	Public Debt Increase	- Governments borrow to cover subsidies and inefficiencies	- Long-term fiscal stress and inflation risk
	Business Impact	- Electricity unreliability ranks among top barriers	- Source: World Bank Doing Business Report

Category	Aspect	Implication	Examples
Economic Benefits of Reducing Power Losses	Cost Reduction	Lower generation costs = lower consumer tariffs	- Benefits low-income households and SMEs
	Utility Improvement	Increased revenue = infrastructure upgrades	- More investment in substations, conductors

Conclusion

The efficient transmission of electric power is a fundamental component of any modern economy, directly influencing industrial productivity, social development, and national competitiveness. In the context of long-distance power transfer, particularly in countries like Nigeria, transmission inefficiencies manifest in substantial technical and economic losses. These losses are compounded by aging infrastructure, inadequate investment, limited technological upgrades, and a lack of real-time monitoring and control systems.

This study has highlighted the various **technical factors contributing to power losses**, including resistance in conductors, poor voltage regulation, and inadequate grid configuration. It also examined the **economic and social implications**, revealing how these inefficiencies undermine revenue generation, inflate operational costs, discourage investment, and perpetuate energy poverty.

Through a detailed exploration of **advanced transmission technologies** such as High Voltage Direct Current (HVDC), Flexible AC Transmission Systems (FACTS), High-Temperature Low-Sag (HTLS) conductors, Dynamic Line Rating (DLR), and smart grid solutions, the study demonstrated the technical viability and long-term benefits of modernizing the transmission system. The Nigerian case study further illustrates the urgent need for reform, investment, and innovation to reverse current trends and build a resilient and efficient grid.

Recommendations

Based on the findings and analysis in this study, the following strategic recommendations are proposed:

Invest in HVDC systems for long-distance transmission, particularly between Nigeria's generation-rich South and demand-heavy North.

Implement FACTS devices such as STATCOMs, SVCs, and TCSCs to improve power flow control and voltage stability.

Adopt Dynamic Line Rating (DLR) and real-time monitoring tools to maximize line utilization and avoid overheating.

Develop a nationwide SCADA system integrated with Phasor Measurement Units (PMUs) for dynamic monitoring and fault diagnosis.

Finalize and enforce regulations supporting open access transmission and independent transmission operators.

Provide incentives for private investment in transmission through Public-Private Partnerships (PPPs) and Build-Operate-Transfer (BOT) models.

Implement a cost-reflective tariff structure that accounts for infrastructure upgrades and long-term sustainability, while protecting vulnerable groups through targeted subsidies.

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