

CRITICAL REVIEW OF HVDC AND FACTS TECHNOLOGIES FOR VOLTAGE STABILITY ENHANCEMENT AND GRID SUSTAINABILITY IN THE NIGERIAN 330 KV NETWORK

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Received: 29-04-2026

Accepted: 13-07-2026

<https://dx.doi.org/10.4314/sa.v25i4.4>

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Journal Homepage: <http://www.scientia-african.uniportjournal.info>

Publisher: [Faculty of Science, University of Port Harcourt.](#)

ABSTRACT

Voltage stability and a sustainable power infrastructure are crucial concerns in Nigeria's 330 kV transmission system because of long transmission distances, weak interconnections, insufficient reactive power reserves, and growing incorporation of renewable energy sources. This paper offers a systematic and in-depth review of the High Voltage Direct Current (HVDC) and Flexible AC Transmission Systems (FACTS) as one of the possible solutions to the challenges. This paper discusses the working principles, type, and characteristics of control of HVDC and FACTS devices with specific reference to how HVDC and FACTS can be utilized to enhance the wheeling capacity of transmission lines, voltage and power flow control, and voltage stability. A systematic review approach is used to explore the more recent literature. It pays attention to major developments, the characteristics of comparison with the performance, and its applicability to weak and developing power systems. In addition, the paper also defines the applicability of these technologies in attaining sustainable development goals through enhancing grid stability, minimizing transmission losses, and facilitating versatile and robust power system operation. The results show that Voltage Source Converter (VSC)-based HVDC systems are better in terms of controllability, effective long-distance power transmission, and integration of renewable energy, whereas FACTS devices like STATCOM, SVC, and UPFC are effective in offering reactive power compensations quickly and dynamically in AC networks. Despite these advantages, several research gaps are identified, including limited Nigeria-specific implementation studies, a lack of coordinated HVDC–FACTS control strategies, and an insufficient techno-economic evaluation framework.

Keywords: HVDC, FACTS, Voltage Stability, Nigeria Grid, Sustainable Infrastructure, VSC-HVDC, LCC-HVDC

INTRODUCTION

The diminution of fossil fuels (Qin et al., 2024) and the increasing need to use green energy to minimize carbon emissions have quickly transformed how electrical power should be generated, transmitted, and distributed

(Medina et al., 2022). This has resulted in a higher adoption of renewable energy sources (wind and solar power). Nevertheless, the majority of these renewable energy sources are not close to load centers (Sun et al., 2017) and occasionally off-grid, which means they have to be transmitted (over long distances) and

connected to the grid (Islam et al., 2024). Indeed, this transition poses major challenges because the nature of renewable energy resources' variation and intermittency affects the stability and reliability of a power system, particularly in a formative grid like the Nigerian grid (Cavus, 2025).

In Nigeria, the rising electricity demand, due to the increasing electrical load, necessitated by industrialization and the rise in the number of electronic appliances (Aneke & Engla, 2019), has strained the available electricity power infrastructures, which are weak, congested, and prone to volatility (Akwukwaegbu et al., 2021). These developments have led to the necessity to install additional transmission lines, but economic factors do not make it possible for the power operators (Jimoh & Raji, 2023). These will make the power system network (PSN) operate on the brink of its stability limits, impact the infrastructure, and affect the stability of the whole power system (Okakwu et al., 2017). Indeed, over the period of time, 2000 to 2025, the power grid in Nigeria has failed at least 564 times, either partially or in totality (Jimoh & Raji, 2023). This has dire consequences for the protection of systems and removes the most important service, to offer reliable and continuous power to the customers. Considering these, transmission line reinforcement is in demand of modern electronic-based technology, such as High Voltage Direct Current (HVDC) and Flexible Alternating Current Transmission Systems (FACTS), to improve the power-carrying capacity of the existing infrastructure. These technological advances are indispensable to the achievement of bulk power long-distance transmission, interconnection of asynchronous grids, global energy transition, loadability, etc.

Voltage stability (VS) is one of the most important operational problems in the transmission network in a developing power system, such as the Nigerian power grid. However, an increasing demand, a lack of adequate reactive compensation, and congestion of the network have led to a recurrence of instability of the voltage and grid

collapse (Ogar et al., 2022). Consequently, VS can be considered as the ability of a power system to have acceptable voltage at all the buses after interference or load changes, and prevents a gradual decrease in the magnitude of voltage, which might lead to a system breakdown. The Nigerian grid is known to have long transmission lines, poor bus voltages and reactive power problems, frequent system collapses, among other issues (Aneke & Engla, 2019). The traditional means of reinforcement, such as network expansion, fixed capacitive compensation, and control of generator excitation, are losing their effectiveness to cope with the dynamic, large-scale, and fast-changing nature of the modern power grid, especially under the circumstance of high inverter-based and distributed energy resource penetration.

As a solution, there should be a provision of sufficient support for reactive power, which is a leading element in the functioning of robust and competitive power networks. To this end, the integration of power electronics-based solutions, such as High Voltage Direct Current (HVDC) trans- mission and Flexible AC Transmission Systems (FACTS), provides a technically feasible way towards strengthening reactive power support, enhancing the voltage control, overall system stability, and power flow management.

This work investigates the technical capabilities of HVDC and FACTS controllers in improving the voltage profiles, power transfer capability, and system reliability. It further considers the applicability of these technologies to the Nigerian 330 kV grid, with regard to the structural and operational characteristics. The paper goes on to demonstrate their relative merits and limitations, and how they can strengthen the modern grid. The analysis also puts these technologies in the bigger picture of sustainable energy infrastructure development, particularly in line with Sustainable Development Goal 7 (Affordable and Clean Energy) and Sustainable Development Goal 9 (Industry, Innovation and Infrastructure) by indicating that these technologies are essential

for better transmission efficiency and grid resilience, and infrastructure modernization. The rest of this paper is organized as follows: Section 2 is the review of related work and identification of research gaps and future directions; Section 3 gives the background of the 330 kV Nigerian transmission grid; Section 4 is the definition of the concept and mechanism of voltage stability; Section 5 is a review of analytical tools for voltage stability assessment; Section 6 is a discussion of HVDC technologies and their impact in the stability of the system; Section 7 is a discussion of FACTS devices and their role in voltage support; Section 8 discuss the sustainable development goals; Section 9 is a discussion on HVDC and

FACTS as engineering innovations for supporting SDGs; Section 10 discuss contemporary HVDC and FACTS technologies for voltage stability enhancement and sustainable power infrastructure, and Section 11 concludes the paper with some important findings and recommendations.

Overview of Key Literature on HVDC and FACTS Technologies

A summary of the reviewed literature on HVDC and FACTS technologies, with emphasis on voltage stability enhancement in the Nigerian 330 kV grid, is presented in Table 1.

Table 1: Summary of Key Literature on HVDC and FACTS Technologies

Author(s)	Year	Methodology	Key Findings	Research Gap
Xiao et al.	2021	Review of the hybrid HVDC systems	HVDC enhances stability and enables renewable integration	Limited focus on weak grids like Nigeria
Marouani et al.	2023	Optimization-based study	FACTS devices improve the voltage profile and reduce losses	No hybrid HVDC–FACTS coordination
Acaroglu et al.	2021	Technical and economic review	HVDC is efficient for long-distance transmission	Lack of region-specific implementation studies
Boubii et al.	2024	Control system design	HVDC improves renewable energy stability	No application to developing grids
Xing et al.	2023	Analytical modeling	VSC-HVDC supports weak grids effectively	Limited economic analysis
Pfeifenberger et al.	2023	Economic assessment	HVDC improves operational efficiency and market benefits	Lack of African grid case studies
Alajrash et al.	2024	Comprehensive review of FACTS	FACTS enhances dynamic voltage control	Limited integration with HVDC systems

Identified Research Gaps

Despite the extensive body of literature on HVDC and FACTS technologies, several critical gaps remain, particularly in the context of developing power systems such as the Nigerian 330 kV transmission network.

Firstly, most existing studies focus on well-developed and strongly interconnected power systems, with limited attention given to weak

and highly stressed grids typical of developing countries. This limits the direct applicability of such findings to the Nigerian power system.

Secondly, the coordinated operation, optimization, and control of HVDC and FACTS devices within a hybrid AC/DC system remain insufficiently explored, despite both technologies having independently demonstrated the ability to enhance voltage stability.

Thirdly, most research materials that can be found focus on technical performance with no consideration of economics. Very little has been done on the cost and benefit analysis, economic viability, and long-run economic effects of the implementation of these technologies in the developing economies.

Lastly, the literature lacks research specific to the Nigerian 330 kV transmission grid that incorporates actual operating information, system restrictions, and issues unique to the region.

Moreover, studies of multi-terminal HVDC (MT-HVDC) systems and their use in large-scale interconnected grids in Africa remain immature. Such systems have the potential to enhance grid flexibility and resilience, which has not been properly explored.

The identified gaps indicate the need for more context-dependent, holistic, and cost-effective solutions towards the modernization of the power systems with HVDC and FACTS technologies.

Future Research Directions

Based on the identified gaps, some significant research directions for the future are suggested. First, coordinated control strategies for hybrid HVDC and FACTS systems need to be developed to maximize their combined benefits in voltage stability enhancement and power flow control. More so, to allow the optimization of the system in real-time and in an adaptive way, advanced control methods can be considered, such as artificial intelligence and machine learning-based control.

Secondly, the design and implementation of multi-terminal HVDC (MT-HVDC) systems for large-scale power networks also need further research. These systems have great potential in integrating renewable sources of energy and improving grid stability in geographically separated areas. Thirdly, to determine the feasibility of HVDC and FACTS implementation, economic evaluation models specific to the developing countries, such as Nigeria, need to be established. These

models are supposed to include the capital costs, operational savings, reliability, as well as environmental benefits. Also, it is necessary to have more detailed case studies of the Nigerian 330 kV grid with realistic system data and real-world operating conditions. This will give them some practical information about the ideal placement of these devices, the performance of the systems, and the planning of investments.

Lastly, further research is required in the field of combining wide-area monitoring systems (WAMS) and smart grid technologies to enable the efficient implementation and operation of HVDC and FACTS devices in contemporary power systems.

Overview of the Nigerian 330 kV Transmission Network

The recent demand for electricity in Nigeria is far greater than what is generated. This results in the transmission network being heavily loaded and stressed beyond permissible limits. The Nigerian grid network consists of generating stations built mostly in remote areas close to where raw materials (water for hydroelectric stations, gas and coal for thermal plants, wind and sunlight for renewable sources of electricity) are readily available (E. N. Aneke et al., 2021; Olabisi & Ayeni, 2023). Meanwhile, the end-users are found in population-dense areas, mostly metropolises and industrialized zones. Therefore, to transfer the generated power to end-users at a reduce power loss, high voltage transmission is introduced.

In the national grid, the Nigerian 330 kV transmission system is the primary backbone and is concerned with bulk transmission of power among the geographically distributed sources of generation and the main load centers (E. N. Aneke et al., 2021). The Transmission Company of Nigeria (TCN), an agency under the Power Holding Company, is vested with transmitting electricity to the entire country through the transmission network. The agency transmits 330 kV to 132 kV, which is stepped down to 33 kV and 11 kV, known as the distribution network (Jimoh

& Raji, 2023; Ogar et al., 2022). The grid consists of a few large hydroelectric power stations (Kainji, Jebba, and Shiroro) in the Middle Belt and Northern part, and a small number of mostly gas-fired thermal power stations in the Southern area, including Egbin, Sapele, Delta (Ughelli), Afam, Okpai, Olorunsogo, and Omotosho (Ogar et al., 2022). The system topology has three functional corridors, including Northern, South-Western, and South-Eastern. Long-distance 330 kV, two-circuit transmission lines, in particular, between Jebba and Osogbo have been the covert means of inter-regional power transfer, especially between the North and the South (Badrudeen et al., 2022b). The South-Western corridor is a major concentration area of loads and a transmission center, and major substations in the area, such as Ikeja West and Benin, are interconnection centers to the South-East over transmission paths to Onitsha and Alaoji (Okakwu et al., 2017).

The 330 kV structure has the capability to exchange energy all over the nation, yet operational troubles because of transmission distances, uneven distribution of production, and dependence on corridors limits its operation (Akwukwaegbu et al., 2021). More so, the network features are manifested by the presence of quite weak tie-lines at some points, high reactive power under load, and voltage sensitivity during overloading or emergency conditions. The risk of voltage instabilities is also caused by the selective redundancy of some of the transmission corridors, especially when there is peak demand or in cases where generation is less than the load demand. According to (Abdulkareem et al., 2021; Adebajji et al., 2022; Akuru & Okoro, 2022; Akwukwaegbu et al., 2021; Ayamolowo et al., 2019; Okakwu et al., 2017; Oluseyi et al., 2017; Qin et al., 2024), the 330 kV transmission network is characterized by:

1. Long North–South transmission corridors
2. High reactive losses over extended lines
3. Limited dynamic compensation

devices

4. Weak voltage buses during peak loading
5. Frequent grid collapses indicate insufficient voltage support and poor stability margins under contingency conditions.

These two features of the Nigerian 330 kV grid render it an ideal grid for the proposed innovative solution of stability enhancement, which includes HVDC connections with FACTS-based reactive compensation power.

Fundamentals of Voltage Stability

Voltage stability (VS) refers to the ability of a power system to maintain acceptable voltage levels under normal operating conditions and after disturbances (Aghdam & Khoshkhoo, 2020). It simply means that such a system must have the ability to dampen out oscillations as quickly as possible so that the entire system re-establishes the initial state or settles to a new steady-state operating condition in a finite time. Moreover, the type of disturbance and the initial condition of a power system determine whether an interconnected power system will regain its former stable operating state or return to a new state when subjected to a disturbance. The deviations are associated with a variation in load, short-circuits, disconnections of power transmission lines, or loss of generation, variation in voltage, and similar causes, which can lead to voltage collapse.

Voltage collapse occurs when the reactive power demand in a power system is greater than the reactive power supply in the system, making it impossible for the system to sustain voltage levels acceptable at the system buses (Samuel et al., 2021). This situation is often aggravated by voltage drops caused by the flow of active and reactive power through the inductive reactance of the transmission lines in the network (Hatziaargyriou et al., 2020). Other factors, which may contribute to this condition, may include a sudden increase in load demand, loss of an important element of the power system, such as generators or transmission lines, and a faulty on-load tap-

changing transformer (Modarresi et al., 2016). Critical limit values can be determined for each power system for these associated quantities that characterize the stability limit. In the assessment of VS of an electric power system, a distinction is made between different classes of voltage stability.

Classification, therefore, is the key to useful practical study and determination of voltage stability (VS) problems. Consequently, VS is broadly classified as large and small disturbance voltage stability. These types of VS are further subdivided into long-term and short-term classes depending on the time scale of the system response. These classifications are discussed in detail in Samuel et al. (2021).

The basic understanding of voltage stability also involves the investigation of the underlying relationship in power transfer in AC transmission systems. The basic real and reactive power transfer equations for a lossless transmission line in AC transmission are given by:

$$P = \frac{V_1 V_2}{X} \sin(\delta) \quad (1)$$

$$Q = \frac{V_1^2}{X} - \frac{V_1 V_2}{X} \cos(\delta) \text{ or } \frac{V_1(V_1 - V_2)}{X} \cos(\delta) \quad (2)$$

where V_1 and V_2 are the sending and receiving end voltages, X is the line reactance, and δ is the power angle between the two buses.

This relation means that the amount of power that can be transmitted through a transmission line is strongly affected by the size of the voltages and the line reactance. In practical power systems, voltage magnitude is largely maintained through adequate reactive power support. When the supply of reactive power is not sufficient, the magnitude of voltage starts becoming less, and thereby the maximum transferable power too becomes less, according to the power-transfer relationship. If this condition continues, it may cause a progressive reduction in voltage and eventually voltage collapse. To assess such conditions, a

number of methods have been devised. The methods include, but are not limited to:

1. PV (Power Voltage) curves
2. QV (Reactive Power Voltage) curves.
3. L-index stability indicator
4. Continuation Power Flow analysis

The results obtained from the applied voltage stability assessment methodologies provide key information on susceptible buses of economic importance, sensitive transmission paths, and reactive power needs of the power network. Following the identification of these susceptible loci within the system, appropriate remedial measures can be taken to enhance the overall stability of such a system. Of interest is that some of the most successful technological innovations to maintain stability in voltage levels for modern power systems are Flexible AC Transmission System (FACTS) devices and High-Voltage Direct Current (HVDC) transmission technologies. These allow dynamic voltage regulation, reactive power compensation, and improved power flow control, which will increase the transmission network load capacity and reliability.

Consequently, the use of HVDC and FACTS controllers has become one of the areas of research to address the issue of voltage instability occurrence and prevention of voltage collapse, particularly in cases of extensive interconnected loads in power systems such as the Nigerian 330 kV transmission grid.

METHODOLOGY

This paper adopts the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework to ensure a transparent and reproducible literature review process. The PRISMA process flow for the systematic literature review (SLR) is: Identification, Screening, Eligibility, and Analysis

Data Sources and Search Strategy

This paper used the following keywords in its search: HVDC, FACTS, Voltage Stability, Power system stability, VSC-HVDC, LCC-

HVDC, Reactive power compensation, and Nigerian 330 kV Grid, to obtain relevant literature from the most popular scientific databases, such as IEEE Xplore, ScienceDirect, SpringerLink, and Google Scholar.

Inclusion and Exclusion Criteria

To guarantee the quality and relevance of the chosen studies, literature is included if:

1. It was a peer-reviewed journal article or conference paper
2. It was published between 2015 and 2025
3. The research borders on HVDC, FACTS, and voltage stability
4. The papers addressed weak grids and emerging power systems.

Furthermore, literature is excluded if the paper:

- i. is a non-peer-reviewed article, a preprint, and an unpublished report
- ii. Focuses on the distribution system instead of the transmission system
- iii. with insufficient technical depth

Screening and Selection Process

The preliminary search yielded a large number of publications. These were filtered according to the relevance of titles and abstracts. Screening of the Full text was then performed, and studies that passed the inclusion criteria were retained. A total of 200 records were initially identified. After removing duplicates, 150 pieces of literature remained. Further screening using title and abstract reduced the number of papers to 80, and the full-text assessment was conducted on 80 articles. Finally, 50 studies were selected for detailed review.

Data Extraction and Analysis

The key information extracted from every study is the methodology, application focus,

the key findings, and limitations. The literature was then analyzed thematically with a focus on studies that enhanced voltage stability, integrated renewable energy, and its applicability to small networks such as the Nigerian 330 kV network.

High Voltage Direct Current and Flexible Alternating Current Transmission Systems Technology

High Voltage Direct Current and Its Technology

HVDC transmission systems are systems of transmission of power using direct current. It is expanding the capacity of the transmission systems and reducing power losses on the transmission line (Saadeh et al., 2023). It comprises an AC/DC converter station (rectifier) at the sending terminal and a DC/AC converter station (inverter) at the receiving terminal interconnected by an HVDC transmission line, as shown in Figure 1. In its simplest scheme, power is transmitted from the rectifier to the inverter, making the power transmission unidirectional. But in contemporary times, with HVDC technologies, power transmission is capable of being controlled to permit bidirectional power flow when needed. Therefore, HVDC transmission with its technology has power flow controllability and reactive power support that is independent. The HVDC technology has been crucial for maintaining voltage stability over long distances and for facilitating power transfer with minimal losses Elgenedy et al., 2020. The conversion of electrical current in HVDC transmission from AC to DC at the transmitting end and from DC to AC at the receiving end is a fundamental process that arises in the HVDC transmission system (Sanchez Garciarivas et al., 2021). The technologies to achieve this conversion are of three types, namely: Natural Commutated Converter, Capacitor Commutated Converter, and Force Commutated Converter.

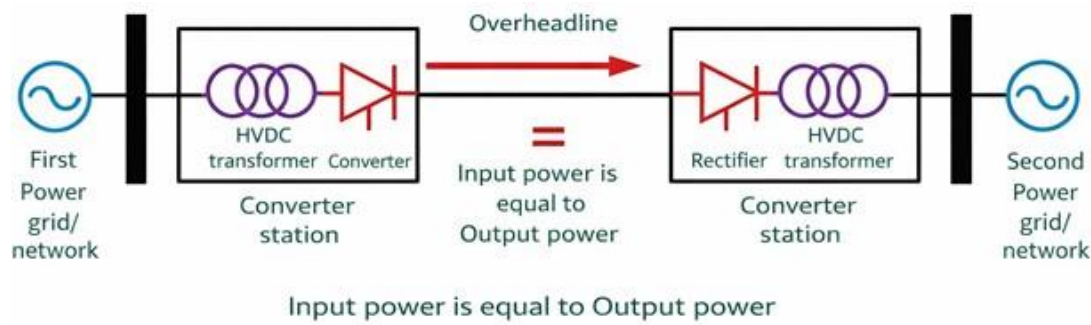


Figure 1: HVDC Single Line Diagram

Natural Commutated Converters

One of the most widely used converter technologies in HVDC today is the natural commutated converter (NCC), also known as the line-commutated converter (LCC) (Dey & Bhattacharya, 2020; Zhang et al., 2023). The basic component supporting this conversion process is a semiconductor device, i.e., the thyristor, which can withstand peak currents up to 4000 A and voltages up to 10 kV. With a series of thyristors, the voltage rating may be increased to several hundred kilovolts (Ludin et al., 2022; Xiao et al., 2021). The DC voltage of the rectifying bridge is adjustable at a controlled firing angle, and the thyristor valve operates at net frequencies of 50 Hz or 60 Hz (Bernat & Preece, 2019; Mankour & Sami, 2023). This controllability also allows quick and effective control of transmitted power.

Capacitor Commutated Converters

Capacitor commutated converters (CCC) are an enhancement of NCCs (Mankour & Sami, 2023). The CCC concept involves commutation capacitors placed in series between the converter transformers and thyristor valves (Guo et al., 2020). The commutation capacitors enhance the commutation performance of the converters in the weak networks (Xue et al., 2017). The main benefits of CCC technology include the high anti-disturbance level, which minimizes inverter-side faults (Gao & Ma, 2012), and excellent performance, compared to NCC technology, in a weak AC system, where traditional NCCs are more likely to exhibit a commutation failure because of their inability to support reactive power (Zhao et al., 2024).

Nonetheless, the CCC technology has been limited to large-scale HVDC applications because of the unbalanced capacitor voltages, higher voltages on converter valves, and complicated capacitor control demands (Zhao et al., 2024). Moreover, it has poor performance in extreme DC fault conditions, where the increased energy in the series capacitors may make fault recovery more difficult.

Forced Commutated Converters

The Forced Commutated Converters (FCC) is a category of HVDC converters, and its valves are designed with semiconductors that can be switched on and off (Acaroğlu et al., 2021; Bermudez & Nilsson, 2025). They provide a variety of benefits, such as passive networks (no generation and feed-in), independent control of active and reactive power, and enhanced power quality (Song et al., 2017). Examples of FCCs include voltage source converters (VSCs). VSCs typically make use of two materials as semiconductors, namely, the Gate Turn-Off Thyristor (GTO) and the Insulated Gate Bipolar Transistor (IGBT) (Stan et al., 2022). The converter works on Pulse Width Modulation (PWM). The VSC does not commute at the net frequency, but at a high frequency. PWM allows adjusting the PWM pattern to any phase angle and/or amplitude with a given limit, which can be changed almost immediately (Fernandes et al., 2025; Sanchez Garciarivas et al., 2021). Independent control of both active and reactive power is thus brought about through the PWM (Song et al., 2017). This is why the PWM Voltage Source Converter is almost a perfect

element of the transmission network (Ebrahim et al., 2021). In terms of the transmission networks, it is a massless, non-generative motor or generator that is able to manage both the active and reactive power almost immediately.

Comparison between HVDC Technologies

Table 2 compares the three converter technologies discussed above in a number of important features, such as the type of commutation, the type of semiconductor device, the strategy of control, the dependence of frequency, the practical application, and so on.

Table 2: Comparative analysis of HVDC Technology

Feature / Aspect	NCC	CCC	FCC
Main Semiconductor	Thyristor (turn-on only)	Thyristor and Commutation Capacitors	GTO / IGBT
Commutation Type	Dependent on AC system voltage (natural commutation)	Assisted by series Capacitors (improved commutation)	Self-commutated (forced commutation)
Control of Power	The firing angle controls active power; reactive power is dependent on the AC system.	Improved reactive power handling due to capacitors	Independent and instantaneous control of both active and reactive power
Frequency Dependency	Operates at grid frequency (50/60 Hz)	Still tied to grid frequency, but with enhanced stability	Operates with high-frequency PWM, not limited to grid frequency
Suitability/application	Strong AC networks	Weak AC networks (improved stability)	Weak/passive networks, renewable energy integration, asynchronous interconnections
Power Transfer Capacity	Very high (GW scale, backbone of bulk transmission)	Medium to high (depends on system strength)	Low to medium (scaling up with technology)
Losses	Low conduction losses, but the reactive power demand is high	Similar to LCC but with reduced commutation failures	Higher switching losses due to PWM, but compensated by flexibility
Maturity / Applications	Most mature and widely deployed (classic HVDC links)	Niche applications in weak grids (less common today)	Rapidly growing for offshore wind, urban grids, and multi-terminal HVDC
Analogy with a truck/car	Heavy-duty truck: strong and reliable, but less flexible	Modified truck with better stability on rough roads	Agile electric car: highly flexible, controllable, and efficient in modern grids

HVDC for Enhancing Voltage Stability and Sustainable Power Infrastructure

There are two major power-converter technologies for HVDC grids: the thyristor-based classical technology and the current-

source converter, which are based on Line-Commutated Converter (LCC) and Voltage-Source Converter (VSC) technologies, respectively (Ludin et al., 2022; Xiao et al., 2021). The LCC/CSC-HVDC uses thyristors, while the VSC-HVDC uses IGBTs; both are

suitable for a wide range of applications (Acaroğlu et al., 2021; Zhang et al., 2023). For long-distance, high-capacity transmission links, CSC-HVDC and VSC-HVDC technologies offer higher efficiency and greater power transfer capacity than classical AC solutions (Davidson & Dorn, 2023). In operation, the LCC requires a strong AC power source, whereas the VSC uses semiconductor switches that can be actively controlled to turn on and off via gate control (Bermudez & Nilsson, 2025; Ebrahim et al., 2021).

VSC-based systems offer numerous advantages over classical systems. Therefore, in recent years, due to the development and advantages of VSC technology over LCC, it has played a prominent role in various HVDC projects (Elgenedy et al., 2020; Fernandes et al., 2025). Additionally, the newly developed Modular Multilevel Converter (MMC)

technology has gained advantages over two- and three-level VSC technology (Ahrabi & Li, 2021), and greater focus should be placed on developing HVDC grids based on MMC technology (Mohammadi et al., 2024). In cases of power transmission from offshore power plants or from other remote areas with limited space, VSC-HVDC is the preferred technology, offering strong active and reactive power control capabilities (Stan et al., 2022). VSC-HVDC systems can inject or absorb reactive power dynamically, thereby stabilizing weak buses in stressed regions of the 330 kV network. A proposed application includes a North-South HVDC link to reduce overloading and improve stability margins. The conceptual representation of HVDC integration into the Nigerian 330 kV grid is shown in Figure 2, while the comparative differences between these LCC and VSC HVDC technologies are summarized in Table 3.



Figure 2: North-South Conceptual Representation of HVDC Integration into the Nigerian 330 kV Grid

Table 3: Technical Comparison of LCC-HVDC and VSC-HVDC Systems

Feature	LCC-HVDC	VSC-HVDC	Reference
Switching Device	Uses Thyristor	Uses IGBT	Acaroglu et al., 2021; Zhang et al., 2023
Commutation Method	Depends on a strong AC system voltage for commutation	Self-commutated, i.e., independent of the AC system; switching is controlled via gate signals	Bermudez and Nilsson, 2025; Ebrahim et al., 2021
Grid Strength Requirement	Requires strong AC systems	It can work with weak or even passive grids	Bermudez and Nilsson, 2025
Reactive Power requirement	It consumes large reactive power in the range of ($\sim 40\text{--}60\%$)	It can generate or absorb reactive power	Fernandes et al., 2025
Voltage Control	Limited voltage support	Excellent voltage regulation	Elgenedy et al., 2020
Control Capability	Limited control over active and reactive power	Capable of independent control of active and reactive power	Elgenedy et al., 2020; Fernandes et al., 2025.
Black-Start Capability	No	Yes	Xiao et al., 2021
Commutation Failure	Possible during AC Faults	No commutation failure	Mohammadi et al., 2024
Power Flow Reversal	Requires polarity reversal to achieve power flow reversal	Controlled electronically and does not require polarity reversal	Mohammadi et al., 2024; Stan et al., 2022
Power Quality and Harmonics	It's associated with High harmonics, thus, require large filters	It has Low harmonics due to PWM switching and a better waveform	Mohammadi et al., 2024
Station Size	Bulkier installation with large filters and transformers	Compact design, suitable for constrained spaces	Stan et al., 2022
Losses	Lower ($\sim 0.7\%$)	Higher ($\sim 1\text{--}1.6\%$)	Song et al., 2017
Application Efficiency	Efficient for long-distance, high-capacity power transfer	Also efficient for long-distance power transfer, with added operational flexibility	Ludin et al., 2022; Xiao et al., 2021.
Power Rating	Very high (up to ~ 10 GW)	Lower but improving	Bernat and Preece, 2019.
Typical Applications	Bulk power transmission over long distances (e.g., intercontinental HVDC links)	Offshore wind integration, weak grid connections, urban or remote renewable sites	Stan et al., 2022
Converter Topology Development	Traditional thyristor-based converters	The Modular Multilevel Converter (MMC) variant offers improved scalability, efficiency, and waveform quality.	Ahrabi and Li, 2021; Mohammadi et al., 2024.

Flexible Alternating Current Transmission System Technology

Flexible AC Transmission Systems (FACTS) are a family of power electronic devices designed to enhance the controllability and increase the power transfer capability of AC transmission networks (Alajrash et al., 2024). The strategic deployment of FACTS controllers is a proven engineering innovation for mitigating voltage instability, reducing transmission losses, and improving the overall dynamic performance of power systems, making them particularly relevant for

addressing the challenges of the Nigerian 330 kV grid (Marouani et al., 2023).

Classification of FACTS Controllers

FACTS devices can be broadly classified based on their connection to the power system and their control characteristics (Mathad et al., 2013; Zadehbagheri et al., 2023). The main categories include shunt controllers, series controllers, and combined series-shunt controllers. Figure 3 depicts the FACTS classification.

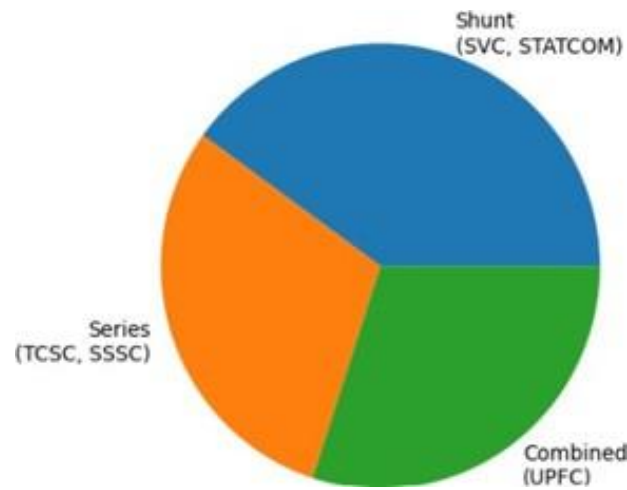


Figure 3: FACTS Classification

Shunt Compensation

Shunt compensation devices are connected in parallel with the transmission line and are primarily used for voltage regulation. The Static VAR Compensator (SVC) is a first-generation FACTS device that uses thyristor-switched capacitors and reactors to provide rapid reactive power compensation. While effective, SVCs can be slower in response and may introduce harmonic distortions (Alajrash et al., 2024). The Static Synchronous Compensator (STATCOM), a second-generation device based on Voltage Source Converter (VSC) technology, offers superior performance compared to SVC. STATCOMs can provide faster and more precise reactive power control, with a symmetrical charge and discharge capability (injecting or absorbing reactive power (Mathad et al., 2013; Umoh et al., 2021), making them highly effective for

dynamic voltage support in weak grids (Xing et al., 2023).

Series Compensation

Series compensation devices are connected in series with the transmission line to control its impedance and, consequently, the power flow. It is of two types, namely, the Thyristor-Controlled Series Capacitor (TCSC) and the Static Synchronous Series Compensator (SSSC). The TCSC allows for rapid and continuous control of the transmission line's reactance, enabling effective power flow management and damping of power oscillations. While the SSSC, the series counterpart of the STATCOM, injects a controllable voltage in series with the transmission line, providing virtual compensation that can be either capacitive or inductive. This allows for precise control of power flow and enhancement of transient

stability (Jebaraj et al., 2012; Mathad et al., 2013).

Combined Controllers

The Unified Power Flow Controller (UPFC) is the most versatile FACTS device, combining the features of both shunt and series controllers to enhance steady state stability, dynamic stability, and transient stability (Inyang et al., 2024; Mathad et al., 2013). A UPFC consists of a STATCOM and an SSSC, coupled via a common DC link to provide flexible control over voltage, reactive power, and power flow, enhancing both dynamic and steady-state voltage stability (Murali et al., 2010; Obukowho et al., 2020). This configuration allows the UPFC to independently and simultaneously control the voltage, impedance, and phase angle of the transmission line, providing comprehensive control over active and reactive power flow (Alajrash et al., 2024). Hence, it is said to have two degrees of freedom. It consists of two AC/DC converters: one connected in series with the transmission line via a series transformer, and the other in parallel with the line through a shunt transformer (Umoh et al., 2021).

Sustainable Development Goals

The Sustainable Development Goals (SDGs) outline the 2030 Agenda of global change by focusing on the multifaceted and interconnected issues humanity has to face (Ortigara et al., 2018). The general goal of SDGs is to achieve the well-being of humans, economic prosperity, and environmental sustainability (Pradhan et al., 2017). The SDGs have a multidimensional approach to development, unlike the traditional development frameworks whose priorities are often confined to a few (United Nations, 2015). The SDG developmental goals considered in this study are SDG 7 and 9.

SDG 7

SDG 7 (Affordable and Clean Energy) aims to ensure access to affordable, reliable, sustainable, and modern energy for all.” Key targets under this goal include increasing the

share of renewable energy in the global energy mix and enhancing energy efficiency (Antônio, 2025). The backbone of a modern energy system is a stable and strong transmission grid that facilitates the integration of large-scale renewable energy sources, as well as ensures that the power generated is delivered to end-users with a minimum number of losses (World Bank, 2025).

SDG 9

SDG 9 (Industry, Innovation and Infrastructure) aims to develop resilient infrastructure, advance sustainable industrialization that is inclusive and sustainable, and enhance innovation (Antônio, 2025). This objective underscores the necessity to have quality, dependable, and sustainable infrastructure that can facilitate the growth of the economy and human prosperity. A poor power grid is a key constraint to the development of industries and innovation, which is why spending on grid modernization is an insurgent facilitator towards the realization of SDG 9 (Antônio, 2025).

HVDC and FACTS as Engineering Innovations Supporting Sustainable Power Infrastructure, and Affordable and Clean Energy

HVDC and FACTS are among the major engineering solutions that can be used to upgrade the Nigerian 330 kV transmission network into a sustainable energy infrastructure, which will directly contribute to the goals of SDG 7 and SDG 9. These technologies specifically contribute to achieving sustainable energy access and the creation of resilient and innovative infrastructure, which is the main goal of the SDGs in general (Antônio, 2025). Therefore, this work examines how FACTS and HVDC technologies can improve the 330 kV transmission system in Nigeria with specific reference to its impact on SDG 7 (“Affordable and Clean Energy”) and SDG 9 (“Industry, Innovation, and Infrastructure”).

The modernization of power transmission infrastructure in Nigeria, achieved by the implementation of these technologies, will serve as a strategic need for long-term sustainable development, going further than traditional technical upgrades. More so, by enhancing the voltage stability and increasing the wheeling power transfer capacity of the transmission grid using these technologies, the overall efficiency and reliability of the power system will be improved significantly. This leads to a reduction in transmission losses, which in turn contributes to making electricity more affordable. A more reliable power supply also reduces the reliance on expensive and polluting backup generators, further contributing to the goals of affordable and clean energy (Pfeifenberger et al., 2023).

Also, a more robust and adaptable grid is needed to incorporate large-scale renewable energy sources, including solar farms in the northern region and wind farms in the southern region of Nigeria. These renewable sources are intermittent, and therefore, the technologies that are required are those that are able to react quickly to variations in generation and load. Therefore, FACTS and HVDC devices, with their rapid control features and capability to regulate power flow and weak grids, are most appropriate towards this end (Boubii et al., 2024; Kumar et al., 2016). These technologies can diversify the energy mix in Nigeria by enabling the incorporation of renewable energy, as well as mitigating its carbon footprint, which directly addresses SDG 7.

Furthermore, industrialization, investment, and the development of a digital economy are impossible without a stable and efficient power grid, which can be modernized with HVDC and FACTS, and which is a key requirement of SDG 9. Thus, the economic potential of Nigeria can be unlocked by a modernized grid, which can provide a stable, high-quality power supply and help it move toward a more sustainable and prosperous future. Nevertheless, the implementation of these new technologies requires developing local technical capacity, creating a new gap in

research and development in the field of power engineering.

The Benefits of FACTS and VSC-HVDC Technology Application in the 330 kV grid

Studies on the Nigerian 330 kV grid have identified several weak buses and congested transmission corridors, particularly in the North-South power transfer axis and the South-East region (Badrudeen et al., 2022a). Therefore, the strategic placement of VSC-HVDC and FACTS devices in these weak zones is crucial for enhancing voltage stability, increasing power transfer capacity, and reducing losses (Ezeruigbo et al., 2021). The benefits of using the technologies are as follows:

Dynamic Voltage Regulation Capabilities

The main benefit of FACTS technologies in the case of the Nigerian grid is that they can offer dynamic voltage regulation. In contrast to traditional compensation approaches, like fixed capacitors or reactors, FACTS devices have the ability to react quickly to varying conditions in the system and maintain a stable voltage profile even when the system is disturbed. This is critical in avoiding the cascade failure and grid collapses that have marred the Nigerian power system in the past (Ezeruigbo et al., 2021). FACTS controllers' deployment is an important engineering innovation, which can help to make the power infrastructure in Nigeria more resilient and sustainable.

Control of Power Flow and Voltage Regulation

HVDC and FACTS systems give very accurate and direct control of the active power flow between interconnected locations, and control the voltages at the two ends of the transmission link. As well, the voltage in the AC system, at critical points, can be stabilized by varying the DC voltage to ensure grid stability and reduce the flow of power to prevent possible voltage instability. This is especially applicable in weak AC systems, long transmission lines, or AC systems that are not adequately supported with reactive power. This is a major advantage

over traditional AC transmission systems, whereby voltage regulation is less frequently controllable. Minimization of Voltage Fluctuations and Transients

HVDC and FACTS technologies tend to be more stable than traditional AC systems under most disturbances. The fact that they can inject or absorb active power on demand allows them to help in maintaining voltage stability and overcoming variability during dynamic occurrences. HVDC technology allows low-frequency oscillations that tend to arise in the AC grid after disturbances to be suppressed by allowing quick and accurate modulation of power flow. In contrast to AC transmission, HVDC lines do not use reactive power to transmit power, and as a result, there are no reactive power losses to accumulate in the lines as they get longer. This enables HVDC links to deliver a more stable voltage profile along the transmission line, minimizing the threat of voltage collapse during stressed operating conditions.

Enhanced stability in Weak Grids

The HVDC technology is also useful where the grids are weak, as this is characterized by low fault levels, low generation capacity, and widespread dependence on loads. Stability of voltages in such environments is usually delicate; nevertheless, with HVDC, the transition of power between a strong and a weaker grid can be performed seamlessly. This technology is therefore important in balancing system voltages when there is peak demand or when there is a fluctuation in the conditions of renewable sources of power. The other important benefit is that it can interface two asynchronous AC grids and provide electrical isolation that reduces the transfer of transient disturbances, oscillations, or voltage instabilities between systems. This renders HVDC an efficient technology to strengthen weak or isolated networks.

Voltage Stability in Multi-Terminal Systems

In contrast to the conventional point-to-point HVDC, multi-terminal HVDC (MT-HVDC)

systems spread multiple AC networks on a common DC backbone. The design has considerable benefits in terms of stability of voltages, especially in large and sophisticated grids. In addition, the converter terminals can be controlled independently, and hence they allow a dynamic and flexible control of power flow and voltage across various components of the network. The MT-HVDC design offers a powerful framework for the interconnection of renewable energy, enabling the injection of multiple power sources from offshore wind and remote photovoltaic stations without altering the DC voltage profiles and improving grid stability.

Mitigation of Voltage Collapse

Voltage collapse is a phenomenon where a power system is unable to sustain voltages at full load, usually due to insufficiency of reactive power. This can lead to excessive voltage drop and even overall outages of AC systems. HVDC and FACTS systems can eliminate this shortcoming by passing active power without the need to pass reactive power, which is an inherent resistor to voltage collapse. This makes FACTS and HVDC, particularly VSC-HVDC and UPFC, an effective means of maintaining voltage breakdown.

Incorporation of Renewable Energy Sources

The intermittent nature of renewable energy sources and the high voltage drop with long transmission line lengths make them hard to fit into the conventional AC grids. HVDC systems, in contrast, enable the efficient transmission of renewable power over long distances without reactive losses in power and eliminate the fluctuations of voltages due to variable generation. This has allowed HVDC to be used as the technology of choice when interconnecting offshore wind farms and remote solar power generation to the main grid due to its stability and reliability in transmitting power. Grid Strengthening and System Flexibility: In addition to particular applications, HVDC enhances the overall grid strength by giving strong interconnections

between regions. It also allows grids running at different frequencies or voltage levels to be connected asynchronously, enabling them to share power without destabilizing each other. This is not only able to prevent voltage instability, but also assists in balancing the load and generation on large areas.

Comparative Technical and Economic Analysis of HVDC/FACTS

The choice to invest in new transmission technologies such as HVDC and FACTS has to be analyzed carefully in terms of their technical performance and economic feasibility in comparison to traditional compensation techniques. In this section, a comparative analysis of the performance, reduction of transmission loss, and enhancement of power transfer capacity will be discussed.

Performance Comparison: Conventional Compensation and HVDC/FACTS

Traditional compensation schemes, like shunt capacitors and reactors, offer a simple degree of reactive power assistance, but do not have the dynamic control of modern power electronics. Such passive devices do not have the capability to address some intricate voltage stability problems that occur in weak and heavily loaded grids, such as the Nigerian 330 kV system (Sode-Yome et al., 2012). Conversely, the FACTS devices and HVDC systems have better dynamic performance. Table 4 demonstrates that the VSC-based technologies, such as STATCOM and VSC-HVDC, can regulate voltage and power flow at a very fast rate, with accuracy and in real time, which is highly important to control the stability of the 330 kV grid during transient events (Alajrash et al., 2024; Xing et al., 2023). Although conventional techniques can be used to enhance the voltage profile at steady-state conditions, these techniques are less responsive to the sudden changes due to faults or the intermittency of renewable energy sources.

Table 4: Performance Comparison of Conventional Compensation and HVDC/FACTS

Technology	Response Speed	Control Capability	Footprint	Cost
Shunt Capacitors/Reactors	Slow	Limited (Switched)	Medium	Low
SVC	Fast	Good (Thyristor-based)	Large	Medium
STATCOM	Very Fast	Excellent (VSC-based)	Compact	High
VSC-HVDC	Very Fast	Excellent (Independent P-Q) Compact	Ver/y	High

Technical Comparison

Through research, it was gathered that the use of SVC, STATCOM, and VSC-HVDC technologies in a weak transmission corridor of 330 kV leads to a great enhancement of the voltage stability of the 330 kV transmission

grid. The extended technical comparison, as indicated in Table 4, shows that SVC enhances the voltage profile by about 60%, STATCOM by 80%, and VSC-HVDC by 95%. This illustrates the excellent functioning of VSC-HVDC in weak grid networks.

Table 4: Comparison of the voltage stability improvement of the chosen technologies

Technology	Voltage Stability Improvement	Loss Reduction	Response Time
SVC	~ 60%	10–15%	Medium
STATCOM	~ 80%	15–25%	Fast
VSC-HVDC	~ 90% – 95%	25–35%	Very Fast

Transmission Loss Reduction

The opportunity to achieve significant cuts in transmission losses is one of the greatest economic advantages of HVDC and FACTS technologies deployment. The transmission networks and high loading in the Nigerian grid due to long transmission corridors are factors contributing to high I^2R losses. FACTS devices are able to reduce these losses by optimizing power flow and enhancing the voltage profile (Marouani et al., 2023). On the other hand, HVDC transmission has been found to be efficient in long-distance power transfer, because it does not suffer reactive power loss, and conductor losses are less compared to AC lines. In the case of bulk generation in remote locations (e.g., northern solar farms) and transmission to southern load centers in Nigeria, HVDC is a more effective option than AC transmission, which leads to operational cost savings in the long term (Pfeifenberger et al., 2023).

Capacity of Power Transfer

The power transfer capacity of a transmission line is limited by thermal, voltage, and stability constraints. The limits can be extended with the use of HVDC and FACTS technologies, permitting more power to be sent via existing corridors. FACTS capacitors, such as TCSC and SSSC, operate in series to directly enhance the capacity to pass power through the line, and counteract the line's natural reactance, making the line electrically shorter (Sode-Yome et al., 2012). Shunt devices such as STATCOM are used to boost power transfer by offering strong voltage support, avoiding voltage drops in the middle of long transmission lines, commonly the limiting element. VSC-HVDC link may form an asynchronous interconnection, avoid overloaded AC connections, and offer a completely controllable power path. This not only expands the overall power transfer capacity but also the overall security and reliability of the grid through the establishment of alternative power corridors (Xing et al., 2023). The ability to unlock additional capacity from the existing transmission

infrastructure can eliminate the need for building new lines, representing a significant capital expenditure saving.

Challenges Faced During Implementation and Policy Implications

Although HVDC and FACTS technologies have great technical advantages, their extensive deployment or usage in the Nigerian 330 kV transmission system has a number of implementation issues and demands serious policy consideration. These challenges span financial, regulatory, technical, and operational domains.

Financial and Investment Barriers

One of the major challenges facing the use of HVDC and FACTS devices in most developing countries, including Nigeria, is the high capital cost. Finding the funds to finance such mega infrastructure projects is a major challenge that may necessitate a blend of government and private investment. A systematic review of renewable energy investment in Sub-Saharan Africa underscores that policy and financial obstacles are significant hurdles to opening up the energy potential of the region. To attract private investment, a predictable and stable policy environment, transparent procurement procedures, and risk mitigation strategies to guarantee a payback on investment are required.

Regulatory Framework

An ineffective or inefficient regulatory framework may suffocate the implementation of new technologies. In the case of Nigeria, Transmission Company of Nigeria (TCN) and Nigerian Electricity Regulatory Commission (NERC) need to work together to establish a conducive regulatory environment that will attract investment towards grid modernization. This involves the creation of transparent technical codes and standards to interconnect the HVDC and FACTS devices, a cost-recovery method that enables the utilities to cover their investments, and simplification of the approvals procedures required to start the new transmission projects. Nevertheless,

regulatory frameworks in other jurisdictions, including FERC Order 1000 in the United States, may offer beneficial examples of how to do regional transmission planning and allocate costs, but any incorporated framework must conform to the local legal and economic environment in Nigeria (Pfeifenberger et al., 2023).

Technical Skill and Maintenance Requirements

HVDC and FACTS technologies are also more complicated than traditional transmission equipment, and they demand special technical skills to design, operate, and maintain. A local human capacity needs to be developed via training programs and knowledge transfer initiatives. This involves developing a team of technicians and engineers skilled in power electronics, control systems and the specialized maintenance needed on these sophisticated gadgets. Absence of native technical know-how may result in dependence on outsourced contractors, which has the effect of increasing the costs of operation and may slow down maintenance and repair services.

Protection and Coordination in Hybrid Networks

The combination of HVDC and FACTS devices results in a hybrid AC/DC network and poses new problems in system protection and coordination. The fault nature of a hybrid grid is much more dissimilar to the fault nature of a conventional AC system, necessitating the creation of new protection schemes and coordination strategies (Abdelwanis & Elmezain, 2024). The rapid response of power electronic devices can lead to high fault currents and complex transient behaviour, which can be challenging for conventional protection relays to handle. Hence, ensuring the reliable and selective operation of protection systems in a hybrid network is crucial for preventing the malfunctioning operation of relays and avoiding cascading failures. Therefore, recent research has focused on developing advanced protection algorithms and communication-assisted schemes to address these challenges, but their

implementation requires careful planning and testing (Vrtal et al., 2021).

Contemporary FACTS and HVDC Technology for Voltage Stability Enhancement and Sustainable Power Infrastructure

There are two HVDC grid power converters and three FACTS technologies commercially developed, both of which are grounded on thyristor-based classical technology (Davidson & Dorn, 2023). They are Line-Commutated Converters (LCC) and the Voltage Source Converters (VSC) (Mohammadi et al., 2024). The LCC-HVDC and VSC-HVDC transmission technologies serve to accelerate the bulk power transfer over long distances with a low number of losses, reactive power compensation, and the incorporation of asynchronous grids (Watson & Watson, 2020; Zonetti et al., 2015) and weak networks into the existing grid to enhance the power system stability (Irnawan et al., 2025). The benefits that VSC-HVDC and LCC-HVDC will offer to the Nigerian power systems are (Ahrabi & Li, 2021):

- i. Improved long-distance bulk transfer
- ii. Reduced transmission losses
- iii. Precise control of power flow
- iv. Voltage support in weak grids
- v. Interconnecting asynchronous grid
- vi. Integration of renewable energy (solar and wind) into the grid

Equally, FACTS equipment, such as Static VAR Compensators (SVC), Static Synchronous Compensators (STATCOM), and Unified Power Flow Controllers (UPFC), also provide reactive power and dynamic voltage regulation and alleviate voltage sag, imbalance, and oscillatory behaviour (Alhamrouni et al., 2024; Teferra & Ngoo, 2021).

Advantages of VSC-HVDC Over FACTS for Voltage Stability Enhancement and Sustainable Power Infrastructure

VSC-HVDC transmission is crucial in improving Voltage stability in contemporary power systems. It possesses certain advantages

over the nearest competing technology, the UPFC. Research has demonstrated that, just as VSC-HVDC, UPFC possesses two degrees of freedom; therefore, it regulates active and reactive power simultaneously. Nevertheless,

the VSC-HVDC technology possesses the following advantages compared to FACTS devices, as outlined in Table 5 (Acaroğlu et al., 2021; Song et al., 2017; Xiao et al., 2021).

Table 5: Comparison of VSC-HVDC and FACTS Devices

Feature	VSC-HVDC	FACTS Devices
Voltage Control and Stability	Provides direct control of active and reactive power, making it highly effective in preventing voltage collapse	Can only modulate AC parameters; limited in direct voltage stability control
Long-Distance and Bulk Power Transmission	Suitable for long-distance bulk power transmission with minimal losses; supports remote and weak grids	Primarily used within AC networks; no direct long-distance transmission capability
Reactive Power Characteristics	Does not suffer from reactive power problems; independent control of reactive power	Operates within the AC system; reactive power issues still exist
Disturbance Isolation	Acts as a firewall, preventing cascading failures and isolating disturbances	Enhances local stability but cannot fully isolate disturbances
Black Start Capability	Capable of black start and system Restoration	Cannot provide independent power supply for restoration
Transmission Losses	Lower losses over long distances (reduced resistive and reactive losses)	Improves the efficiency of AC lines, but is less effective in loss reduction
Interconnection of Grids	Enables interconnection of asynchronous grids (different frequencies/voltages)	Cannot interconnect separate asynchronous systems
Cost Consideration	Uses conventional transformers; generally, more cost-effective in large-scale applications	Devices like UPFC require series transformer installation, increasing cost

DISCUSSION

The review shows that the HVDC and FACTS technologies have considerable technical benefits compared to conventional compensation methods. HVDC systems, especially Voltage Source Converter (VSC)-based systems, are the most controllable and also have better long-distance power transmission, are more efficient, and can interconnect asynchronous and weak grids. On the same note, FACTS equipment like STATCOM, SVC, and UPFC offer dynamic voltage regulation, enhanced power-flow regulation, and augmented transmission capacity to existing AC networks. These complementary features render these

technologies significant sources of current grid stability and flexibility.

The paper also notes the strategic importance of these technologies in meeting the Sustainable Development Goals (SDGs), SDG 7 and SDG 9, and provides an effective energy supply, integrates renewable energy, and enhances grid resilience. The thematic and comparative analysis of the literature that is available reveals that, despite the great gains that have been made in the world, there has been little use of HVDC and FACTS technologies in power system development, especially in the Nigerian scenario.

The gaps identified as crucial in the study included the inability to coordinate HVDC-FACTS control strategies, the lack of economic feasibility studies for emerging economies and multi-terminal HVDC systems, and implementation frameworks specific to Nigeria. These gaps should be addressed to make a powerful, future-oriented power transmission system a reality.

CONCLUSION

The paper has undertaken a detailed and organized review of the HVDC and FACTS technologies as potential alternatives or possible options for improving the voltage stability and the power infrastructure sustainability of the Nigerian 330 kV transmission system. The paper has discussed the structural and operational issues of the Nigerian grid, such as long transmission lines, ineffective interconnections, deficient reactive power supply, and frequent system failures, which all highlight the necessity of advanced transmission technologies. In all, HVDC and FACTS technologies integration is a revolutionary direction toward improving the stability of the voltage, increasing the efficiency of the transmission system, and providing the sustainability of the power infrastructure in Nigeria. The implementation should be context-specific, more advanced, and techno-economic optimized to encourage large-scale implementation in future research. These technologies will not only enhance the performance of the grid but will also be a key contributor to the transformation of Nigeria into a resilient, efficient, and sustainable energy future.

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