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Roles of FACTS Devices in Modern Transmission: A Review of Challenges, Solutions, and Research Direction

Sabo Aliyu[1], Sadiq N. Buba[2*]
[1]Department of Electrical and Electronics Engineering, Faculty of Engineering, Post Graduate School, Nigerian Defense Academy Nigeria
[2]Kaduna Electricity Distribution Company, Kaduna State, Nigeria

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ABSTRACT

Flexible AC Transmission Systems (FACTS) play a critical role in enhancing the stability, controllability, and efficiency of modern power transmission networks. This review examines the main FACTS devices—SVC, STATCOM, TCSC, SSSC, and UPFC—covering their classifications, working principles, integration methods, and comparative performance. Detailed schematics and tables are used to clarify their operation, highlight technical overlaps, and map device capabilities to specific system challenges. Key issues such as cost, control complexity, dynamic performance, and harmonic distortion are critically assessed, with proposed cross-device solutions and hybrid configurations presented to address these limitations. The review further emphasizes emerging trends, including AI-driven control strategies, hybrid FACTS architectures, and applications in renewable-rich smart grids. By combining comparative insights with a forward-looking perspective, this paper provides guidance for engineers, researchers, and policymakers on deploying FACTS technologies to build more resilient, adaptive power systems.

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1. INTRODUCTION

The increasing complexity of modern electrical grids—driven by urbanization, fluctuating load demand, and renewable energy integration—has highlighted the limitations of traditional transmission infrastructure in delivering stable and efficient power [1]. Power systems often encounter issues such as voltage instability, excessive transmission losses, and inefficient power flow control [2], [3]. These challenges have intensified the need for advanced technologies that enable dynamic, real-time control. Flexible AC Transmission Systems (FACTS), introduced by the Electric Power Research Institute (EPRI), have emerged as a critical solution to modern power system constraints. These devices use high-speed power electronic components to regulate key transmission parameters such as voltage, impedance, and phase angle, thereby enhancing grid stability and improving system flexibility [4], [5]. Various FACTS devices have been developed to serve different functions. For instance, the Thyristor-Controlled Series Capacitor (TCSC) is widely adopted for power flow regulation and oscillation damping [6]. The Static VAR Compensator (SVC) and the Static Synchronous Compensator (STATCOM) provide fast reactive power support to maintain voltage levels and improve power factor [7]. Meanwhile, the Unified Power Flow Controller (UPFC) stands out for its ability to simultaneously control voltage magnitude, phase angle, and line impedance enabling full power flow control [8]. In addition to their operational benefits, researchers have focused on optimizing the location and sizing of FACTS devices using heuristic and metaheuristic algorithms, including Modified Whale Optimization [9], Differential Evolution

*Corresponding Author
Email: sadiqnguraa@gmail.com

[10], and Lightning Attachment Procedures [11]. These techniques enhance the technical and economic impact of FACTS deployment by minimizing transmission losses and voltage deviations. Furthermore, the integration of Artificial Intelligence (AI) into FACTS control schemes is emerging as a transformative trend, particularly in smart grid and renewable-rich systems [12]. Despite these advancements, existing research often lacks a unified comparative assessment of different FACTS technologies. This paper aims to fill this gap by presenting a structured review of FACTS devices, discussing their operating principles, advantages, limitations, and strategic deployment methods. The novelty of this work lies in its inclusion of comparative tables, hybrid device trends, and AI-driven enhancements, offering practical guidance for engineers, researchers, and utility planners.

2. METHOD

This study adopts a structured, systematic methodology to review, analyze, and synthesize the relevant literature on Flexible AC Transmission Systems (FACTS) devices. The approach is designed to ensure thorough coverage of the field, focusing on both classical applications and modern enhancements, such as AI-based control and renewable energy integration.

2.1 Literature Search Strategy:

A comprehensive search was conducted across peer-reviewed databases, including IEEE Xplore, ScienceDirect, and Google Scholar, targeting publications from 2019 to 2025. Boolean logic was applied using keywords such as:

- "FACTS and power system stability"
- "FACTS and voltage control"
- "FACTS and transmission efficiency"
- "AI-based control of FACTS"
- "FACTS and renewable integration"

Search results were filtered to exclude non-peer-reviewed articles, proprietary reports, and irrelevant studies.
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2.2 Inclusion and Exclusion Criteria:

To maintain relevance and academic quality, the following criteria were applied:

- **Inclusion Criteria**:
  - ✓ Studies focused on classification, control techniques, performance analysis, optimization, and real-world applications of FACTS devices.
  - ✓ Papers that examined the integration of FACTS with renewable energy systems or AI-driven control.
- **Exclusion Criteria**:
  - ✓ Articles not related to FACTS devices in transmission systems.
  - ✓ Non-technical or non-peer-reviewed sources.

2.3 Data Extraction and Analysis:

After selection, data were extracted based on:

- Type and classification of FACTS device.
- Control strategy employed.
- System model or test system used.
- Application domain (e.g., voltage support, power flow control, stability enhancement).

The analysis included:

- **Categorical grouping** of FACTS devices (Series, Shunt, Combined Series-Shunt).
- **Comparative review tables** summarizing functionality, advantages, limitations, and ideal application scenarios.
- Integration strategies for FACTS in smart grid and renewable-heavy systems.

2.4 Reference Management:

All references and citations were organized using Mendeley, ensuring proper formatting and traceability. Extracted insights were cross-referenced and validated through multiple sources to guarantee consistency and accuracy.

2.5 Overview of FACTS Devices:

The growing demand for reliable and efficient power transmission has led to the development of Flexible AC Transmission Systems (FACTS), a technology aimed at enhancing controllability, stability, and power transfer capabilities in modern electrical grids [13], [14]. FACTS devices use power electronics to dynamically regulate voltage, impedance, and phase angles, improving overall system performance and reducing transmission losses [15], [16]. FACTS devices are broadly classified into three main categories based on their mode of operation, as follows:

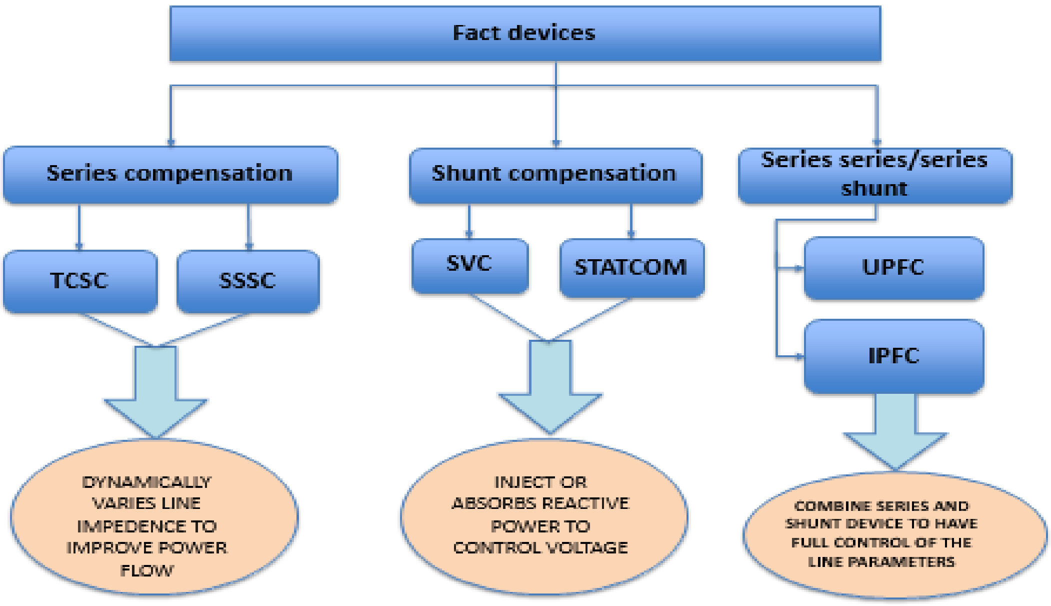

Figure 1. Classification of Facts Devices

This figure illustrates the three major categories of FACTS controllers: series, shunt, and combined. Series controllers regulate transmission-line impedance, shunt devices provide voltage and reactive power support, and combined controllers integrate both functions. The classification provides a clear framework for comparing device capabilities and applications. It also establishes the foundation for discussing how each FACTS technology contributes to improved stability and controllability in power networks.

2.6 Review of Related Literature:

The deployment of FACTS devices has been widely researched to improve voltage stability, minimize losses, and optimize power flow in modern transmission networks [12]. Various studies have examined these devices from multiple perspectives, including their configuration, application domains, control techniques, and performance in renewable-integrated grids. This section presents a thematic review organized by device type, application, and system-level performance.

2.6.1 Device-Based Studies:

SVC and STATCOM are the most widely deployed shunt-type FACTS devices, primarily for voltage regulation. Yaseen and Bali [17] and Carlak and Kayar [18] highlighted the role of STATCOM and SVC in voltage and VAR regulation, demonstrating the superior performance of STATCOM in low-voltage conditions. Meanwhile, UPFC has drawn attention for its full power-flow control capability. The benefits of UPFC in optimizing power transfer and maintaining stability in integrated systems were demonstrated by Yaseen and Bali [17] and further supported by optimization-based deployment studies, such as that by Hassan et al. [19].

2.6.2 Series Compensation and Hybrid Controllers:

Series compensators like TCSC and SSSC have also been thoroughly investigated. Yahia et al. [20] examined their roles in improving dynamic grid performance under wind integration scenarios, while Kalpaktsoglou et al. [21] compared series and shunt compensation schemes in renewable-based systems. Zakri et al. [22] proposed modeling approaches for TCSC in practical grids. Furthermore, hybrid shunt-series controllers were introduced by Tiwari et al. [23], demonstrating potential to enhance voltage stability through coordinated control.

2.6.3 Optimization and Control Strategies:

Modern FACTS applications increasingly leverage optimization and AI-based control. Zadehbagheri [24] proposed optimal placement of FACTS devices using evolutionary strategies to reduce system losses and enhance voltage profiles. Swarupa et al. [25] reviewed the integration of machine learning techniques in FACTS-based power quality enhancement. Meanwhile, Reddy et al. [26] demonstrated AI-based controllers for grid-connected distribution systems, highlighting improved adaptability and performance.

2.6.4 Comparative and Application-Focused Studies:

Comprehensive comparisons have also been made between traditional and advanced FACTS devices. Carbonara et al. [27] offered an updated review of FACTS versus conventional solutions, showing the superiority of advanced devices in dynamic performance. Chethan and Kuppan [12] reviewed optimization techniques for FACTS deployment, offering insights into various device configurations. Additionally, Nepsha et al. [15] evaluated the application of FACTS devices in specialized environments, such as coal mine power systems, demonstrating their flexibility and system-level impact.

3. RESULTS

3.1 Series compensation devices:

Series compensation is a class of FACTS devices that are connected in series with the transmission line to improve power transfer capability, voltage stability, and system stability**.** Series compensation devices play a crucial role in improving the power transfer capability of transmission lines by reducing their effective reactance, allowing more power to be transferred, and by injecting a controlled series voltage. These devices enhance power flow, mitigate oscillations, and improve system stability. The two widely studied series compensation devices are the;

- Thyristor-Controlled Series Capacitor (TCSC)
- Static Synchronous Series Compensator (SSSC).

3.1.1 Thyristor-Controlled Series Capacitor (TCSC):

The Thyristor-Controlled Series Capacitor (TCSC) is a type of series FACTS device used in power transmission systems to enhance power transfer capability, improve voltage stability, and damp power oscillations [2], [28]. It consists mainly of a series capacitor connected in parallel with a thyristor-controlled reactor (TCR), allowing dynamic control of the line's effective reactance [20], [28]. By adjusting the thyristor firing angle, the TCSC can operate in different modes capacitive, inductive, or bypass—depending on system demands. In capacitive mode, it increases power flow and stability; in inductive or bypass modes, it limits power flow to protect the system. TCSC's fast and flexible response makes it a vital tool in modern transmission networks for maintaining system reliability and efficiency. A TCSC comprises of the following key components.

3.1.1.1 Components of TCSC:

- Series Capacitor (C): the main element that provides series compensation by reducing the transmission line's effective reactance.
- Thyristor-Controlled Reactor (TCR): Consists of an inductor connected in parallel with the capacitor and controlled by Thyristor switches. It helps adjust the effective compensation by regulating the current flow through the reactor.
- Thyristor Valves (SCRs): Silicon-Controlled Rectifiers (SCRs) are used to dynamically switch the inductor in and out of the circuit.
- Metal-Oxide Varistor (MOV): Protects the capacitor from overvoltage conditions by absorbing excess energy.
- Damping Circuit: Ensures stability by reducing high-frequency oscillations in the system.
- Control and Protection System: Monitors system conditions and adjusts Thyristor firing angles to regulate compensation.

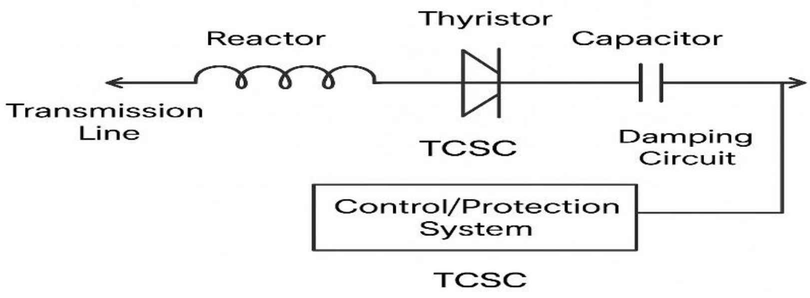

Figure 2. Circuit Diagram of TCSC

The schematic above shows the main components of a Thyristor-Controlled Series Capacitor (TCSC), including the capacitor, thyristor-controlled reactor, and protective circuits [21]. By varying the thyristors firing angle, the effective line reactance can be adjusted. This allows the device to operate in capacitive or inductive modes, enabling power-flow regulation and damping of oscillations. The figure illustrate how TCSC enables flexible series compensation to improve transmission performance.

3.1.1.2 Working Principle of TCSC

The Thyristor-Controlled Series Capacitor (TCSC) operates by dynamically adjusting the effective reactance of a transmission line through controlled switching of a parallel thyristor-controlled reactor (TCR) across a series capacitor [22]. This enables flexible control of power flow, damping of oscillations, and enhancement of system stability [29]. The TCSC functions through three main operating stages, which are controlled by the firing angle of the thyristors, and these stages are outlined below:

1. Blocked Mode (Normal Capacitor Mode)
   - In this mode, the thyristors are kept OFF, so no current flows through the thyristor-controlled reactor (TCR).
   - The series capacitor operates as a fixed capacitor, providing a constant level of compensation.
   - This mode is typically used when the system is stable, and no dynamic adjustments are required.
2. Partially Conducting Mode (Controlled Capacitive Mode)
   - Here, the thyristors are fired at specific angles, allowing partial current conduction through the inductor (TCR).
   - This causes a continuous variation in the TCSC's effective reactance.
   - The thyristor firing angle determines whether the net reactance increases or decreases, providing dynamic compensation based on real-time system conditions.
   - This mode is used to enhance power transfer and improve stability under varying load conditions.
3. Bypass Mode (Fully Conducting Mode)
   - In this mode, the thyristors are fully turned ON, causing the inductor to completely bypass the capacitor.
   - As a result, the capacitor is short-circuited, and no series compensation is provided.
   - This mode is used during fault conditions or system disturbances to protect the capacitor and maintain stability.

By transitioning between these modes, the TCSC effectively regulates the power flow, mitigates voltage fluctuations, and enhances overall transmission system performance. Its ability to dynamically adjust reactance in real time makes it a critical component in modern power networks. To better understand, let's consider how the thyristor firing angle influences the compensation level.

Table 1. Summary of Firing Angle Effect on TCSC Operation

S/N	Firing Angle (α)	TCSC Mode	Effect on Series Compensation
1	Close to 180°	Blocked Mode (Fixed Capacitor Mode)	Constant capacitive reactance, no dynamic control
2	Between 90° and 180°	Partially Conducting Mode (Controlled Compensation Mode)	Variable capacitive compensation based on α
3	Close to 90°	Bypass Mode (Fully Conducting Mode)	Capacitor is bypassed, no series compensation

This table summarizes how different thyristor firing angles affect TCSC operation. Small firing angles correspond to capacitive behavior, while larger angles shift the device toward inductive or bypass modes. Such dynamic control enables fine regulation of line reactance. The tabulated explanation demonstrates how TCSC adapts to varying grid conditions.

Table 2. Key Link between δ and α in TCSC Operation

S/N	Firing Angle (α)	TCSC Mode	Effect on Reactance (Xeq)	Impact on Power Angle (δ)	Power Transfer (P)
1	Close to 180°	Blocked Mode (Fixed Capacitor)	Constant capacitive reactance	δ unchanged	Power transfer remains steady
2	90° < α < 180°	Partially Conducting Mode (Controlled Compensation)	Reactance decreases dynamically	δ decreases for same power transfer	Power transfer increases
3	Close to 90°	Bypass Mode (Inductive Mode)	Reactance increases	δ increases for same power transfer	Power transfer decreases

The table highlights how changes in firing angle influence line reactance and, in turn, the power angle δ and transmitted power P. Smaller δ values improve stability by reducing stress on transmission lines. This linkage shows the importance of precise α control for maintaining reliable operation. The table underscores the interaction between TCSC settings and system performance.

3.1.2 Static Synchronous Series Compensator (SSSC):

The Static Synchronous Series Compensator (SSSC) is a voltage-source converter (VSC)-based series FACTS device that controls power flow in a transmission line by injecting a controllable AC voltage in series with the line. Unlike traditional series capacitors, the SSSC can provide both capacitive and inductive compensation without using physical reactive components, enabling precise and rapid power flow control. It operates independently of line current and can dynamically regulate the line impedance to either increase or decrease power transfer. With its ability to enhance system stability, damp oscillations, and improve transmission efficiency, the SSSC plays a crucial role in flexible and reliable power system operation. Below are the components that make up the device.

3.1.2.1 Components Of SSSC Device:

1. Voltage Source Converter (VSC):
   - Converts DC voltage to a controllable AC voltage for injection into the transmission line in series.
2. DC Energy Source or DC Capacitor:
   - Provides the required DC voltage input to the VSC. It stores and stabilizes the DC link voltage.
3. Series Coupling Transformer:
   - Connects the VSC output to the transmission line and injects the synthesized AC voltage in series with it.
4. Control System / Digital Signal Processor (DSP):
   - Monitors power system conditions and controls the magnitude and phase angle of the injected voltage in real-time.
5. Cooling System:
   - Maintains the operating temperature of the power electronics and prevents overheating.

6. Protection System:
   - Ensures safe operation by detecting faults and abnormal conditions in the SSSC and isolating it when necessary.

These components work together to provide flexible and dynamic control of power flow and enhance the stability of transmission systems. For better understanding, let us look at its circuit diagram and discuss its working principle.

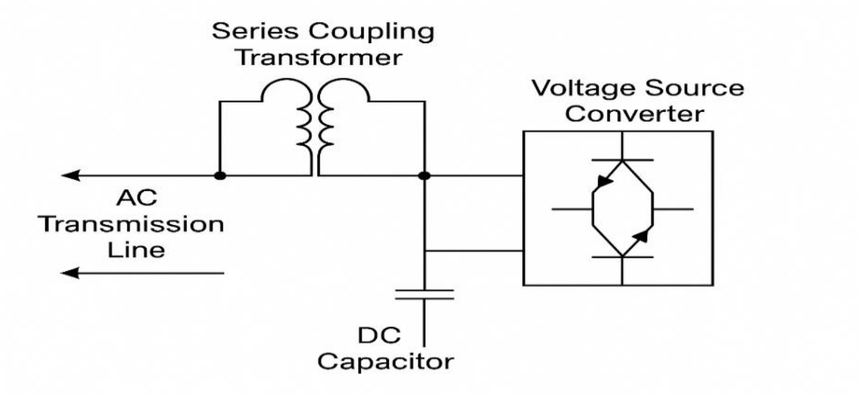

Figure 3. Circuit Diagram of SSSC

This diagram shows the Static Synchronous Series Compensator (SSSC), which uses a Voltage Source Converter (VSC) and a series-coupled transformer. The device injects a controllable AC voltage in series with the line, typically in quadrature with current, to provide reactive compensation. Depending the on control settings, it can either increase or decrease the effective line reactance. The figure underscores the SSSC's ability to regulate power flow rapidly and improve dynamic stability.

3.1.2.2 Working Principle of SSSC:

The Static Synchronous Series Compensator (SSSC) controls power flow by injecting a controllable AC voltage in series with the transmission line through a Voltage Source Converter (VSC). This voltage, supplied by a DC capacitor or source and coupled via a transformer, is typically in quadrature with the line current, providing reactive compensation without supplying real power. By adjusting the magnitude and phase of the injected voltage, the SSSC can reduce or increase line reactance, thereby enhancing power transfer, damping oscillations, and improving voltage stability. Its integration into transmission networks requires coordinated protection and control, but it offers fast, precise regulation of line impedance for reliable system operation.

3.2 Shunt Compensation Devices:

Shunt compensation involves connecting a device in parallel with the transmission line or the load to inject or absorb reactive power, thereby helping regulate voltage, improve power factor, and maintain system stability. The primary objective of shunt compensation is to maintain a stable voltage profile, especially during load fluctuations or fault conditions, and to improve the quality and reliability of power transmission. Shunt compensators are particularly effective in mitigating voltage dips, enhancing transient stability, and reducing losses due to reactive power flow [3]. The two widely studied shunt compensation devices are the;

- Static var compensation device (SVC).
- Static Synchronous Compensator (STATCOM).

3.2.1 Static Var Compensation Device (SVC):

The Static Var Compensator (SVC) is a shunt-connected device under the FACTS (Flexible AC Transmission Systems) family, primarily used to regulate voltage levels, improve power quality, and enhance the stability of power transmission networks [25]. It achieves this by providing fast-acting reactive power via power electronics [18]. The SVC typically consists of combinations of Thyristor-Controlled Reactors (TCRs) and Thyristor-Switched Capacitors (TSCs), which are controlled without mechanical switches. By adjusting the thyristor firing angles, the SVC can dynamically vary the amount of reactive power it absorbs (inductive) or supplies (capacitive) to the grid.

When the system voltage drops below a desired level, the SVC supplies reactive power through its capacitor banks, helping ~~to~~ raise the voltage. Conversely, when the voltage rises above the set point, the SVC absorbs reactive power through reactors, which helps reduce the voltage. This fast continuous control of reactive power enables the SVC to stabilize voltage fluctuations, dampen power oscillations, and enhance network transmission capacity. In addition to voltage regulation, SVCs are also used to improve power factor, reduce transmission losses, and support dynamic stability during faults or large load variations. They are commonly installed in high-voltage transmission systems and industrial plants where voltage stability and reactive power control are critical. Below is a figure illustrating how this device is connected to the AC transmission network.

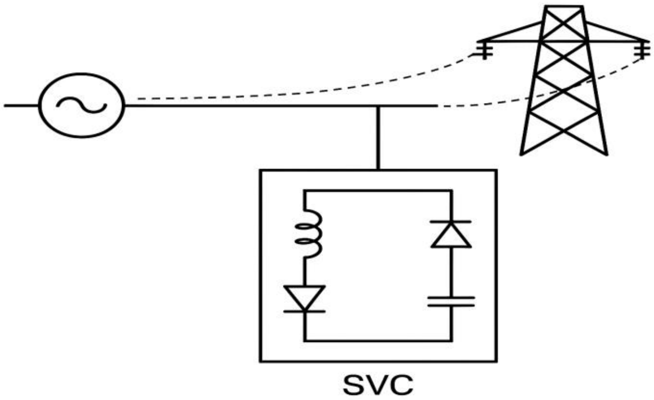

Figure 4. Schematic Electrical Diagram of an SVC Connected to a Transmission Line

The schematic shows a Static VAR Compensator (SVC), built from combinations of thyristor-controlled reactors (TCRs) and thyristor-switched capacitors (TSCs). By dynamically switching between capacitive and inductive compensation, the SVC regulates bus voltage in real time. This makes it effective for mitigating voltage fluctuations and enhancing steady-state stability. The figure emphasizes its role as a widely used shunt device in transmission networks.

3.2.2 Static Synchronous Compensator (STATCOM):

The Static Synchronous Compensator (STATCOM) is a shunt-connected FACTS device that provides rapid, precise reactive power compensation to regulate voltage levels and enhance power system stability [20]. Unlike the SVC, which uses passive components and thyristors, the STATCOM uses Voltage Source Converter (VSC) technology, enabling it to generate a controllable AC voltage in phase with the grid [25]. This makes it more efficient and responsive, especially during low-voltage conditions. The basic working principle of STATCOM involves converting DC voltage into a controllable AC voltage using IGBTs (Insulated Gate Bipolar Transistors) or GTOs (Gate Turn-Off thyristors) within the VSC [30]. By controlling the magnitude and phase angle of this AC voltage, STATCOM can either inject or absorb reactive power from the grid. When the output voltage of the converter is higher than the bus voltage, STATCOM supplies reactive power (capacitive mode). When it is lower, it absorbs reactive power (inductive mode).

STATCOM's ability to operate effectively even at low system voltages gives it a significant edge over conventional devices such as SVCs. It responds almost instantaneously (within milliseconds), making it suitable for real-time voltage regulation, dynamic stability support, and power quality enhancement [2]. It is widely used in transmission networks, wind farms, solar systems, and industrial applications requiring robust voltage and reactive power control.

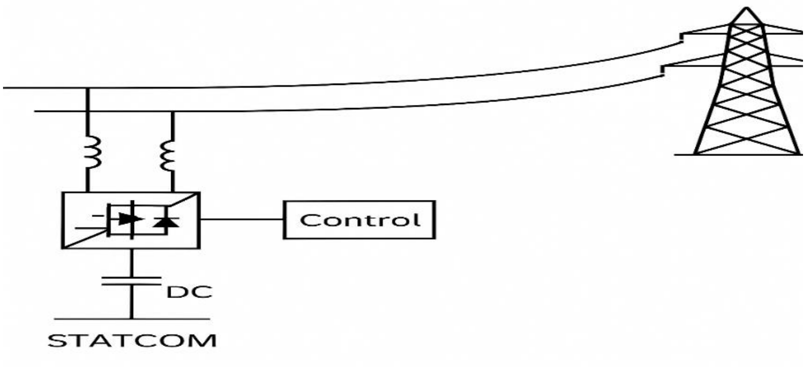

Figure 5. Schematic Electrical Diagram of STATCOM Connected to a Transmission Line

This schematic depicts the Static Synchronous Compensator (STATCOM), a shunt device based on a Voltage Source Converter (VSC). Unlike SVC, STATCOM can maintain high performance even at low voltages, providing superior reactive power support. Its fast response makes it suitable for integrating renewables and strengthening weak grids. The figure highlights its converter-based design and versatility in voltage regulation.

3.3 Unified Power Flow Controllers (UPFC, IPFC):

The Unified Power Flow Controller (UPFC) is one of the most versatile and powerful FACTS devices, designed to simultaneously control multiple parameters of a power transmission system namely, voltage magnitude, phase angle, and line impedance. This capability allows the UPFC to manage real and reactive power flows effectively, making it a highly flexible solution for modern power networks [17], [24].

The UPFC combines the functionalities of two other key FACTS devices: the Static Synchronous Compensator (STATCOM) and the Static Synchronous Series Compensator (SSSC) [23]. These two converters are interconnected via a common DC link, allowing coordinated control. The shunt converter (STATCOM part) is responsible for voltage regulation and reactive power support, while the series converter (SSSC part) injects a controllable series voltage into the transmission line, thereby influencing power flow direction and magnitude [17].

By adjusting the magnitude and angle of the series-injected voltage, the UPFC can dynamically regulate power flow without changing generation or load [31]. It is particularly valuable in congested or heavily loaded power corridors, enhancing system stability, reducing transmission losses, and enabling better utilization of existing infrastructure [19], [24].

3.3.1 Working principle of UPFC:

The UPFC operates by integrating two Voltage Source Converters (VSCs) through a common DC link to independently or simultaneously control multiple transmission line parameters:

3.3.2 Components of UPFC:

- Shunt Converter (STATCOM function):
  Injects or absorbs reactive power into or from the system, helps with voltage regulation, and maintains the DC link voltage.
- Series Converter (SSSC function):
  Injects a controllable AC voltage in series with the transmission line to control power flow by adjusting the line's apparent impedance, phase angle, and voltage magnitude.
- DC Link (Capacitor):
  Transfers energy between the two converters and maintains a constant DC voltage level.

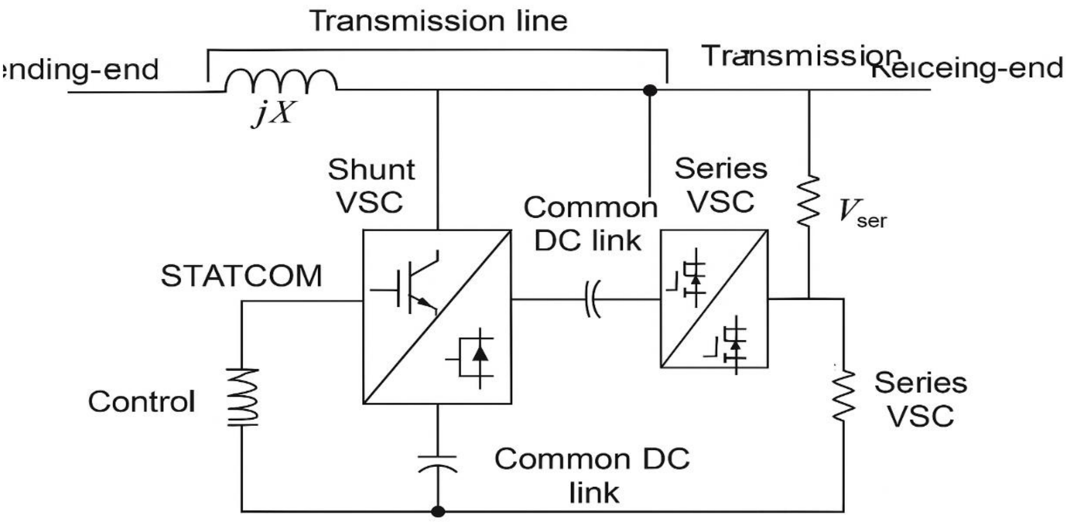

Figure 6. Circuit Diagram of UPFC

The Unified Power Flow Controller (UPFC) is shown here, integrating series and shunt VSCs through a common DC link. This configuration allows simultaneous control of line impedance, voltage, and phase angle. The UPFC is the most versatile FACTS device, capable of addressing multiple system constraints at once. The schematic highlights its multifunctional architecture and advanced role in modern transmission systems.

4. DISCUSSION

This section presents a comprehensive set of tables and figures that highlight the challenges, similarities, and future research trends associated with various FACTS devices. The tables provide a comparative analysis of key FACTS devices—such as SVC, STATCOM, TCSC, SSSC, and UPFC—covering their applications, advantages, and limitations in modern power transmission systems [32]. One table specifically outlines the shared components and functions across these devices, emphasizing their roles in voltage control, reactive power compensation, and power flow regulation. In addition, the included sections discuss on the challenges, solutions, and future trends, illustrating how FACTS devices (e.g., SVC and STATCOM) are integrated into transmission networks, providing clarity on their operational principles and outlining their challenges. The narrative also delves into emerging trends, such as the growing interest in hybrid configurations, the integration of advanced control algorithms, and the deployment of FACTS in renewable-rich grids [32], [33]. These insights collectively support a deeper understanding of how FACTS devices enhance grid stability, efficiency, and flexibility, while identifying areas where further innovation and research are needed.

4.1 Challenges of FACTS Devices:

FACTS devices are essential tools for enhancing transmission efficiency and stability. However, these devices may face challenges such as cost, complexity, control coordination, and potential instability. Several studies [27], [30], [13] have highlighted that while devices such as UPFCs and STATCOMs provide excellent dynamic performance, their high capital costs and complex control architectures limit widespread deployment. For instance, Carbonara et al. [13] emphasized that UPFC requires careful converter coordination, while Chethan and Kuppan [30] noted the risk of misoperation in large-scale systems.

4.2 Solutions to the Challenges:

To overcome these limitations, researchers have proposed various solutions, including optimization techniques and hybrid configurations [27]. Optimization-based placements using metaheuristic algorithms like Genetic Algorithms and Whale Optimization have been explored to minimize installation costs and maximize voltage support [24], [34]. Additionally, the work of Yaseen and Bali [20] demonstrated that optimally located UPFCs can effectively mitigate post-contingency instabilities. AI-based coordination strategies and intelligent controllers also offer promising results in dynamic environments.

4.3 Research Trends in FACTS Deployment:

FACTS technology is evolving rapidly, with increasing research focused on intelligent systems, renewables integration, and hybrid FACTS deployment [26], [32]. Recent trends show growing integration of AI and machine learning in FACTS control strategies. Swarupa et al. [35] employed neural networks for voltage regulation, while Reddy et al. [36] demonstrated real-time adaptability using AI-based controllers in grid-connected systems. Moreover, Yahia et al. [2] analyzed the impact of FACTS on wind-based grids, confirming that SSSC and TCSC can effectively stabilize variable inputs. These studies suggest that FACTS will remain a cornerstone of grid modernization efforts, particularly in renewable-dominated smart grids. Tables 3 – Table 6 below provide a structured comparison of FACTS devices, including their shared components, functional differences, technical challenges, and application areas. These summaries are intended to give readers a clear overview of how different controllers relate to one another, and each table is explained in detail for clarity.

Table 3. Similarities in Components and Applications of FACTS Devices

FACTS Devices	Common Components	Common Applications
SVC & STATCOM	Reactive power compensators (capacitors/reactors), thyristors/IGBTs	Voltage control, dynamic VAR support
STATCOM & SSSC	Voltage Source Converter (VSC), DC link capacitor	Voltage injection, fast dynamic response
TCSC & SSSC	Series compensation, line impedance control	Power flow regulation, damping oscillations
UPFC (STATCOM + SSSC)	Two VSCs, shared DC link, control unit	Voltage control, real & reactive power flow, stability improvement

This table identifies commonalities across FACTS devices, such as the use of voltage-source converters in SSSC and STATCOM. Highlighting these overlaps shows how device technologies build upon one another. It also suggests potential for hybrid designs that combine the advantages of multiple devices. The summary emphasizes the interconnected development of FACTS technologies.

Table 4. Comparison of Major FACTS Devices

FACTS Device	Application	Advantages	Disadvantages
SVC (Static VAR Compensator)	Voltage regulation and reactive power compensation	Simple design, fast response, widely used	Limited control over real power, may cause harmonic issues
STATCOM (Static Synchronous Compensator)	Voltage support and dynamic reactive power injection	Faster response than SVC, better performance under low voltages	Costlier than SVC, complex converter-based system
TCSC (Thyristor-Controlled Series Capacitor)	Power flow control, transient stability improvement	Reduces sub-synchronous resonance, dynamic impedance control	May trigger control instability if not tuned properly
SSSC (Static Synchronous Series Compensator)	Real/reactive power control via series voltage injection	Full control of power flow, fast dynamic response	Requires VSC, complex and expensive
UPFC (Unified Power Flow Controller)	Simultaneous control of voltage, impedance, and phase angle	Most versatile, complete power flow control	High cost, complex control, requires coordination of converters

The table above provides a comparative overview of different FACTS devices by function, location, and capability. It serves as a quick reference for engineers when selecting appropriate controllers for specific needs. The contrasts also reveal trade-offs between cost, complexity, and flexibility. This summary highlights the complementary roles of various FACTS devices in practice.

Table 5. Challenges of FACTS Devices and Cross-Device Solutions

FACTS Device	Challenges in Power Systems	Complementary Solution Using Another Device
SSSC	Complex design; high cost due to VSC and power electronics	TCSC can serve as a cost-effective alternative where full dynamic control is not required
STATCOM	High installation cost; limited real power control	UPFC extends functionality by combining reactive and real power control in one unit
SVC	Slower dynamic response under severe voltage dips; limited performance under low voltage conditions	STATCOM offers faster response and better low-voltage performance due to VSC technology
TCSC	Susceptible to sub-synchronous resonance (SSR); limited controllability	SSSC provides enhanced control using VSC and reduces resonance issues
UPFC	High complexity and cost; control coordination required between converters	STATCOM or SSSC may be deployed independently in less critical areas to reduce complexity and cost

This table outlines key technical challenges, such as voltage instability and power oscillations, along with the FACTS devices best suited to address them. It shows that no single device resolves all issues, but combined applications provide comprehensive solutions. The comparison underscores the value of strategic deployment across different devices. The table provides clarity on how FACTS controllers collectively contribute to system stability.

Table 6. Areas of Application and Suitable FACTS Devices

Power System Problem / Objective	Recommended FACTS Device(s)	Justification / Role
Voltage Instability / Sag	SVC, STATCOM	Provide dynamic reactive power support and voltage regulation at critical buses
Power Flow Management	TCSC, SSSC, UPFC	Control line impedance and phase angle to reroute power and balance system loading
Transient and Dynamic Stability	TCSC, UPFC	Improve damping of oscillations and enhance fault recovery through fast control
Reactive Power Compensation	SVC, STATCOM	Maintain reactive power balance for stable operation during load variation
Series Compensation for Long Transmission Lines	TCSC, SSSC	Increase power transfer capability and reduce losses by injecting compensating voltage
Multi-Parameter Control (P, Q, Voltage)	UPFC	Simultaneous control of multiple parameters to fully optimize system performance
Renewable Grid Integration (e.g., wind, solar)	STATCOM, UPFC	Handle fast fluctuations in generation and stabilize weak grids with rapid response

This table links specific operational challenges, such as renewable integration or congestion management, with the most effective FACTS solutions. It provides a practical mapping between grid problems and controller choices. The summary demonstrates how device capabilities align with emerging needs in modern power systems. The table reinforces the practical significance of FACTS deployment strategies.

In addition to technical descriptions, it is important to consider how FACTS devices are applied in practice and how they are studied in research. Figures 7 and Figure 8 summarize the distribution of applications across different devices and the trends in research focus over recent years.

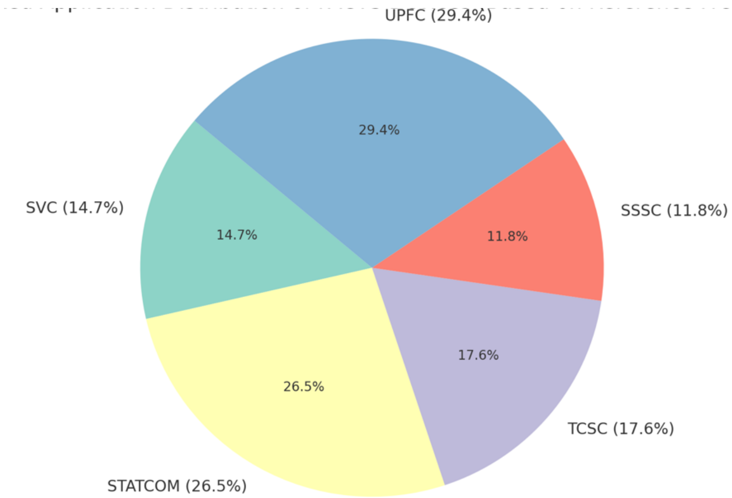

Figure 7. Application Distribution of FACTS Devices.

This chart presents the relative application of different FACTS controllers as reported in reviewed studies. It shows that STATCOM and UPFC dominate, reflecting their multifunctional capabilities and suitability for modern grid challenges, while SVC and TCSC remain in use for specific purposes. The figure highlights how research and industry prioritize converter-based solutions that offer greater flexibility and faster response compared to traditional controllers.

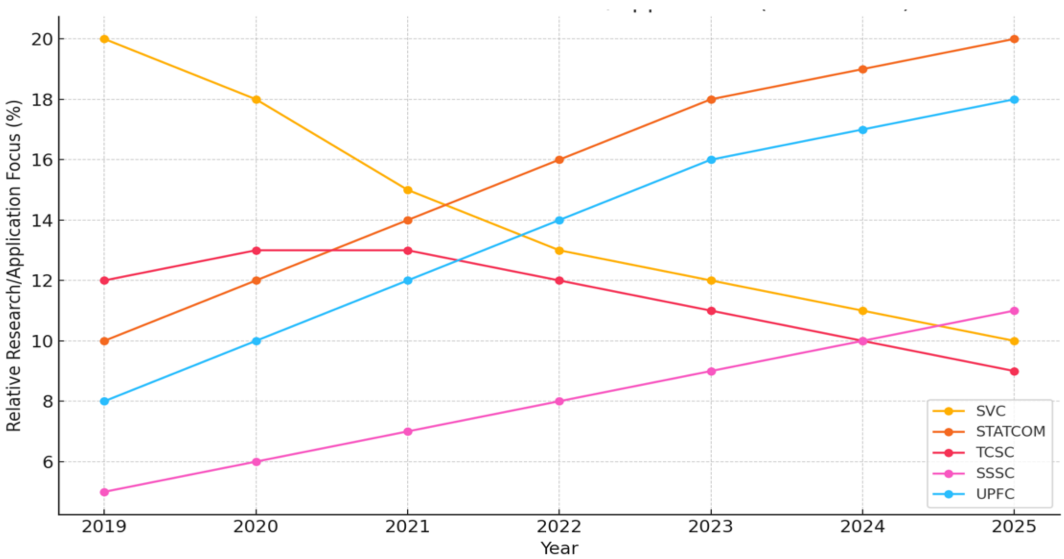

Figure 8. Research and Application Trend of FACTS Devices (2019–2025).

The figure illustrates the evolution of FACTS-related research and applications over recent years. A steady rise in STATCOM and UPFC studies reflects the growing demand for advanced solutions compatible with renewable integration and intelligent control. In contrast, interest in traditional devices such as SVC and TCSC has declined gradually, though they remain relevant in niche applications. The trend underscores a transition toward multifunctional FACTS technologies better suited to future power system needs.

4.4 Graphical Analysis

The graphical results presented in Figures 7 and Figure 8 highlight important trends in the research and application of FACTS devices. The dominance of STATCOM and UPFC reflects the industry's move toward converter-based solutions that provide rapid dynamic response and multifunctional control, which are increasingly essential for renewable energy integration and modern grid flexibility. In contrast, traditional devices such as SVC and TCSC, while still relevant for specific tasks, are declining, indicating their limited suitability for emerging challenges. These patterns suggest that future research will focus more on advanced FACTS configurations, hybrid systems, and intelligent control strategies. Overall, the graphical analysis reinforces the transition toward more versatile and adaptive FACTS technologies that can support next-generation power systems.

5 CONCLUSION

This paper has presented a structured review of the roles of Flexible AC Transmission Systems (FACTS) in modern power networks. By analyzing key devices—SVC, STATCOM, TCSC, SSSC, and UPFC—the study examined their classifications, working principles, integration methods, and comparative performance. Detailed schematics and discussions clarified their operation within transmission lines, while highlighting their distinct contributions to voltage regulation, power flow management, stability enhancement, and reactive power compensation. The review also addressed challenges such as cost, dynamic performance limitations, harmonic distortion, and control complexity. To mitigate these issues, comparative tables and cross-device solutions were provided, showing how different FACTS controllers can complement one another. Furthermore, hybrid configurations and coordinated deployment strategies were discussed as practical approaches to achieving system reliability. Looking ahead, the analysis underscored the growing importance of STATCOM and UPFC, reflecting a wider industry shift toward converter-based technologies. Future trends point toward AI-driven control, hybrid FACTS architectures, and wider deployment in renewable-dominated smart grids. By combining comparative insights with a forward-looking perspective, this review provides a practical guide for engineers, researchers, and policymakers seeking to maximize the efficiency, resilience, and adaptability of transmission systems through FACTS technologies.

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REFERENCE

[1] R. A. Zeitawyeh and A. Faza, “Optimal Reactive Power Planning Using FACTS Devices for Voltage Stability Enhancement in Power Transmission Systems,” *Energy Sci. Eng.*, 2025. https://doi.org/10.1002/ese3.70064.

[2] D. Akhmetbaev and A. Akhmetbaev, “Application of static thyristor compensators to increase the reliability of distribution networks,” *E3S Web of Conferences*, pp. 1–6, 2024. https://doi.org/10.1051/e3sconf/202458401015.

[3] M. Santhosh Raikar and G. D. Kamalapur, “" Transient stability Studies of series FACT Device: A Comparative Study of GCSC and TSSC", *Int. J. Adv. Sci. Eng.*, vol. 9, no. 2, pp. 2698–2708, 2022. https://doi.org/10.29294/ijase.9.2.2022.2698-2708.

[4] A. Sabo et al., “FACTS Devices as a Solution to Power Industries Problems: A Review,” *Eur. J. Theor. Appl. Sci.*, vol. 2, no. 3, pp. 82–87, 2024. https://doi.org/10.59324/ejtas.2024.2(3).09.

[5] M. A. Al-Flaiyeh and N. H. Aziz, “Enhancement Stability of the Power System Using Static Synchronous compensators Connected in Different Formats,” *Tikrit J. Eng. Sci.*, vol. 28, no. 1, pp. 1–12, 2021. https://doi.org/10.25130/tjes.28.1.01.

[6] C. O. Onah, “The Impact of Static Synchronous Compensator (STATCOM) on Power System Performance: A Case Study of the Nigeria 330 kV Power System Network,” pp. 42–52, 2020. https://doi.org/10.9790/1813-0907014252.

[7] H. M. Daealhaq, Y. F. kfajey, and A. S. Tukkee, “Power Loss Reduction and Voltage Profile Improvement Using Optimal Placement of FACTS Devices,” *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 1067, no. 1, p. 012128, 2021. https://doi.org/10.1088/1757-899x/1067/1/012128.

[8] N. H. Khan et al., “A Novel Modified Lightning Attachment Procedure Optimization Technique for Optimal Allocation of the FACTS Devices in Power Systems,” *IEEE Access*, vol. 9, no. February, pp. 47976–47997, 2021. https://doi.org/10.1109/ACCESS.2021.3059201.

[9] M. K. Kar, S. Kanungo, F. Alsaif, and T. S. Ustun, “Optimal Placement of FACTS Devices Using Modified Whale Optimization Algorithm for Minimization of Transmission Losses,” *IEEE Access*, vol. PP, p. 1, 2024. https://doi.org/10.1109/ACCESS.2024.3458039.

[10] N. H. Khan et al., “Enhanced skill optimization algorithm: Solution to the stochastic reactive power dispatch framework with optimal inclusion of renewable resources using large-scale network,” *IET Renew. Power Gener.*, vol. 18, no. November, pp. 4565–4583, 2024. https://doi.org/10.1049/rpg2.13167.

[11] M. L. Woldesemayat and A. T. Tantu, “Security Enhancement of Power Systems through Interline Power Flow Controller (IPFC) under Contingency Condition: A Case Study and Analysis-EEP 400 kV System,” *J. Electr. Comput. Eng.*, vol. 2022. https://doi.org/10.1155/2022/5897285.

[12] M. Chethan and R. Kuppan, “A review of FACTS device implementation in power systems using optimization techniques,” *J. Eng. Appl. Sci.*, vol. 71, no. 1, pp. 1–36, 2024. https://doi.org/10.1186/s44147-023-00312-7.

[13] J. G. Kassakian, D. J. Perreault, G. C. Verghese, and M. F. Schlecht, *Principles of Power Electronics*. 2023. https://doi.org/10.1017/9781009023894.

[14] J. Issa, "functions of facts devices with innovation technology in the electrical energy system," *J. Eng. Sci.*, vol. 7, no. 5, p. 55, 2024. https://doi.org/10.5281/zenodo.11127779
[15] F. Nepsha, V. Voronin, R. Belyaevsky, V. Efremenko, and K. Varnavskiy, "Application of FACTS Devices in Power Supply Systems of Coal Mines," *E3S Web of Conferences*, 2020, pp. 1–8. https://doi.org/10.1051/e3sconf/202017403026.
[16] W. Akhtar and D. Vishwakarma, "Transient Stability Improvement using FACTS Devices," *Int. J. Sci. Res.*, vol. 5, no. 5, pp. 1553–1556, 2016. https://doi.org/10.21275/v5i5.nov163763.
[17] M. D. Yaseen and S. K. Bali, "A UPFC based Optimal Power Flow of an Integrated Power System," *Int. J. Comput. Exp. Sci. Eng.*, vol. 10, no. 4, pp. 1501–1510, 2024. https://doi.org/10.22399/ijcesen.622.
[18] H. F. Carlak and E. Kayar, "Volt/VAr Regulation of the West Mediterranean Regional Electrical Grids Using SVC/STATCOM Devices With Neural Network Algorithms," *Wind Energy*, vol. 28, no. 2, 2025. https://doi.org/10.1002/we.2976.
[19] Y. F. Hassan, M. K. Hadi, H. Daealhaq, A. A. R. Altahir, and M. L. Othman, "Best Positions for UPFC for Power Quality Enhancement under Various Contingencies," *AIP Conference Proceedings*, 2024. https://doi.org/10.1063/5.0205456.
[20] S. Yahia, R. Taha, and E. Ayachi, "Wind conversion systems effects on power grid and ability of thyristor controlled series capacitor and static synchronous series compensator devices for dynamic performance enhancing," *Meas. Control (United Kingdom)*, 2024. https://doi.org/10.1177/00202940241268714.
[21] D. Kalpaktsoglou, A. Tsiakalos, S. Pouros, and Roumeliotis, "Comparison between thyristor switched series capacitors and thyristor switched parallel capacitors for wind power systems-a simulation study," *WSEAS Trans. Power Syst.*, vol. 15, pp. 257–264, 2020. https://doi.org/10.37394/232016.2020.15.30.
[22] A. A. Zakri, T. R. Siregar, M. W. Mustafa, and W. Sunanda, "Modelling and Analysis using The Thyristors Controlled Series Compensators for Electrical Power Systems," *ELKOMIKA J. Tek. Energi Elektr. Tek. Telekomun. Tek. Elektron.*, vol. 11, no. 3, p. 691, 2023. https://doi.org/10.26760/elkomika.v11i3.691.
[23] S. Tiwari, A. Kumar, and S. Sengupta, "Voltage stability analysis with a novel hybrid controller using shunt and series combination of FACTS device," *2018 3rd IEEE International Conference on Recent Trends in Electronics, Information and Communication Technology, RTEICT 2018 - Proceedings*, IEEE, 2018, pp. 885–890. https://doi.org/10.1109/RTEICT42901.2018.9012250.
[24] M. Zadehbagheri, "Optimal Placement of FACTS Devices in Unbalanced Power Networks to Improvement of Voltage Stability and Loss Reduction," *Lecture Notes in Electrical Engineering*, 2025, pp. 461–470. https://doi.org/10.1007/978-981-96-1965-8_43.
[25] M. L. Swarupa, K. Rayudu, C. S. Kumar, S. L. Gundebommu, and P. Kamalakar, "Machine Learning Techniques for Power Quality Enhancement of Power Distribution Systems with FACTS devices," *Eng. Technol. Appl. Sci. Res.*, vol. 14, no. 4, pp. 14939–14944, 2024. https://doi.org/10.48084/etasr.7233.
[26] G. Pandu Ranga Reddy, G. Harshitha, P. Lakshmi Priya, J. V. N. S. Roshini, and M. Harshiya, "Enhancement of Power Quality in Grid-Connected Distribution Systems Employing AI-Based Controllers," *E3S Web of Conferences*, 2024. https://doi.org/10.1051/e3sconf/202454010015.
[27] A. Carbonara, S. Dambone Sessa, A. L'Abbate, F. Sanniti, and R. Chiumeo, "Comparison of Advanced Flexible Alternating Current Transmission System (FACTS) Devices with Conventional Technologies for Power System Stability Enhancement: An Updated Review †," 2024. https://doi.org/10.3390/electronics13214262.
[28] M. D. Yaseen and S. K. Bali, "A Multi Objective Solution to Integrated Power System in the Presence of Thyristor Controlled Series Compensator," *Contemp. Math.*, vol. 5, no. 3, pp. 2619–2631, 2024. https://doi.org/10.37256/cm.5320243978.
[29] D. Kalpaktsoglou, S. Pouros, and K. Kleidis, "Improving the efficiency of a wind turbine using Thyristor Switched Series Capacitors- A simulation study," *WSEAS Trans. Power Syst.*, vol. 14, pp. 33–38, 2019.
[30] A. M. Eltamaly, "Energy management using statcom for enhancing the electric," pp. 423–434.
[31] B. Bahadori, A. Nahavandi, and M. Abasi, "Estimation of Positive-, Negative-, and Zero-Sequence Current and Voltage Phasors of UIPC VSCs for Short-Circuit Faults in Transmission Lines," *Eng. Reports*, vol. 7, no. 2, pp. 1–20, 2025. https://doi.org/10.1002/eng2.70006.
[32] C.- Rapporteur, "Doctorat LMD en Electrotechnique Intitulé de la Thèse : Contribution à l ' optimisation de l ' intégration des énergies Zahia DJEBLAHI Soutenue publiquement le Devant le jury composé de : LMD Doctorate in Electrotechnics Thesis Title : Contribution to the," 2025.
[33] F. Relić, H. Glavaš, I. Petrović, and M. Stojkov, "Advances in FACTS Technology for Transient Stability in Power Systems," vol. 3651, pp. 370–380, 2023. https://doi.org/10.20944/preprints202312.0781.v1
[34] S. Ajib, A. Alahmer, H. Rezk, and M. I. Alamayreh, "Editorial: Advancements and future directions in process design for sustainable energy systems," 2024. https://doi.org/10.3389/fenrg.2024.1456450.
[35] M. Madhusudhan, H. Pradeepa, M. V. L. Kumar, and S. K. Bilgundi, "Multimachine Stability Enhancement Using Fuzzy-Logic Based PSS Tuning With Shunt FACTS Device," *Indones. J. Electr. Eng. Informatics*, vol. 11, no. 1, pp. 133–151, 2023. https://doi.org/10.52549/ijeei.v11i1.3931.
[36] Y. Al Mashhadany, A. K. Abbas, and S. Algburi, "Study and Analysis of Power System Stability Based on FACT Controller System," *Indones. J. Electr. Eng. Informatics*, vol. 10, no. 2, pp. 317–332, 2022. https://doi.org/10.52549/ijeei.v10i2.3630.

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BIOGRAPHIES OF AUTHORS:

Engr. Dr. Sabo Aliyu (Ph.D) MIEEE. PES. (Member, IEEE) completed his Bachelor's degree in Electrical Engineering from the Prestigious Ahmadu Bello University, Zaria, Kaduna State, Nigeria in 2011. Engr. Dr. Sabo Aliyu completed his M.Sc and Ph.D Degrees in Electrical Power Systems Engineering from Universiti Putra Malaysia. His main research areas include the application of Neuro-Fuzzy Controller to power system, Computational Intelligence techniques, Power System Oscillation Damping Controller Designs, Power Systems Optimizations, Power Flow and Optimal Power Flow, Power Quality, and Robust controllers with several online publications. Engr. Dr.Sabo Aliyu is currently a Senior Lecturer at Nigerian Defence Academy, Kaduna State, Nigeria. He is a registered Engineer under the Council for the Regulation of Engineering in Nigeria (COREN).

Engr. Sadiq N. Buba is a Protection Engineer at Kaduna Electricity Distribution Company, (KAEDCO) Nigeria. He received his B.Eng. from Modibbo Adama University of Technology Yola in Electrical and Electronics Engineering department in the year 2020. He is presently an M.Eng student in the department of Electrical and Electronics Engineering (Power and Machine major) from the post graduate school Nigeria defense academy, Nigeria. He is also a member of International Association of Engineers (IAENG). Contact email: sadiqnguraa@gmail.com .