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FACTS: Present and Future

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Abstract:- Flexible AC Transmission Systems (FACTS) are pivotal in modernizing power systems, enhancing their stability, controllability, and efficiency. Currently, FACTS devices such as Static VAR Compensators (SVCs), Static Synchronous Compensators (STATCOMs), and Unified Power Flow Controllers (UPFCs) are employed to manage power flow, mitigate system instabilities, and improve voltage regulation across transmission networks. These technologies address present challenges, including the integration of renewable energy sources, reduction of transmission losses, and enhancement of system reliability in the face of fluctuating power demands. However, the growing complexity of power grids, driven by the increasing penetration of intermittent renewable energy, electric vehicles, and distributed generation, necessitates advanced and scalable solutions. The future of FACTS lies in the development of more sophisticated, adaptive, and intelligent devices that leverage real-time data analytics, artificial intelligence, and machine learning to optimize power flow dynamically. Future advancements are expected to focus on enhancing the interoperability of FACTS with smart grid technologies, improving the resilience of power systems against cyber-physical threats, and facilitating the transition towards more decentralized and sustainable energy systems. Moreover, the integration of energy storage with FACTS devices could revolutionize their functionality, offering not only reactive power compensation but also energy balancing capabilities. This paper explores the current applications of FACTS and envisions their future role in addressing the evolving challenges of global power systems, emphasizing the importance of innovation and strategic investment in the ongoing transformation of electrical networks.

Keywords:- *Power Systems, Power Electronics, Classifications of FACTS Devices.*

I. INTRODUCTION

Power systems are the backbone of modern society, ensuring the reliable generation, transmission, and distribution of electricity to meet the growing demands of industries, businesses, and households[1]. As global energy consumption continues to rise, power systems face increasing challenges related to efficiency, stability, and the integration of renewable energy sources. The importance of maintaining a robust and flexible power grid cannot be overstated, as it directly impacts economic development, technological progress, and quality of life. To address these challenges, the role of power electronics technology in power systems has become more prominent, revolutionizing how electrical power is managed and controlled[2].

Power electronics technologies, such as Flexible AC Transmission Systems (FACTS), have transformed traditional power systems by enhancing their operational capabilities. FACTS devices use advanced semiconductor technology to provide dynamic control over voltage, power flow, and reactive power, significantly improving grid stability and efficiency[3]. These technologies allow for more precise and rapid adjustments to power system parameters, enabling better management of power quality, reduction of transmission losses, and increased capacity utilization of existing infrastructure[4].

The involvement of power electronics in power systems is not limited to addressing present challenges; it also paves the way for future innovations. As power grids evolve towards smarter, more resilient networks, the integration of power electronics technologies like FACTS will play a crucial role in supporting the transition to renewable energy, enhancing grid flexibility, and enabling real-time system control. This paper explores the current state and future prospects of FACTS, highlighting their essential role in the ongoing transformation of global power systems[5].

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II. FACTS: A LEADER IN TRANSMISSION TECHNOLOGY

Flexible AC Transmission Systems (FACTS) represent a leading innovation in the field of transmission technology, revolutionizing how electrical power is managed and distributed across the grid. FACTS devices improve the efficiency, stability, and reliability of power transmission, addressing traditional limitations of electrical networks. By allowing for real-time control of power flow and reactive power compensation, FACTS enhance the ability of transmission systems to handle variable loads and integrate renewable energy sources effectively[6].

As a leader in transmission technology, FACTS offer several key advantages.

- *Enhanced Grid Stability and Control:*

FACTS devices, such as Static Synchronous Compensators (STATCOM) and Unified Power Flow Controllers (UPFC), provide rapid response to voltage fluctuations and transient disturbances. This capability enhances system stability, reduces the risk of blackouts, and supports continuous operation even under adverse conditions.

- *Increased Power Transfer Capability:*

FACTS enable existing transmission lines to carry more power without the need for extensive infrastructure upgrades. By dynamically managing the power flow, FACTS devices can maximize the capacity of the grid, reduce congestion, and optimize the overall utilization of transmission assets.

- *Improved Power Quality and Reduced Losses:*

FACTS mitigate issues such as voltage sags, flickers, and harmonics, significantly improving power quality. They also minimize transmission losses by adjusting the reactive power in the system, contributing to more efficient energy distribution.

- *Facilitation of Renewable Integration:*

The growing integration of renewable energy sources like wind and solar poses challenges to grid stability due to their intermittent nature. FACTS devices support this integration by providing fast reactive power support, stabilizing voltage levels, and ensuring smooth power transfer.

- *Scalable and Flexible Solutions:*

FACTS technologies are modular and can be customized to address specific transmission challenges, making them versatile tools for both new and existing grid systems.

As transmission technology continues to evolve, FACTS will play a crucial role in the development of smart grids and the transition towards more sustainable, reliable, and efficient power networks worldwide[7].

III. CHANGING SCENARIO IN POWER SYSTEMS PARAMETERS: ROLE OF FACTS

Flexible AC Transmission Systems (FACTS) are at the forefront of the evolving power system landscape, driven by the need for enhanced flexibility, stability, and efficiency in modern grids. The integration of FACTS has fundamentally changed how power system parameters such as voltage stability, power flow, and reactive power management are controlled. Below are the key ways in which FACTS are altering power system parameters[8]:

- *Voltage Stability and Control:*

FACTS devices like Static Synchronous Compensators (STATCOM) and Static VAR Compensators (SVC) have significantly improved voltage stability across power networks. These devices provide rapid voltage support, especially during disturbances, by dynamically adjusting reactive power. This capability is crucial for maintaining voltage levels within desired limits, thus preventing voltage collapse, especially in grids with high levels of intermittent renewable energy.

- *Enhanced Power Flow Management:*

Traditional power systems face challenges with optimal power flow due to the physical constraints of transmission lines and varying load conditions. FACTS devices, such as the Unified Power Flow Controller (UPFC) and Thyristor-Controlled Series Capacitors (TCSC), enable real-time control of power flow along transmission lines. These technologies allow operators to redirect power away from congested paths, maximize line utilization, and improve overall system efficiency without the need for costly infrastructure upgrades.

- *Improved Reactive Power Compensation:*

Managing reactive power is critical for maintaining the voltage levels necessary for the efficient operation of power systems. FACTS technologies provide superior reactive power compensation compared to traditional methods. This enhancement reduces transmission losses, minimizes the need for additional generation resources, and ensures that the grid operates closer to its optimal state, especially under variable load conditions.

- *Dynamic Stability and Damping of Oscillations:*

Power systems are prone to oscillations due to changes in load, faults, or integration of renewable energy sources. FACTS devices like the Static Synchronous Series Compensator (SSSC) and TCSC help dampen these oscillations, enhancing the dynamic stability of the system. By providing rapid adjustments to system impedance and power flow, these devices mitigate oscillatory behavior, thus improving the reliability and robustness of the grid.

- *Supporting Renewable Energy Integration:*

The shift towards renewable energy sources such as wind and solar has introduced variability and unpredictability in power generation. FACTS devices are pivotal in smoothing out these fluctuations, providing voltage and reactive power support to accommodate renewable energy's intermittent

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nature. This ensures that renewable sources can be integrated into the grid without compromising system stability or performance.

- *Increased Transmission Capacity and Efficiency:*

FACTS technologies enhance the operational capacity of existing transmission lines by managing line impedance and optimizing the power transfer. This reduces the need for building new transmission infrastructure, which is costly and time-consuming. FACTS can therefore increase the power handling capability of existing lines, making the grid more efficient and capable of meeting growing demand.

- *Flexible and Modular Solutions:*

FACTS devices offer modular and scalable solutions that can be tailored to specific system needs. This flexibility allows power operators to address localized problems within the grid without extensive overhauls, adapting to changes in demand patterns, generation mix, and grid configuration as required.

These changes highlight the transformative impact of FACTS on power system parameters, making them indispensable tools in managing modern electrical grids. By offering enhanced control, stability, and efficiency, FACTS are critical in addressing the evolving challenges of today's power systems, paving the way for a more resilient and adaptive energy future[9].

IV. FUTURE TRENDS IN FACTS (FLEXIBLE AC TRANSMISSION SYSTEMS)

The future of Flexible AC Transmission Systems (FACTS) is closely linked to the evolving needs of modern power grids, which are becoming more complex, dynamic, and increasingly reliant on renewable energy sources[10]. As transmission technology advances, several key trends are expected to shape the development and deployment of FACTS:

- *Integration with Smart Grids and Digital Technologies:*

The future of FACTS will be deeply intertwined with the evolution of smart grids. Advanced FACTS devices will increasingly integrate with digital technologies such as Internet of Things (IoT), artificial intelligence (AI), and machine learning (ML). These technologies will enable real-time monitoring, predictive analytics, and autonomous control of power flow, enhancing the responsiveness and adaptability of FACTS devices to changing grid conditions.

- *Advanced Energy Storage Integration:*

The coupling of FACTS with energy storage systems is a significant trend that will redefine their capabilities. Integrating battery storage with FACTS can provide not only reactive power compensation but also active power support, enhancing grid stability and allowing for energy balancing. This synergy will be crucial in managing the variability of renewable energy sources, providing both immediate and sustained responses to grid fluctuations.

- *Cyber-Physical Security Enhancements:*

As FACTS become more interconnected within the digital landscape of smart grids, the importance of cybersecurity grows. Future developments will focus on enhancing the cyber-physical security of FACTS devices to protect against potential cyber threats, ensuring the safe and reliable operation of power transmission networks.

- *High-Power Semiconductor Technologies:*

Advances in power electronics, particularly in high-power semiconductor materials like silicon carbide (SiC) and gallium nitride (GaN), will significantly enhance the performance, efficiency, and compactness of FACTS devices. These materials allow for higher switching frequencies, reduced losses, and greater thermal stability, which will lead to more efficient and robust FACTS solutions.

- *Decentralization and Distributed FACTS:*

With the increasing decentralization of energy generation, the future will see more deployment of distributed FACTS (D-FACTS) devices. These smaller, modular devices can be deployed closer to distributed energy resources (DERs) and along various points of the transmission network, providing localized support and improving overall grid flexibility.

- *Enhanced Voltage and Power Flow Management:*

Future FACTS devices will offer improved capabilities for dynamic voltage control and power flow management, addressing more complex power scenarios, including the integration of offshore wind farms, large-scale solar plants, and multi-terminal HVDC systems. Advanced control algorithms will further optimize these devices for better performance under fluctuating conditions.

- *Cost Reduction and Increased Accessibility:*

Ongoing technological advancements and economies of scale are expected to reduce the cost of FACTS devices, making them more accessible for wider deployment. As these technologies become more cost-effective, their adoption will accelerate, particularly in emerging markets where grid infrastructure upgrades are urgently needed.

These future trends position FACTS as a cornerstone technology in the next-generation power grids, offering enhanced capabilities to meet the demands of a rapidly evolving energy landscape characterized by higher efficiency, greater resilience, and increased integration of renewable energy[11].

V. PROSPECTS FOR FACTS DEVICES IN INDIA

The generating stations in India are within the coal belts in the east and south-east. The load centres are in the north-west, west and south. This has favoured long distance HVDCs, which are coming up rapidly. India's power sector is undergoing significant transformation, driven by rapid economic growth, increasing energy demand, and a strong push towards renewable energy integration. The prospects for Flexible AC Transmission Systems (FACTS) devices in India are highly promising, given their potential to address critical

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challenges in the country's power grid. Below are the key factors that highlight the potential and future role of FACTS devices in India[12]:

- *Enhanced Grid Stability and Reliability:*

India's power grid faces frequent stability issues due to high load variability, fluctuating renewable energy generation, and aging infrastructure. FACTS devices such as Static VAR Compensators (SVC) and STATCOMs can significantly improve voltage stability, enhance reactive power compensation, and provide dynamic support to maintain grid reliability. These technologies are crucial in regions with high demand volatility, such as industrial hubs and urban centers.

- *Facilitating Renewable Energy Integration:*

India has set ambitious targets for renewable energy, aiming to achieve 500 GW of non-fossil fuel capacity by 2030. However, integrating large-scale wind and solar power into the grid poses challenges related to variability and intermittency. FACTS devices can help manage these issues by providing fast-acting reactive power support, stabilizing voltage levels, and facilitating smooth power flow, thereby enhancing the integration of renewables into the national grid.

- *Mitigating Transmission Congestion:*

India's power grid often suffers from transmission bottlenecks, especially in regions with high generation capacity but limited transmission infrastructure. FACTS technologies like Unified Power Flow Controllers (UPFC) and Thyristor-Controlled Series Capacitors (TCSC) can optimize power flow, reduce line congestion, and improve the overall transfer capacity of existing transmission corridors. This is crucial for efficiently delivering power from renewable-rich states to demand centers.

- *Improving Power Quality and Reducing Losses:*

Power quality issues such as voltage sags, flickers, and harmonics are prevalent in India, affecting industrial productivity and overall system efficiency. FACTS devices can address these problems by providing precise control over voltage and power flow, enhancing power quality, and minimizing transmission losses. This improvement is vital for industries that rely on high-quality, stable power supply for their operations.

- *Supporting Smart Grid Development:*

India is actively working towards modernizing its power grid with smart technologies to enhance its operational efficiency and reliability. FACTS devices are integral to this development, offering advanced control and automation capabilities that align with smart grid objectives. Their ability to interact with real-time data and intelligent control systems makes them essential components of India's future smart grid infrastructure.

- *Economic Benefits and Cost Efficiency:*

The implementation of FACTS devices can lead to significant economic benefits by postponing or eliminating the need for expensive grid expansion projects. By optimizing the performance of existing transmission infrastructure, FACTS reduce the capital expenditure required for new lines and substations, offering a cost-effective solution for meeting India's growing power demands.

- *Regulatory and Policy Support:*

The Indian government's focus on grid modernization, renewable integration, and energy efficiency provides strong regulatory support for the deployment of FACTS technologies. Initiatives such as the Green Energy Corridor and the National Smart Grid Mission highlight the importance of advanced transmission solutions, creating a favorable policy environment for FACTS investments.

- *Opportunities for Technological Innovation and Local Manufacturing:*

India's emphasis on self-reliance and technological innovation presents opportunities for local manufacturing of FACTS devices. Developing domestic capabilities in designing and producing these advanced technologies can reduce costs, create jobs, and support the country's broader industrial growth agenda.

VI. CLASSIFICATIONS OF FACTS

FACTS devices are categorized based on their functionality, connection to the power system, and the type of power electronic controllers they use. The classification helps in understanding their role in improving grid stability, power flow control, and reactive power management. The classification of FACTS devices provides a clear understanding of their roles in modern power systems. Shunt devices manage reactive power and voltage stability, series devices optimize power flow and control line impedance, and combined devices offer comprehensive management of multiple power system parameters[13]. The choice of FACTS device depends on the specific needs of the grid, such as enhancing stability, managing power flow, or integrating renewable energy sources Here are the main classifications of FACTS:

A. Classification by Connection Type

- *Shunt Devices:*

These devices are connected in parallel with the power system. They primarily provide reactive power compensation to support voltage control and stabilize the grid[14].

- *Examples:*

- *Static VAR Compensator (SVC):*

Uses thyristor-controlled reactors and capacitors to manage reactive power dynamically.

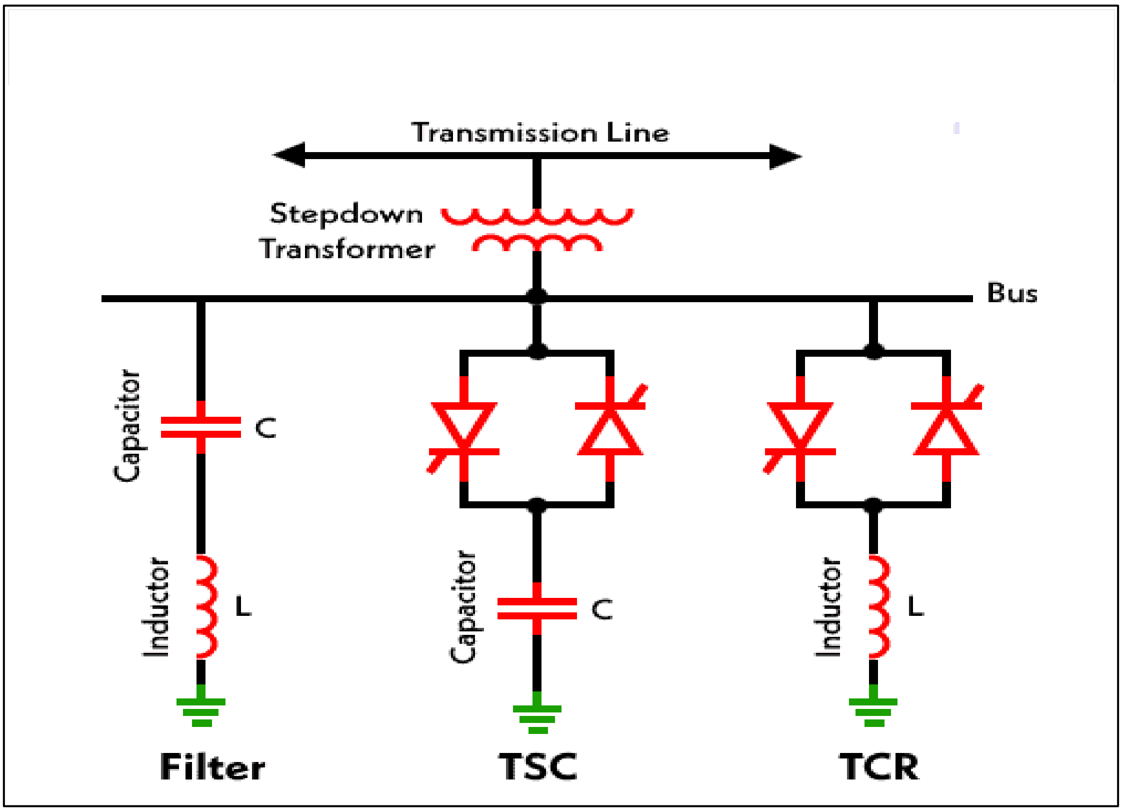

Fig 1 Schematic Diagram of SVC

- *Static Synchronous Compensator (STATCOM):*
  A voltage source converter that offers faster and more flexible reactive power support compared to SVC.

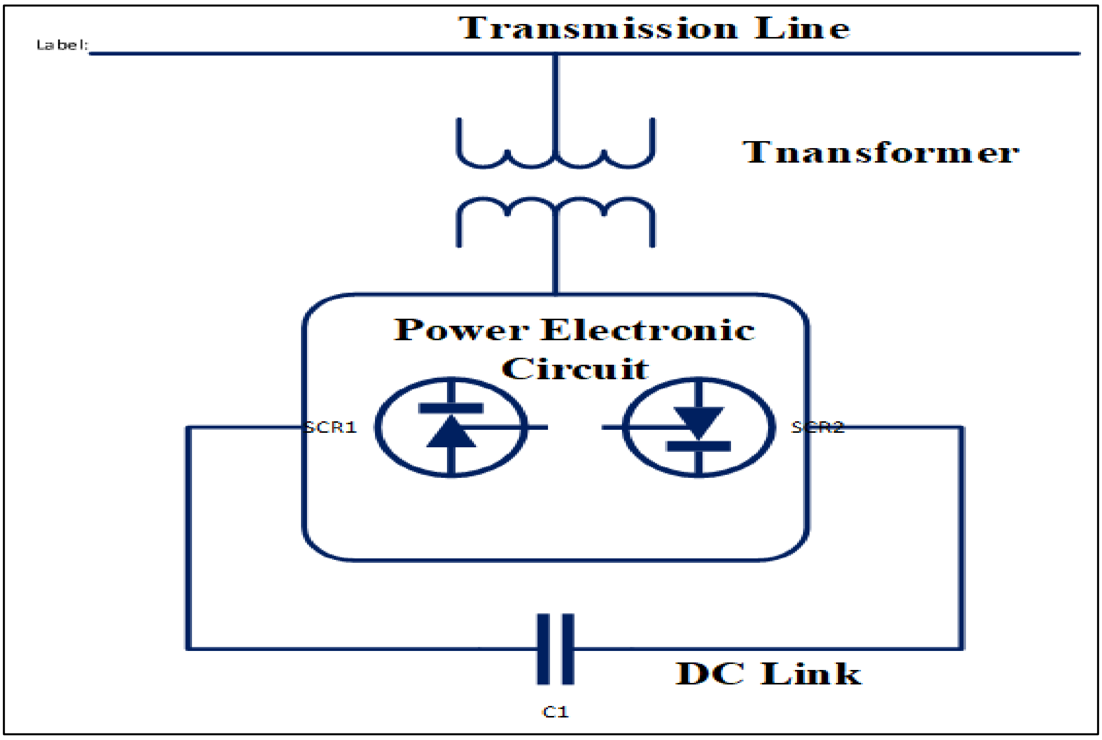

Fig 2 Schematic Diagram of STATCOM

➢ *Series Devices:*

These are connected in series with the transmission line. They control the line impedance and manage power flow along the transmission path, enhancing the line's power transfer capability.

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➢ *Examples:*

- *Thyristor-Controlled Series Capacitor (TCSC):*
  Adjusts line impedance by controlling the insertion of capacitors and reactors.

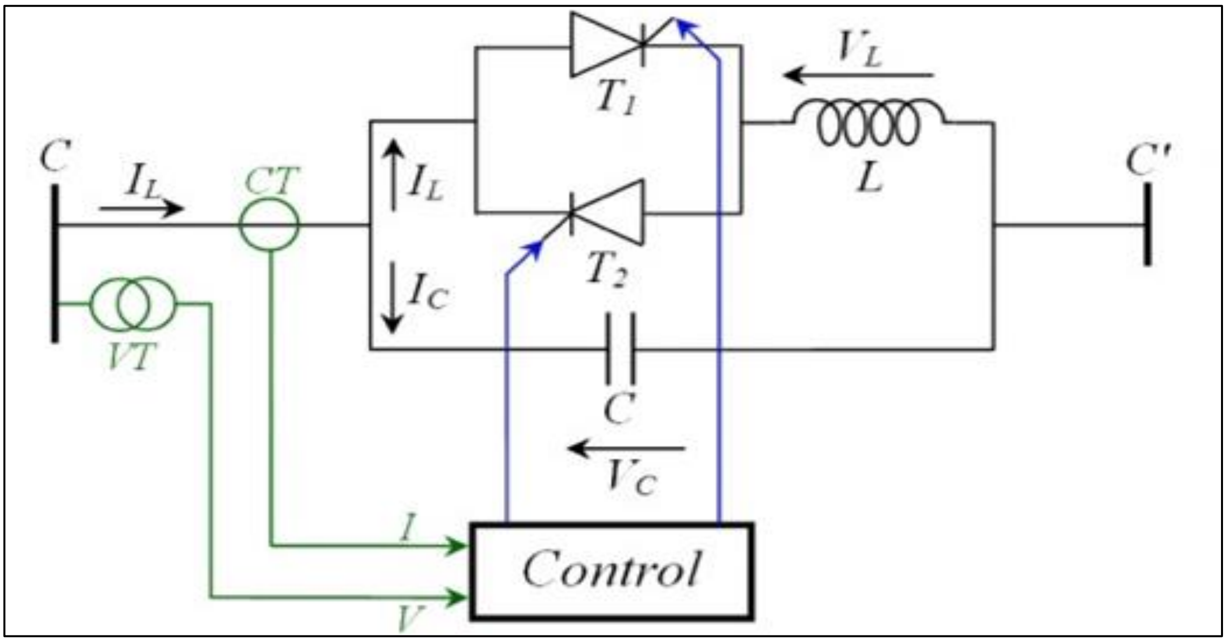

Fig 3 Schematic Diagram of TCSC

- *Static Synchronous Series Compensator (SSSC):*
  A converter-based device that provides controlled series compensation for dynamic power flow management.

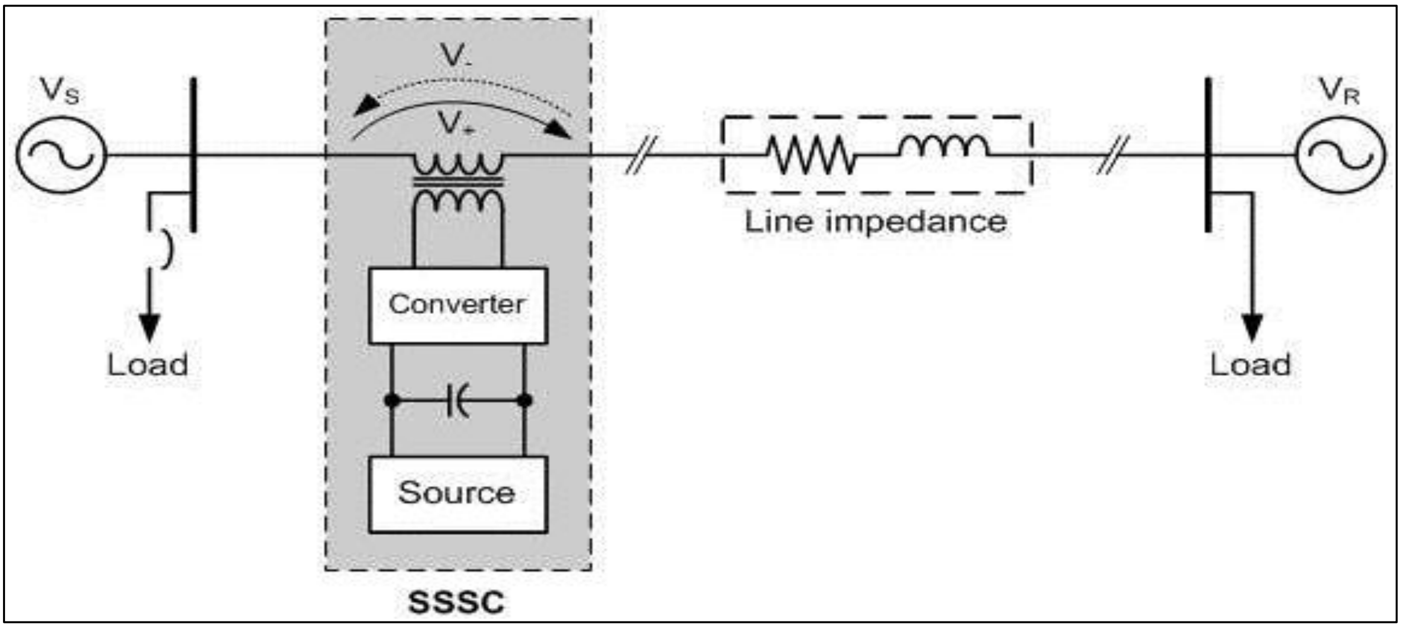

Fig 4 Schematic Diagram of SSSC

➢ *Combined Series-Shunt Devices:*

These devices combine both series and shunt functionalities to offer comprehensive control over voltage, power flow, and reactive power simultaneously[15].

➢ *Examples:*

- *Unified Power Flow Controller (UPFC):*
  The most versatile FACTS device, capable of controlling voltage, impedance, and phase angle, allowing for full power flow management.

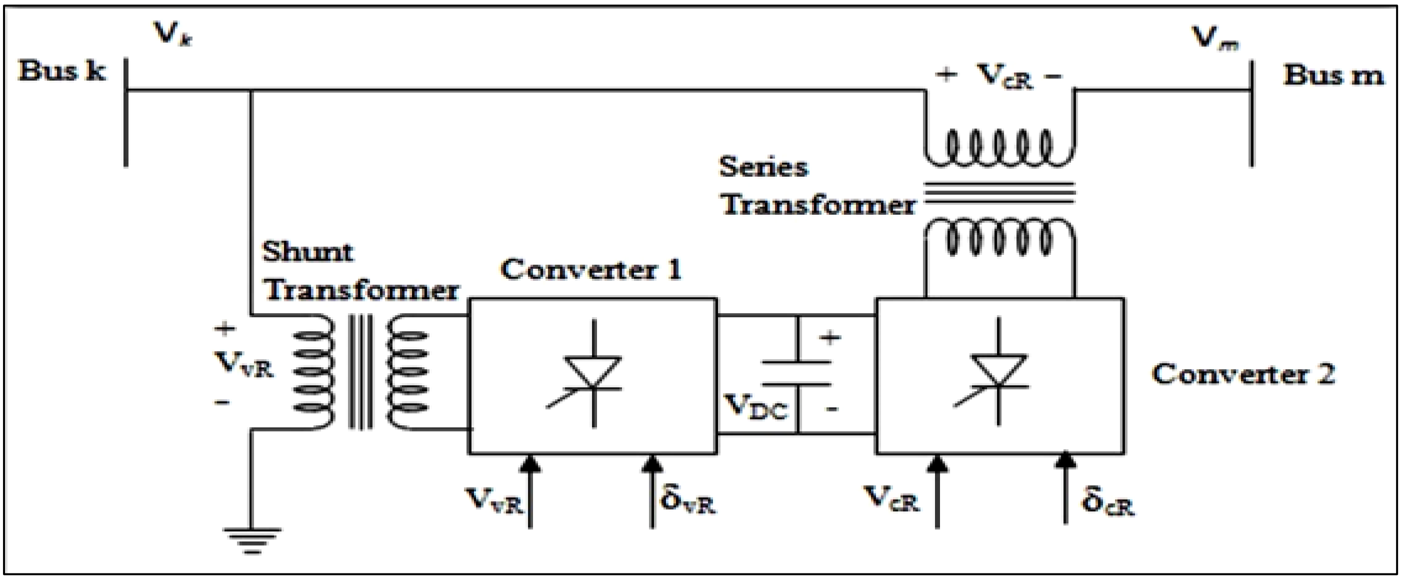

Fig 5 Schematic Diagram of UPFC

- *Interline Power Flow Controller (IPFC):*

Manages power flow across multiple transmission lines by using multiple series converters.

B. Classification by Type of Controller

➢ *Variable Impedance Devices:*

These devices use passive elements like capacitors and reactors controlled by thyristors. They adjust the system parameters indirectly by altering impedance.

- **Examples**: SVC, TCSC

➢ *Voltage Source Converter (VSC)-Based Devices:*

These devices use high-speed switching converters (like IGBTs) to provide more precise and faster control over power system parameters. They can generate or absorb reactive power without needing external passive elements.

- **Examples**: STATCOM, SSSC, UPFC

C. Classification by Functionality

➢ *Reactive Power Compensation:*

Devices that primarily provide reactive power support to maintain voltage levels and improve power quality.

- **Examples**: SVC, STATCOM

➢ *Power Flow Control:*

Devices focused on managing and optimizing the flow of power through transmission lines to reduce congestion and increase transfer capacity.

- **Examples**: TCSC, SSSC, UPFC

➢ *Stability Enhancement:*

Devices that help stabilize the grid by damping power oscillations and enhancing dynamic stability during disturbances.

- **Examples**: TCSC, SSSC, UPFC

VII. CONCLUSION

Flexible AC Transmission Systems (FACTS) represent a critical advancement in modern power systems, offering significant improvements in the stability, control, and efficiency of electrical grids. In the present context, FACTS devices such as Static VAR Compensators (SVC), Static Synchronous Compensators (STATCOM), and Unified Power Flow Controllers (UPFC) play an essential role in addressing the complex challenges faced by power systems worldwide. These devices provide dynamic reactive power compensation, enhance voltage stability, and optimize power flow, allowing existing transmission lines to operate closer to their thermal limits while maintaining system reliability. FACTS have become indispensable in managing the variability of renewable energy sources, such as wind and solar, thereby supporting the global shift towards cleaner energy.

FUTURE SCOPE

Looking to the future, the role of FACTS in power systems is set to expand even further. The increasing complexity of modern grids, driven by the integration of distributed generation, electric vehicles, and microgrids, will demand more advanced and adaptive solutions. Future developments in FACTS technology will likely focus on incorporating artificial intelligence, machine learning, and advanced control algorithms, allowing these devices to respond more quickly and accurately to grid disturbances. Moreover, integrating FACTS with energy storage systems could revolutionize their functionality, providing both reactive power support and active power management capabilities**.**

The continued evolution of FACTS will be vital in the transition towards smart grids, enhancing the resilience, efficiency, and flexibility of power networks. As the demand

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for reliable and sustainable electricity grows, FACTS will play a pivotal role in enabling power systems to meet these challenges. By providing the tools needed to control and optimize the flow of electricity in real time, FACTS will support the development of more robust and adaptable grids that can withstand the pressures of an increasingly dynamic energy landscape. In this way, FACTS technologies will remain at the forefront of power system innovation, driving the future of electrical transmission and distribution.

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