

A Peer Review on FACTS Controllers in Electrical Power Systems

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Abstract: Flexible AC Transmission System (FACTS) controllers are advanced power electronic devices employed in electrical power systems to enhance system stability, reliability, and power transfer capabilities. These controllers enable dynamic and flexible control of various transmission parameters such as voltage, current, impedance, and phase angle, thereby improving the overall power system performance. FACTS devices are broadly classified into series, shunt, series-series, and series-shunt configurations, each designed to manage reactive power and regulate voltage either by injecting voltage in series or current in shunt with the transmission line. Well-known FACTS devices include Static Var Compensators (SVC), Static Synchronous Compensators (STATCOM), Thyristor Controlled Series Capacitors (TCSC), Static Synchronous Series Compensators (SSSC), and Unified Power Flow Controllers (UPFC), each serving specific roles in power flow control, voltage regulation, and transient stability enhancement. The integration of these controllers provides significant benefits such as increased transmission line capacity, improved voltage stability, minimized transmission losses, and damping of power system oscillations. They are capable of rapid response during transient disturbances, effectively mitigating voltage collapses and enhancing system resilience against faults and contingencies. FACTS controllers not only improve steady-state operational parameters but also address dynamic stability and transient conditions, enabling power systems to operate closer to their stability limits while maintaining security. Their deployment helps avoid costly infrastructural expansions by optimizing existing transmission assets, which is critical given environmental and economic constraints. Recent advances in semiconductor technologies and control algorithms have made FACTS devices more reliable, efficient, and adaptable to modern grids, including renewable integration and deregulated power markets. In summary, FACTS controllers play a vital role in modern power systems by providing flexible, efficient, and reliable solutions for power flow management, voltage control, and system stability enhancement, thereby supporting the evolving demands of today's complex electrical networks.

Keywords: Power Systems, FACTS, Voltage Sources Converters, Shunt Controllers, Series Controllers.

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I. INTRODUCTION

The global energy landscape is undergoing an unprecedented transformation, influenced by environmental awareness, technological innovation, and policy-driven transitions. Power systems—once centralized, fossil-fuel-based, and rigid—are now evolving into decentralized, flexible, and intelligent networks. This evolution stems from the urgent need to reduce carbon emissions, optimize energy efficiency, and enhance system reliability. As emerging economies continue to industrialize and urbanize, energy demand is expected to rise significantly, necessitating cleaner and smarter solutions for generation, transmission, and distribution[1]-[2].

Traditionally, power systems operated under centralized control, with generation plants delivering electricity through long transmission lines to end-users.

However, this model is becoming obsolete in the context of modern requirements. The advent of renewable energy resources, distributed energy systems, and advanced automation has introduced new complexities and opportunities. Smart grids enhanced with sensors, control systems, and communication network enable dynamic management of generation and consumption patterns, improving both efficiency and sustainability[3]-[4].

The shift toward renewables presents both opportunities and challenges. Solar and wind power, while clean and abundant, introduce intermittency issues that can destabilize conventional grids. To address this, energy storage systems and advanced forecasting algorithms are increasingly employed. Simultaneously, digitalization plays a central role by allowing operators to leverage big data analytics, machine learning, and IoT technologies for real-

time decision-making. These tools enable the grid to respond adaptively to fluctuations in supply and demand[5]-[6].

Ultimately, the modernization of power systems reflects a global pursuit of sustainable development. It aims to provide affordable, reliable, and clean electricity for all while mitigating environmental impacts. This paper delves into emerging technologies and trends shaping the future of power systems and examines the challenges and opportunities they bring to engineers, policymakers, and stakeholders worldwide[7]-[8].

The global electrical power system is undergoing a revolutionary transformation driven by the twin imperatives of sustainability and technological innovation. Traditional centralized grids, once dominated by large fossil-fuel-based generation units, are evolving into complex, intelligent, and decentralized networks integrating renewable energy sources, digital controls, and advanced communication systems. This evolution is not merely a technical shift but a paradigm change that encompasses economic, environmental, and social dimensions. The growing energy demand due to industrialization, urbanization, and digital connectivity has placed enormous pressure on conventional energy infrastructure. At the same time, the urgent need to mitigate climate change has accelerated the global transition toward low-carbon energy systems. Consequently, modern electrical power systems are being redesigned to incorporate renewable generation, electric mobility, smart grids, and energy storage technologies. These advancements are reshaping how electricity is generated, transmitted, distributed, and utilized. As a result, the power sector is becoming more flexible, efficient, and resilient, setting the foundation for sustainable development in the coming decades. The convergence of power electronics, artificial intelligence, and communication technologies is further enabling a dynamic and intelligent electricity ecosystem, capable of responding in real time to variations in generation and demand[9]-[10].

Flexible Alternating Current Transmission System (FACTS) controllers are an innovative family of power-electronic-based devices designed to enhance the controllability, stability, and efficiency of AC power transmission systems. Originating from advancements in high-voltage direct current (HVDC) technologies, FACTS controllers leverage the capabilities of modern semiconductor devices to regulate power flow, voltage, and reactive power dynamically within electrical networks. Unlike traditional mechanical or passive devices such as capacitors, reactors, and phase-shifting transformers, FACTS

devices utilize swift and precise switching mechanisms that operate within a fraction of an AC cycle, thereby providing real-time control and flexibility. This allows power systems to operate closer to their theoretical limits without compromising stability or reliability, optimizing existing infrastructure and deferring the costs and complexities associated with constructing new transmission lines or substations[11]-[12].

FACTS controllers are broadly categorized into shunt, series, and combined series-shunt types, each designed to target specific parameters within the power system. Shunt controllers like Static VAR Compensators (SVC) and Static Synchronous Compensators (STATCOM) primarily provide reactive power compensation and voltage support by injecting current in parallel with the transmission line. Series controllers such as the Thyristor Controlled Series Capacitor (TCSC) and Static Synchronous Series Compensator (SSSC) modify the line impedance by injecting voltage in series, thus controlling power flow and mitigating stability problems caused by line congestion. The combination of shunt and series functionalities in devices like the Unified Power Flow Controller (UPFC) provides unparalleled control over voltage magnitude, phase angle, and impedance simultaneously, enabling comprehensive management of active and reactive power flows. These controllers work synergistically to reduce power losses, enhance voltage stability, and damp power oscillations, facilitating more reliable grid operation under highly variable and stressed conditions.[13]-[14].

A critical advantage of FACTS controllers is their ability to improve both steady-state and dynamic performance of power systems. In steady-state operations, they allow secure loading of transmission lines nearer to their thermal limits by regulating power flows and mitigating undesirable reactive power circulation. This leads to more efficient utilization of existing lines and delays expensive infrastructure upgrades. During transient events such as faults, sudden load changes, or generator outages, FACTS devices react instantaneously to stabilize voltage and power flows, reducing the risk of cascading outages and blackouts. Their fast response and high controllability address challenges like voltage collapse, sub-synchronous oscillations, and transient instability, which are common in complex and heavily loaded transmission networks. Consequently, FACTS controllers have become vital tools for maintaining grid resilience and ensuring continuous power supply in modern electric power systems[15]-[16].

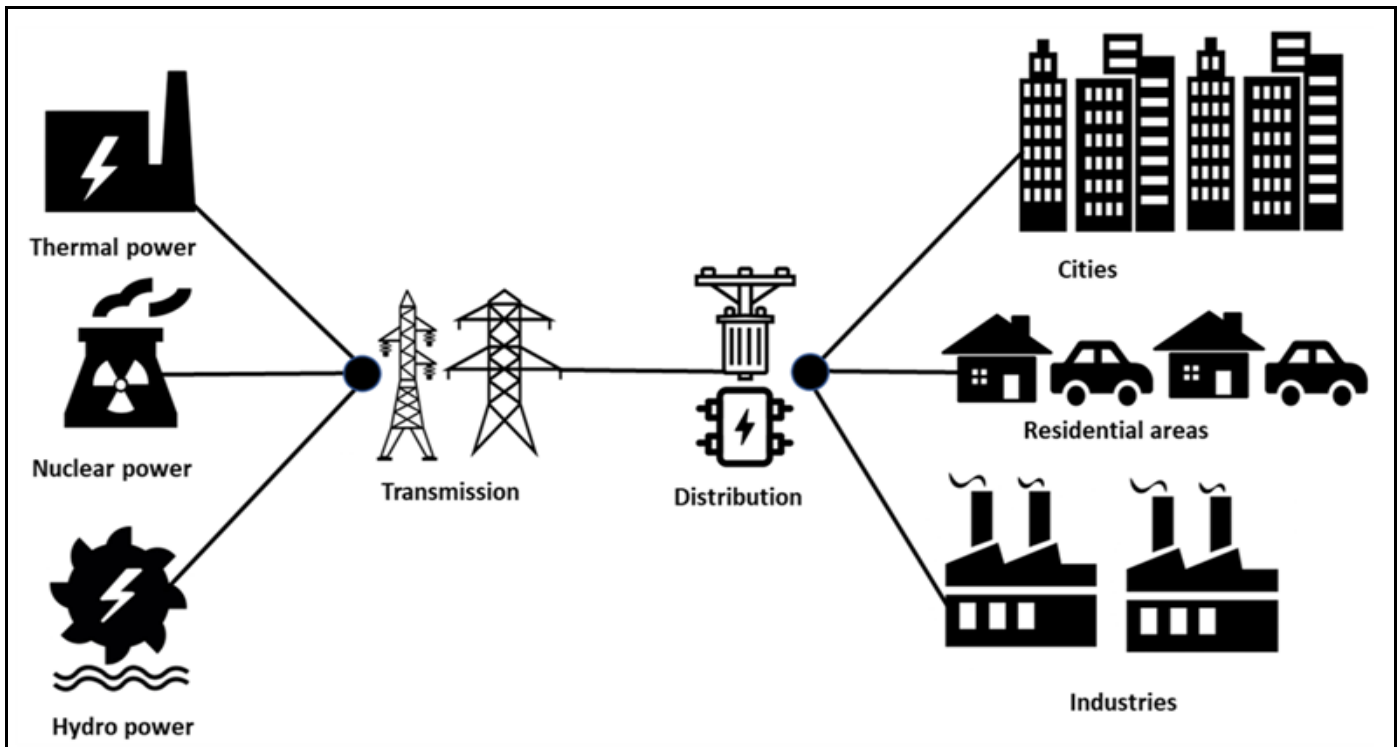


Fig 1 Traditional Thread of Power Systems

The emerging trends in electrical power systems present unprecedented opportunities for innovation, investment, and research. The global energy transition is fostering new business models, such as prosumer-based markets, virtual power plants, and energy-as-a-service (EaaS) frameworks. Moreover, the growing emphasis on energy sustainability and decarbonization is driving government policies, regulatory reforms, and international collaborations aimed at achieving net-zero emissions. Developing nations are particularly poised to benefit from these trends by leapfrogging to modern, decentralized, and renewable-based infrastructures without the constraints of legacy systems. Nevertheless, several challenges remain, including the need for massive infrastructure investments, standardization, and skilled workforce development. Ensuring system reliability, cybersecurity, and affordability in the face of rapid technological change is equally critical. Research in advanced power electronics, grid automation, and hybrid energy systems continues to open new frontiers for innovation. The future of electrical power systems will likely be characterized by high levels of automation, renewable dominance, and consumer participation. As the global community moves toward a more sustainable and digitally connected energy ecosystem, the integration of intelligent control, resilient infrastructure, and environmentally conscious technologies will define the next era of power system development. These transformations not only promise to deliver clean, reliable, and efficient energy but also to catalyze economic growth and environmental stewardship worldwide[17]-[18].

The proliferation of renewable energy sources, distributed generation, and deregulated electricity markets has further underscored the importance of FACTS technologies. The intermittent and variable nature of

renewable generation such as wind and solar introduces fluctuations and uncertainties in power flows, which can threaten grid stability. FACTS controllers mitigate these issues by providing rapid voltage support and adaptive power flow control, facilitating better integration of renewables and enabling the transition to more sustainable energy systems. Moreover, deregulated markets often operate transmission networks nearer to their operational limits for economic reasons, where FACTS devices offer critical support in optimizing power flows and preventing reliability violations. The continual evolution of semiconductor devices and control algorithms has expanded the versatility, efficiency, and cost-effectiveness of FACTS technologies, making them indispensable components in the smart grids of the future.

FACTS controllers represent a transformative evolution in electrical power system engineering, offering flexible, dynamic, and efficient control over power flow, voltage, and system stability. Their deployment enhances transmission capacity, increases operational reliability, and supports the integration of renewable resources, all while minimizing environmental and economic costs associated with network expansion. The rapid advancements in power electronics and control strategies continue to extend the capabilities of FACTS devices, positioning them as essential enablers for the evolving challenges and complexities of modern and future power systems. As grids become more interconnected and complex, the strategic implementation of FACTS technology will be pivotal to achieving resilient, sustainable, and economically optimized electrical energy delivery.

II. FACTS CLASSIFICATIONS

Flexible AC Transmission System (FACTS) controllers are categorized primarily into four types based

on their connection and operation within the power system: series controllers, shunt controllers, combined series-series controllers, and combined series-shunt controllers. Each type has a distinctive role in controlling power flow, voltage, and reactive power to enhance system stability and performance. Series controllers are connected in series with

the transmission line and inject a voltage in series to regulate power flow, control line impedance, and support voltage stability. They typically consist of variable impedance devices such as capacitors or reactors controlled by thyristors.[19].

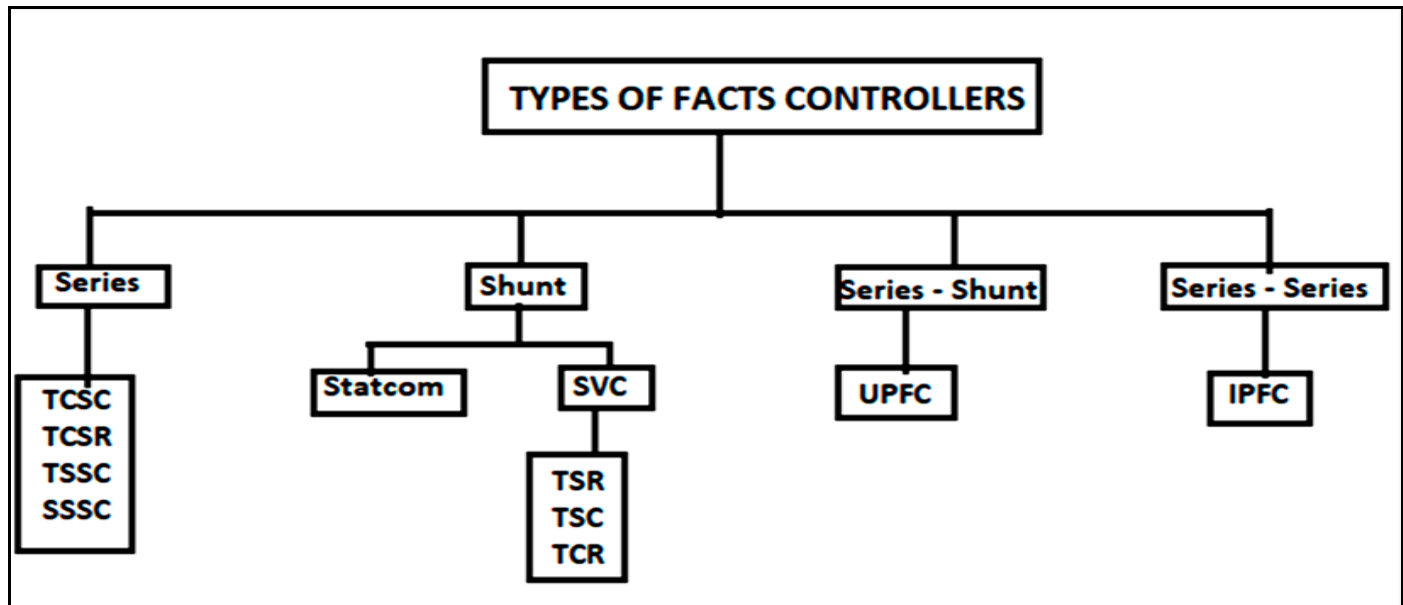


Fig 2 FACTS Types

Flexible AC Transmission Systems (FACTS) controllers are advanced power electronic devices used to improve the controllability, stability, and power transfer capability of modern electrical networks. These controllers are broadly classified into four main categories based on their connection and functionality: shunt controllers, series controllers, combined series-shunt controllers, and combined series-series controllers. Each type plays a unique role in maintaining system performance under varying load and generation conditions[20], [21].

Shunt controllers are connected in parallel with the transmission line and are primarily used for voltage

regulation, reactive power compensation, and power factor correction. They inject or absorb reactive power to maintain the voltage profile within desired limits. Typical examples include the Static Var Compensator (SVC) and the Static Synchronous Compensator (STATCOM). The SVC utilizes thyristor-controlled reactors and capacitors to provide variable reactive support, while the STATCOM, based on voltage source converter (VSC) technology, offers faster and more precise reactive power control. Both devices enhance voltage stability and mitigate voltage fluctuations caused by load variations or system disturbances[22].

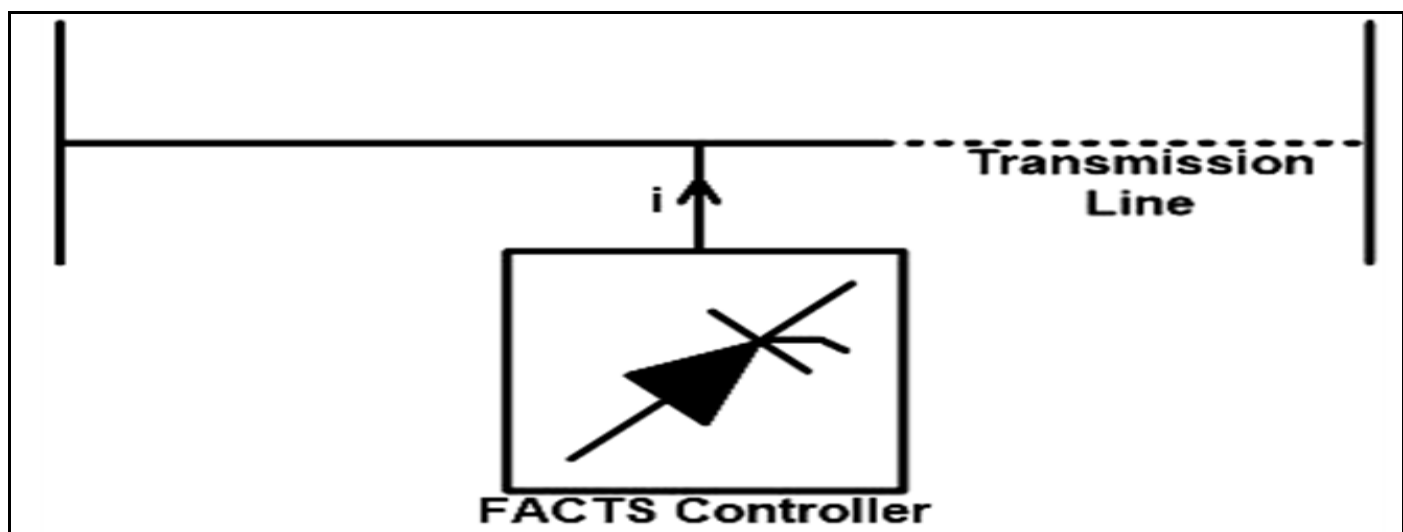


Fig 3 Shunt Type FACTS Controller

➤ **Static Var Compensator (SVC):**

A combination of thyristor-controlled reactor (TCR) and thyristor-switched capacitor (TSC) used to maintain

constant voltage by providing variable reactive power compensation.

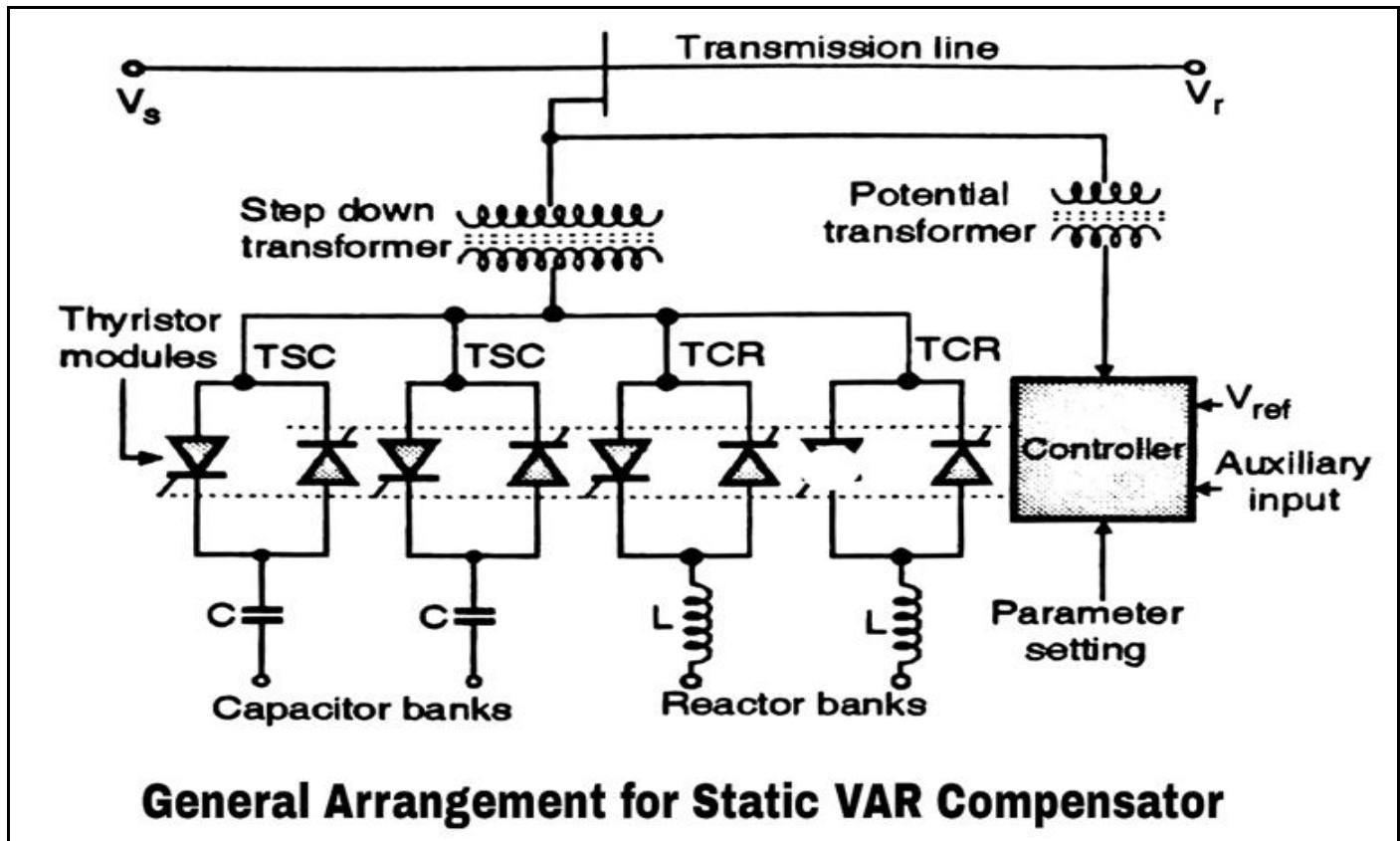


Fig 4 Configuration of SVC

The Static Var Compensator (SVC) is a shunt-connected FACTS controller designed to regulate voltage and improve power-factor by providing variable reactive power compensation. It is made up of Thyristor-Controlled Reactors (TCRs) and Thyristor-Switched Capacitors (TSCs) connected in parallel. The TCR consists of reactors whose current can be continuously controlled by varying the firing angle of thyristors, while the TSC consists of capacitor banks switched in and out in steps through thyristors.

When the system voltage drops, the SVC injects reactive power (capacitive mode) by switching in capacitors. Conversely, when the system voltage rises, it absorbs reactive power (inductive mode) through the reactor branch. The net reactive power output is therefore continuously adjustable within its control range, keeping the bus voltage nearly constant[23].

SVCs are generally installed at substations or load centers to improve voltage regulation, transient stability, and damping of power oscillations. They also reduce flicker in industrial loads such as arc furnaces.

- Advantages: Simple, reliable, and cost-effective for medium-speed voltage regulation.

- Limitation: Performance degrades at very low system voltages, and its response speed is limited by thyristor switching and mechanical tuning of filters.

➤ **Static Synchronous Compensator (STATCOM):**

A voltage-source converter (VSC) based shunt device that provides fast and precise reactive power support independent of system voltage magnitude.

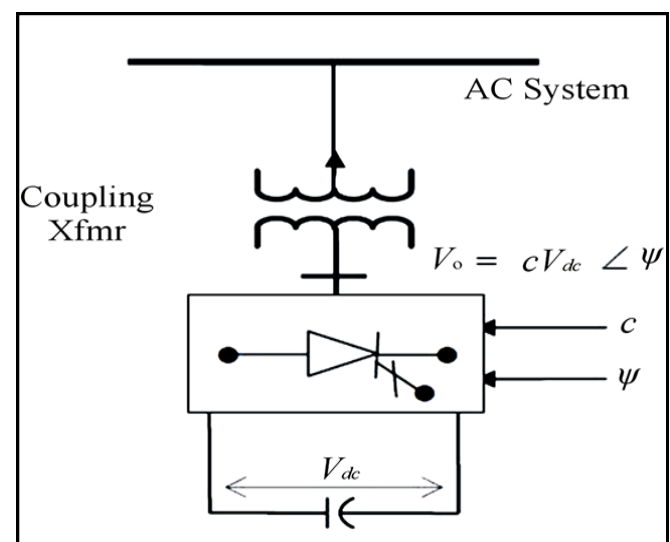


Fig 5 STATCOM

The Static Synchronous Compensator (STATCOM) is a voltage-source converter (VSC) based shunt FACTS controller that provides fast and continuous control of reactive power. Unlike the SVC, which relies on passive components (inductors and capacitors), the STATCOM uses IGBT- or GTO-based converters to generate a controllable AC voltage in phase with the system voltage[24].

If the converter output voltage magnitude is higher than the system voltage, it supplies reactive power (capacitive mode). If it is lower than the system voltage, it absorbs reactive power (inductive mode). The reactive current is almost independent of the system voltage, which enables the STATCOM to maintain excellent performance even during voltage sags or system disturbances[25].

Because of its fully electronic nature, the STATCOM provides faster dynamic response (in milliseconds), smaller footprint, and bidirectional reactive-power capability compared to an SVC.

- Applications: Widely used in transmission voltage stabilization, dynamic reactive-power support for renewable generation (like wind and solar farms), and improving transient and oscillatory stability in modern power grids[26].

Series controllers, on the other hand, are connected in series with the transmission line and are mainly used to control the power flow, line current, and impedance of the transmission network. By varying the series impedance, they effectively regulate the amount of power transmitted through a line. Prominent examples are the Thyristor Controlled Series Capacitor (TCSC) and the Static Synchronous Series Compensator (SSSC). The TCSC adjusts the effective reactance of the line through controlled thyristor firing, thereby improving power flow control and damping sub-synchronous resonance. The SSSC, which employs VSC technology, injects a controllable series voltage, enabling independent control of active and reactive power[27].

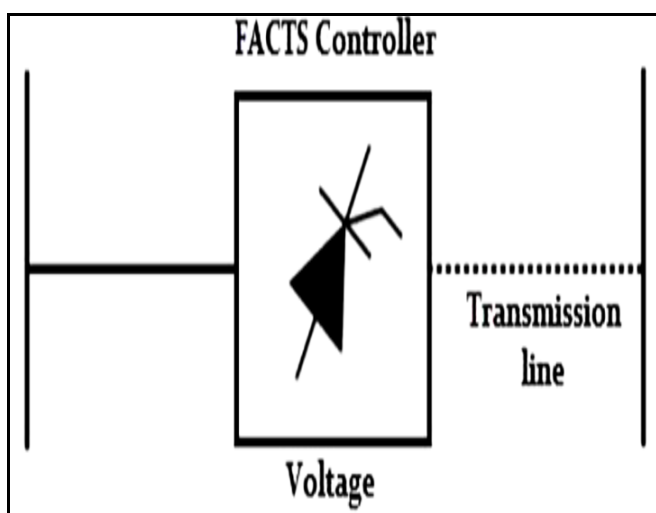


Fig 6 Series Type FACTS Controller

➤ Thyristor Controlled Series Capacitor (TCSC):

A controllable capacitor in series with the line that dynamically adjusts line reactance to regulate power flow and damp oscillations.

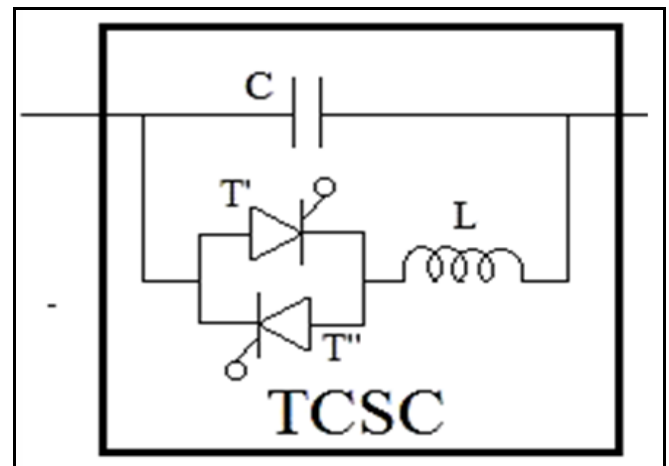


Fig 7 TCSC

The Thyristor-Controlled Series Capacitor (TCSC) is a series-connected FACTS controller used to control the effective line reactance and thereby regulate power flow in transmission lines. It consists of a series capacitor connected in parallel with a Thyristor-Controlled Reactor (TCR). The firing angle of the thyristors in the TCR is adjusted to vary the inductive current flowing through the reactor, which changes the net reactance of the combined capacitor-reactor branch.

When the thyristor firing angle is low, more current flows through the reactor, partially cancelling the capacitive current, thereby reducing the degree of compensation (lower capacitive effect). When the firing angle is high, the reactor conducts for a smaller portion of each cycle, so the capacitive reactance increases, providing higher series compensation. Thus, by varying the thyristor firing angle, the TCSC can operate in three modes:

- Capacitive boost mode – provides variable capacitive reactance to increase power transfer capability.
- Inductive boost mode – offers inductive reactance to limit fault currents.
- Bypass mode – during faults or overvoltage, the capacitor is bypassed by the thyristor valve for protection.

By dynamically adjusting the line reactance, the TCSC effectively controls active power flow, damps power oscillations, and enhances transient stability. It can also mitigate sub synchronous resonance (SSR) problems that occur in series-compensated lines connected to turbine-generator units.

➤ Static Synchronous Series Compensator (SSSC):

A voltage-source converter that injects a controllable AC voltage in series with the line, independent of the line current, to control power flow.

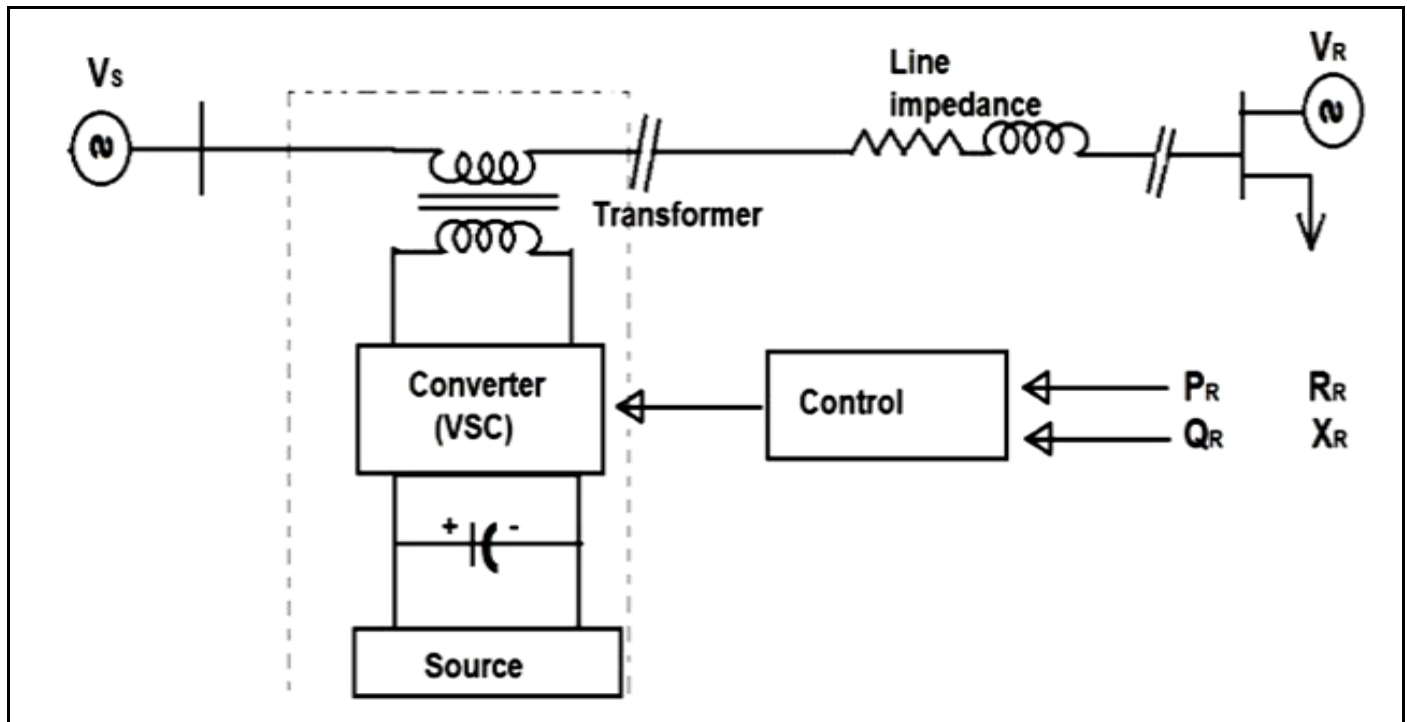


Fig 8 SSSC

The Static Synchronous Series Compensator (SSSC) is a series-connected, voltage-source-converter (VSC) based FACTS controller that provides an independent and controllable series voltage injection in a transmission line. Unlike the TCSC, which uses passive components (capacitor and reactor), the SSSC employs a fully controllable converter to generate a sinusoidal voltage of variable magnitude and phase angle, injected in series with the transmission line through a coupling transformer.

By controlling the amplitude and phase of this injected voltage, the SSSC can increase or decrease the effective line current and power flow.

When the injected voltage is in phase with the line current, it behaves as a capacitive compensator, effectively reducing the line reactance and increasing power transfer. When the injected voltage is in quadrature but opposite in phase, it behaves as an inductive compensator, increasing the line reactance and reducing power flow.

Because the converter can generate both leading and lagging voltages, the SSSC provides bidirectional reactive-power compensation and can even exchange small amounts of real power with the AC system if connected to an external DC source or energy-storage device.

The SSSC offers rapid, smooth, and continuous control of power flow and is effective for damping power oscillations, improving transient stability, and controlling voltage under dynamic conditions. It generates very low harmonics, eliminates the need for bulky filters, and maintains excellent performance even during system voltage dips.

Combined series-shunt controllers integrate both series and shunt functionalities to achieve coordinated control of voltage, impedance, and phase angle in the system. The most powerful example of this category is the Unified Power Flow Controller (UPFC), which combines a STATCOM and an SSSC through a common DC link. The UPFC provides simultaneous control over voltage magnitude, phase angle, and line impedance, making it one of the most versatile FACTS devices. Another example is the Interline Power Flow Controller (IPFC), which uses multiple series converters connected through a common DC link to balance and optimize power flow among several transmission lines within a network.

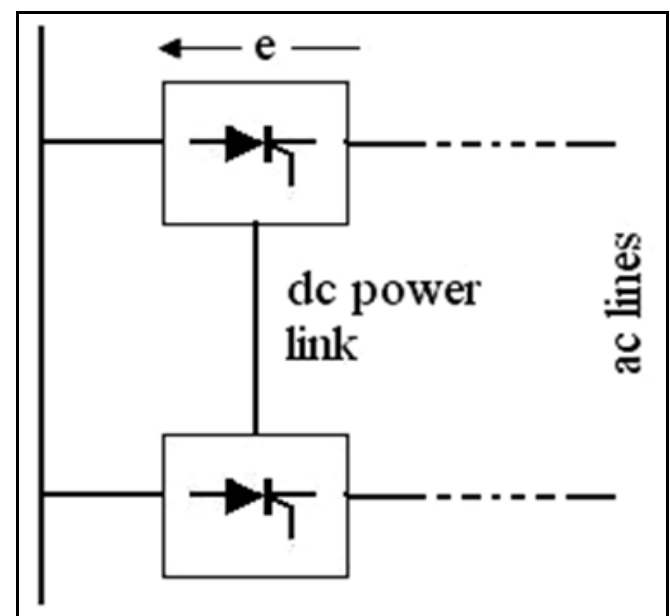


Fig 9 Combined Type FACTS Controller

Combined series-series controllers involve two or more series-connected devices operating in coordination, either within the same line or across multiple lines. These controllers facilitate inter-line power flow management and improve system load ability. The IPFC, in particular, can also be considered a series-series type when used across different transmission lines. Other devices like the Gate Controlled Series Capacitor (GCSC) offer rapid and flexible reactance control using gate-controlled switches, improving power flow regulation and reducing harmonics.

➤ *Unified Power Flow Controller (UPFC):*

The most versatile FACTS device that combines a STATCOM (shunt converter) and an SSSC (series converter) through a common DC link, allowing independent control of active and reactive power.

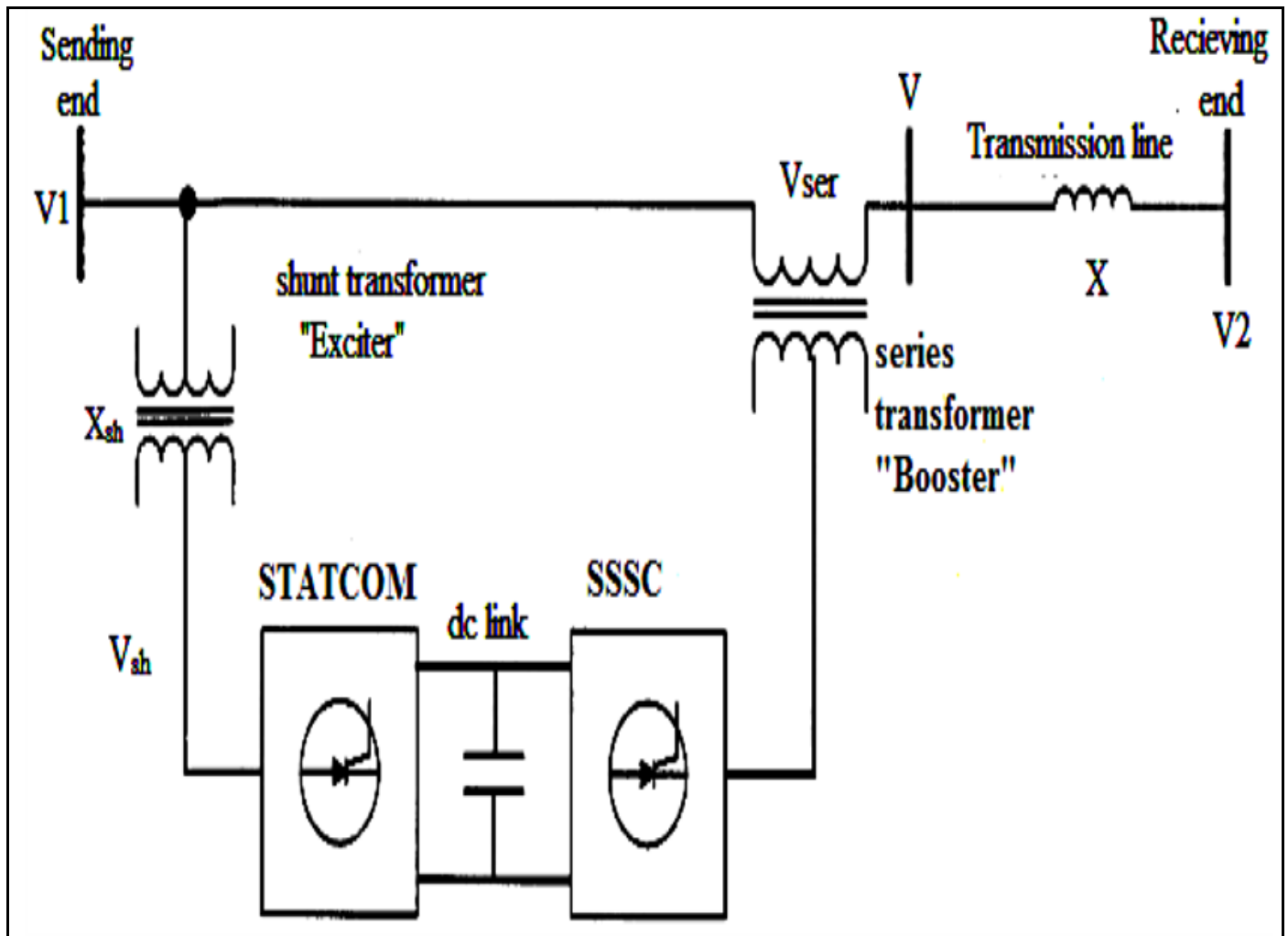


Fig 10 UPFC

FACTS controllers enhance the operational flexibility and reliability of modern power systems by dynamically managing voltage, reactive power, and power flow. Thyristor-based devices such as SVC and TCSC are cost-effective and widely used in traditional systems, whereas VSC-based controllers like STATCOM, SSSC, and UPFC offer superior performance with faster dynamic response and independent control capabilities. The choice of a particular FACTS device depends on the specific system requirement whether it is voltage stabilization, power flow optimization, or oscillation damping ensuring efficient and stable operation of the electrical grid[28].

III. CONCLUSION

Flexible AC Transmission Systems (FACTS) controllers are vital power electronic-based devices designed to enhance the controllability, stability, and power transfer capability of AC transmission networks. They address key challenges in modern power systems, including increased demand, limited expansion possibilities, and the need for better voltage regulation and dynamic stability. FACTS controllers such as STATCOM, SSSC, TCSC, and UPFC enable real-time control of power flow, voltage levels, and system impedance, resulting in improved transient stability, oscillation damping, and reduced transmission losses. These devices increase the loading

capability of existing transmission lines without physical upgrades, thus deferring costly infrastructure expansions. Moreover, FACTS controllers help prevent cascading outages and blackouts by managing power oscillations and voltage instability, contributing to higher system reliability and security. Their flexibility also facilitates the integration of renewable energy sources by stabilizing power fluctuations and allowing efficient power transfer across long distances. FACTS technologies foster greater operational flexibility by providing rapid and precise control compared to conventional mechanical switching methods. Furthermore, challenges like controller interactions in multi-device environments are addressed through coordinated control strategies, ensuring optimal system-wide performance. Overall, FACTS controllers are indispensable tools in modern power systems, supporting secure, efficient, and resilient grid operation under evolving load and generation patterns, thereby playing a critical role in advancing power system stability and economic operation.

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