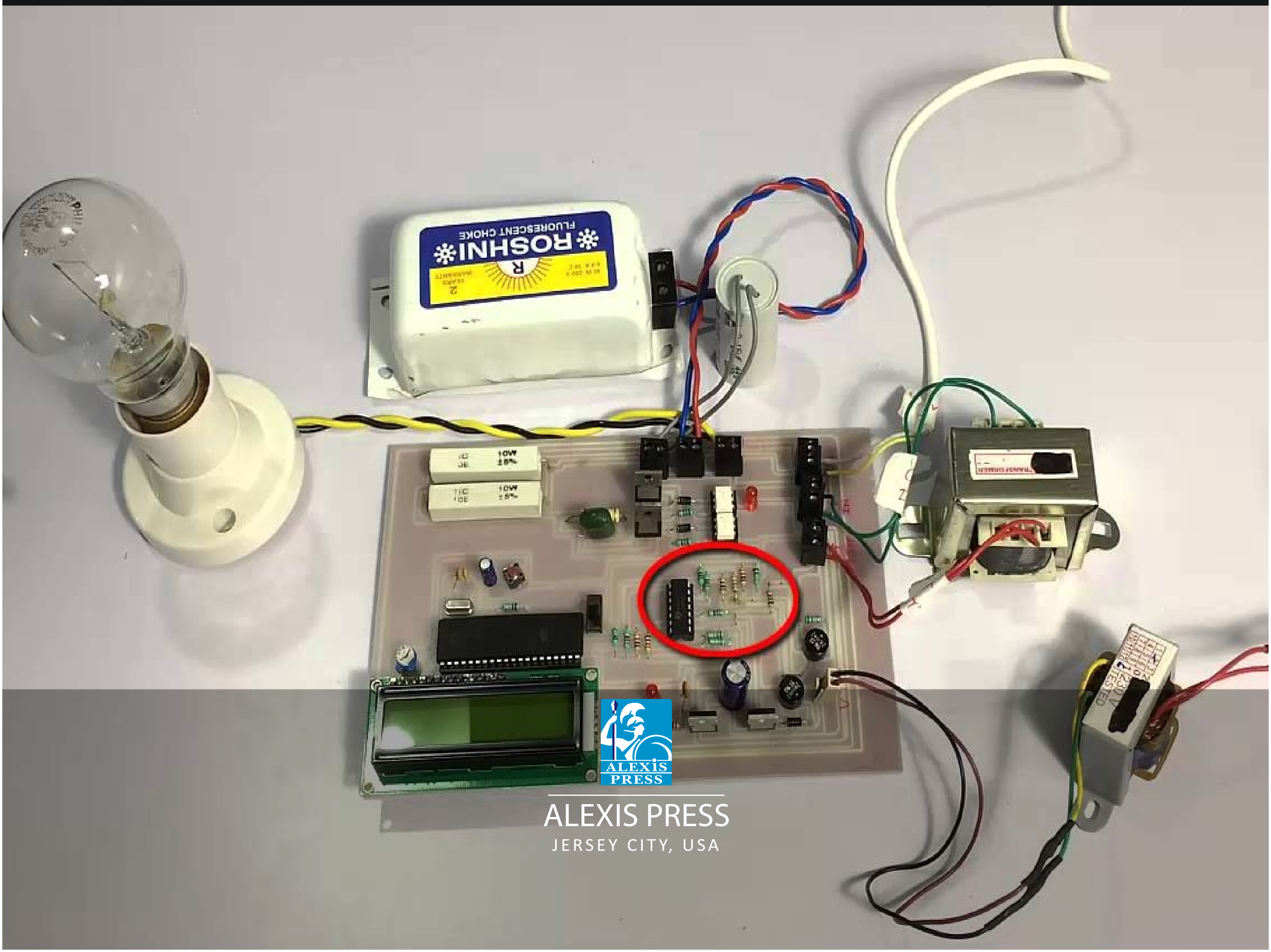
Samreen Fiza
Ginkawar Shwetha

# FLEXIBLE AC TRANSMISSION SYSTEM

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# CONTENTS

# CHAPTER 1

# INTRODUCTION OF FLEXIBLE AC TRANSMISSION SYSTEM

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**ABSTRACT:**

Power transmission systems can now be made more effective, flexible, and reliable thanks to the Flexible AC Transmission System (FACTS) technology. Static variable compensators (SVCs), static synchronous compensators (STATCOMs), and unified power flow controllers (UPFCs) are examples of FACTS devices that provide control capabilities that allow for the management of reactive power and dynamic voltage as well as the reduction of power system oscillations. The operational principles, device categories, and applications of FACTS technology are all described in this chapter. It looks at how FACTS can increase power transfer capacity, decrease power losses, and improve power system stability. The chapter also examines the difficulties in implementing FACTS technology and the ongoing research projects to solve these difficulties. Overall, this essay emphasizes the importance of FACTS technology in contemporary power networks and how it could fundamentally alter how electricity is transferred and managed.

**KEYWORDS:**

AC Transmission System, Facts Devices, Facts Technology, Flexible AC Transmission, Power Flow, Reactive Power.

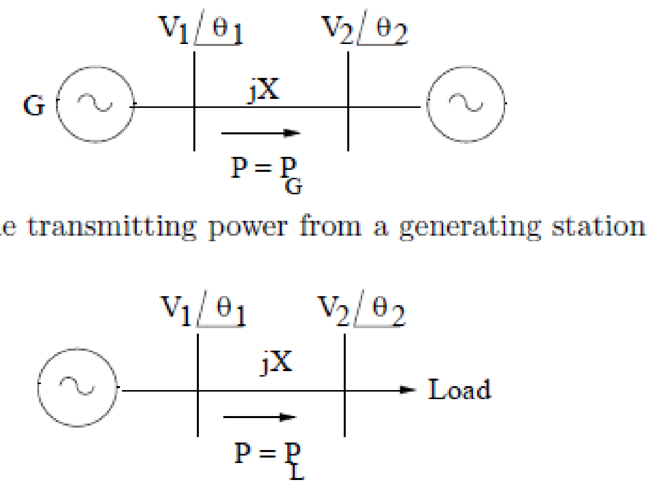
## INTRODUCTION

Modern power systems are built to run efficiently and reliably provide power on demand to varied load centers. Out of consideration for the economy, ecology, and safety, the producing stations are frequently situated in remote areas. For instance, it can be less expensive to build a thermal power plant at the pithead rather than transport coal to the load centers. Remote places typically have access to hydropower. A nuclear power facility could be situated far from populated regions. So, to transport power from the generating stations to the load centers, a grid of transmission lines running at high or very high voltages is needed[1]–[3].Modern power systems are strongly interconnected for economic reasons in addition to the transmission lines that move electricity from sources to loads. The benefit of using load variety, pooling generation reserves, and using large, energy-efficient units without sacrificing reliability goes to the interconnected systems. Security can be negatively erected by ac system interconnection, as disturbances started in one location might spread and propagate throughout the entire system, leading to significant blackouts brought on by cascading outages.

Basic power transmission networks: Most power transmission lines (10 kV to 800 kV) to operate at different voltages are AC lines. The majority of power is transmitted at higher voltages, whereas the distribution networks typically operate below 100 kV. Transformers with great efficiency are used to link the lines with various voltages. Traditionally, there has been no way to manage power flow on AC lines. The mechanically driven circuit breakers (CB) are designed to protect against faults, such as those brought on by ashovers brought on by overvoltages on the lines or decreased clearances to ground. A CB cannot be utilized for power flow management since it can only handle a certain amount of open and closed operations at once. (in contrast to a high-power electronic switch like a thyristor, GTO, IGBT, IGCT, etc.). Thankfully, ac wires have built-in power °ow control because the power at the sending end or the receiving end determines the power °ow. Consider, for instance, a transmission line that runs in Figure 1(a) from a generating station to a load center. The power flow (P) is provided by, assuming the line is lossless and ignoring the line charging.

$$P = V1V2/X \text{ Sin } (\theta_1 - \theta_2)$$

Where X is the reactance of a series line. The power injected by the power station determines the flow of power in the line, presuming V1 and V2 are kept constant (via voltage regulators at the two ends). P = PG is automatically enabled by adjusting the bus angle differences (Note that typically there may be more than one line delivering power from a producing station to a load center). In order to prevent overloading the remaining operational lines if one or more lines trip, the power plant's output may need to be lowered by tripping generators.



(a) A line transmitting power from a generating station

(b) A line supplying power to a load

**Figure 1: Transmission line carrying power**

Another instance of a line providing power to a load at the bus (2) is shown in Figure 1(b). The equation still holds true in this situation, but the provided load controls the power flow in the line. The key distinction between the two scenarios is that the load center in Figure 1(a) is modeled as an infinite bus, capable of absorbing (theoretically) any amount of power provided to it from the producing station. Since the entire load delivered to the load center is equal to the net generation available at that bus, this load center model assumes that the generation available at the load center is significantly larger than the electricity supplied from the remote power station[4]–[6].

By setting up two (or more) power sources as indicated in Figure 2, the reliability of the power supply at a load bus can be increased. P1 and P2 represent the outputs of G1 and G2, respectively (note that losses are still being ignored). However, the amount of power available at the load bus will decrease if one or more lines trip. By building a line to connect the two power plants, as indicated in Figure 2, this issue can be solved. Be aware that the transmission network becomes mesh-like as a result of this. As a result, the load is not reduced when any one-line trips, increasing the system's reliability. P1 can, however, be greater or less than PG1 (the output of G1) in a steady state. Kirchhoff's Voltage Law (KVL) is used to calculate the actual power flows in the three lines that make up a mesh.

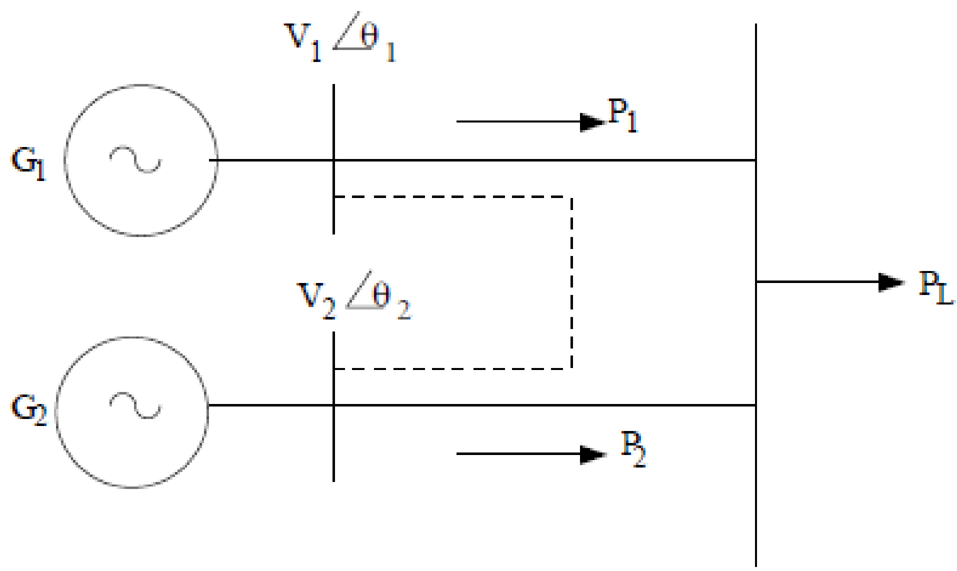



**Figure 2: Two generating stations supplying a load**

Generally speaking, adding an (interconnecting) line can enhance power flow in one line (while reducing power flow in another line). In the context of restructuring, this is an intriguing characteristic of AC transmission lines that are typically not well understood. In general, it may be said that power flows in individual lines in an unregulated AC transmission network with loops (to increase system dependability) are decided by KVL and do not adhere to the terms of the contracts (between energy providers and users). In other words, it is essentially impossible to guarantee that the power flow between two nodes takes a specific course. Only radial networks (without loops) are practical for this, although dependability suffers because even a single interruption might cause load reduction. Consider two power systems that are connected by a tie line and each includes a single power station that serves its local load (Figure 3(a)). In this instance, the mismatch between the generation and load in the various places determines the power flow in the tie line (P) in a steady state. Under dynamic circumstances, this power flow can be calculated using the analogous circuit depicted in Figure 3(b). Angles 1 and 2 are not significantly affected by the tie line power flow if the capacity of the tie is minimal in comparison to the size (generation) of the two areas. To safeguard the tie line or maintain system security, it is necessary to trip the tie during a disturbance because power flow in AC ties is typically uncontrolled.

The power flow of an HVDC line is controlled and regulated in contrast to an AC transmission line. HVDC converter stations are pricey, nevertheless, and are mostly utilized for underwater (submarine) transmission, long-distance bulk power transmission, and asynchronous system connectivity. The issue of commutation failures affecting the operation of multiterminal or multi-feed HVDC systems places further restrictions on the use of HVDC transmission (using thyristor converters). This suggests that HVDC lines are largely utilized for asynchronous interconnection (using Back-to-Back (BTB) links) and point-to-point power transfer.

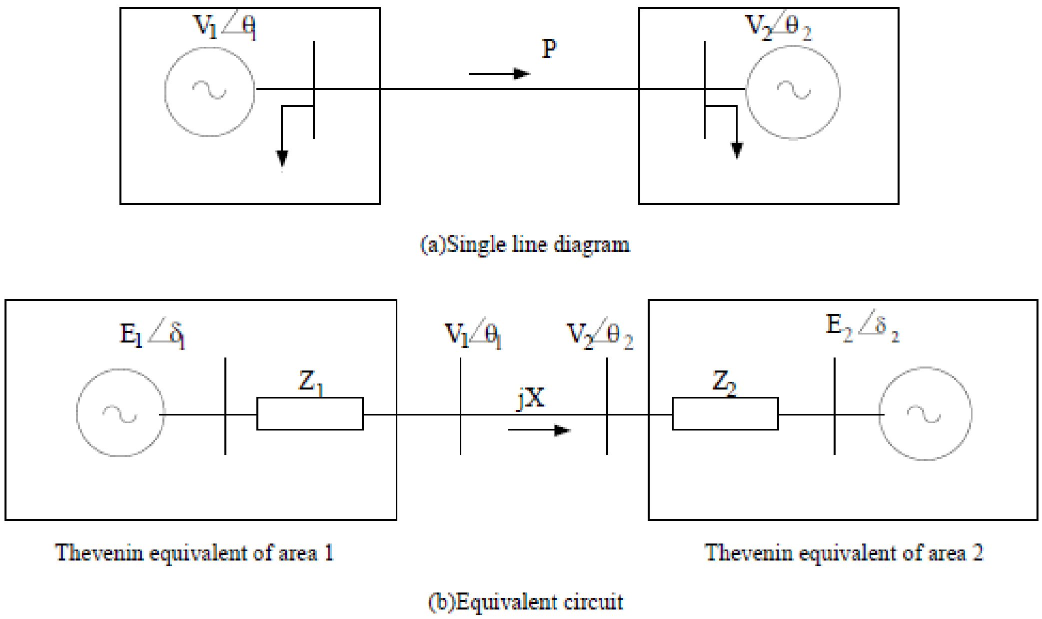



**Figure 3: Two areas connected by a tie line**

## DISCUSSION

**Control of Power Flow in AC Transmission Line:** For the AC power transmission systems to remain stable, their capacity to transfer power must be maximized, and transmission losses must be kept to a minimum. The main ways and tools for controlling power flow in AC transmission lines are to adjust the voltage, reactive power, and phase angle of the network. The devices used to control power flow in AC transmission lines, such as tap changers, phase shifters, and Flexible AC Transmission System (FACTS) components, are discussed in this article.

Tap Changers: Tap changers are frequently used in power transformers to regulate the voltage level at the transmission line's receiving end. They are made up of many taps that are joined to the transformer's primary winding and enable adjustment of the turns ratio and, subsequently, the output voltage. To maintain the desired power flow, the voltage level can be increased or decreased by altering the tap position. To ensure voltage regulation and efficient power flow control, tap changers are often operated automatically based on measurements of the system voltage [7]–[9].

Phase Shifters: In an AC transmission line, phase shifters are tools used to modify the phase angle between the voltages at various locations. They are made up of series and parallel configurations of inductors and capacitors that alter the voltage waveform's phase. The power flow in the transmission line can be managed by adjusting the phase shift's amplitude and direction. When power flow needs to be balanced between several channels, multi-circuit transmission lines or networks that are connected are particularly suitable places to apply phase shifters.

Flexible AC Transmission System (FACTS) Devices: FACTS devices provide sophisticated control capabilities for regulating power flow and system stability. These power electronics-based devices offer in-the-moment control over voltage, reactive power, and phase angle. Static Var Compensators (SVCs), Static Synchronous Compensators (STATCOMs), and

Unified Power Flow Controllers (UPFCs) are a few examples of frequently utilized FACTS devices.

By adjusting the voltage magnitude, SVCs are used to regulate reactive power in the transmission line. They are made up of capacitors and reactors that are parallel to the line and whose reactive power output can be switched or altered to account for system irregularities. SVCs help maintain voltage stability, boost power factor, and improve power transfer efficiency by controlling the reactive power.

Similar to SVCs, STATCOMs support dynamic voltage through the injection or absorption of reactive power. In reaction to system conditions, they generate or absorb reactive power via voltage source converters. System stability and power flow regulation are improved by STATCOMs' quick responses to changes in voltage levels and their capacity to adjust the voltage.

The most cutting-edge FACTS devices are UPFCs, which combine the capabilities of SVCs and STATCOMs with the capacity to regulate actual power flow. Multiple voltage source converters are linked to the transmission line in series and parallel to make up UPFCs. They provide accurate control of power flow and system stability by being able to individually manage the voltage magnitude, phase angle, and active power flow. UPFCs are particularly good at maximizing power flow through networks that are connected or on crowded transmission lines.

Maintaining system stability, maximizing power transfer efficiency, and reducing transmission losses all depend on the effective regulation of power flow in AC transmission lines. The traditional means of controlling voltage and phase angle are tap changers and phase shifters, respectively. FACTS devices, which are more advanced control devices, have been created as a result of power electronics improvements. The FACTS devices SVCs, STATCOMs, and UPFCs provide sophisticated control capabilities for reactive power, voltage, and power flow regulation. Real-time control is possible with these devices, and they can react swiftly to shifting system conditions. Power system operators can optimize power flow, improve system stability, and assure efficient operation by applying various control techniques and technologies.

**Transmission interconnection:**The majority, if not all, of the world's electric power supply networks, are intricately linked together, starting with connections inside utilities' jurisdictions and progressing to inter-utility interconnections, inter-regional connections, and finally, worldwide connections. This is done for financial reasons to lower electricity costs and increase the dependability of the power supply.

**Need for transmission interconnection:**These links are necessary because, in addition to facilitating delivery, the transmission network aims to pool power plants and load centers to reduce total power generation capacity and fuel costs. Transmission linkages make it possible to make use of the variety of loads, the availability of sources, and the cost of fuel to supply the loads with energy at the lowest possible cost while maintaining the necessary reliability. In general, considerably more production resources would be required to provide the demand with the same reliability if a power distribution system were made up of radial lines from individual local generators rather than being a part of a grid system. Additionally, the cost of electricity would be significantly higher. From that vantage point, transmission frequently serves as an alternative to new-generation resources. Whether the system is made up of large or small power plants, less transmission capability means that more generation resources would be needed. In reality, if there is a strong transmission grid, tiny distributed generating becomes more economically viable. Unless system planners employ sophisticated analytical techniques that incorporate transmission planning into an integrated value-based transmission/generation planning scenario, it is impossible to know with any degree of certainty what the ideal balance between generation and transmission is. The transmission capacity was frequently constrained by the price of transmission lines, losses, and the challenges associated with establishing additional transmission lines. Transmission capacity seems to be a common source of economic energy or reserve-sharing constraints, and the situation does not appear to be improving. An efficient electric grid is essential to the competitive environment of dependable electric service in a deregulated electric service market.

On the other side, when power transfers increase, the power system becomes more difficult to manage and its ability to withstand significant outages may decrease. This prevents the full potential of transmission linkages from being used since it may result in enormous power flows with insufficient control, excessive reactive power in various sections of the system, large dynamic swings between different portions of the system, and bottlenecks.

The majority of today's power systems are mechanically operated. Currently used transmission systems are controlled and protected by a wide range of microelectronic, computer, and high-speed communications devices; however, when operating signals are sent to the power circuits, where the final power control action is taken, the switching devices are mechanical, and there is little high-speed control. Because mechanical devices tend to wear out much more quickly than static ones, control cannot be initiated frequently, which is another issue with them.

In reality, the system is uncontrolled from the perspectives of both dynamic and steady-state operations. Engineers, operators, and planners of power systems have developed creative ways to work around this constraint while still ensuring that there are ample operational margins and redundancies in the system. These constitute a resource that can be wisely used with the selective, as-needed application of FACTS technology.

Greater demands have been placed on the transmission network in recent years, and these needs will continue to rise as a result of the rise in nonutility generators as well as the increased rivalry among utilities. The issue that it is highly challenging to obtain new rights of way is added to this. Together, increased transmission demands, a lack of long-term planning, and the requirement to grant customers and generating businesses unrestricted access have tended to diminish supply security and quality. By enabling utilities to maximize the use of their transmission facilities and improve grid dependability, the FACTS technology is crucial for resolving some, but not all, of these issues. However, it must be emphasized that in order to meet any capacity expansion requirements, new lines must be built or existing lines and corridors must have their current and voltage capabilities upgraded.

**The flow of power in an AC system:**Many transmission facilities currently struggle with the inability to control power flow as well as one or more restricting network factors.Given the minimal electrical storage in ac power systems, the electrical generation and load must always be in balance. The electrical system is partially self-regulating. When generation falls short of load, voltage and frequency fall, which reduces load until it equals generation minus transmission losses.

There is, however, just a little margin for such self-regulation. If reactive power assistance is used to maintain voltage, the load will increase, the frequency will continue to fall, and the system will eventually fail. In addition, if there is Voltage collapse may occur in the system due to insufficient reactive power.When sufficient generation is available, surplus energy is used to generate active power. It flows along all parallel routes available, usually involving additional high-voltage and medium-voltage lines, from the generation areas to the deficit locations. Long distances are frequently involved, along with loads and generators. A frequently used illustration of this is the fact that a significant portion of the electricity routed from Ontario Hydro Canada to the North East United States travels via the PJM system via a lengthy loop due to the availability of numerous strong low impedance lines along that loop. Any power transmission system contains both unequal power flows and many major and numerous minor loop flows.

**Power flow in parallel paths:**Take a look at a very straightforward example of power flow [Figure 4(a)], where power is transferred over two parallel channels (potentially corridors of many lines) from a surplus generating arearepresented by an analogous generator on the left—to a deficit generation arearepresented by a different generatoron the right. Power flow is based on the inverse of the various transmission line impedances when there is no control. The lower impedance line may become overloaded and limit the loading on both channels even while the higher impedance path is not fully loaded, in addition to ownership and contractual issues regarding which lines carry how much power. Since this would further reduce impedance and be a waste of money, there would be little motivation to increase the capacity of the overloaded path. This is especially true if the higher impedance path already has ample capacity. The same two paths are depicted in Figure 4(b), but one of them uses HVDC transmission.

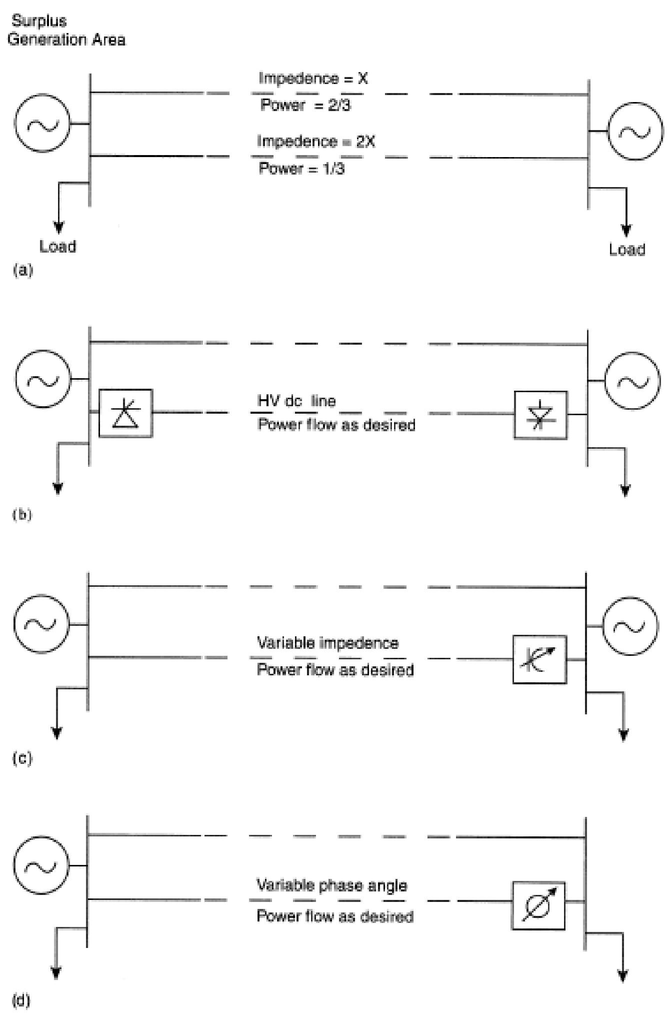


**Figure 4: Power flow in parallel paths**

Since power in HVDC power electronics converters is electronically regulated, power flows according to the operator's commands. The HVDC line can also be used to its maximum thermal capacity if sufficient converter capacity is available because electricity is electronically controlled. Furthermore, an HVDC line can assist the parallel ac transmission line in maintaining stability because of its high-speed control. HVDC is generally not used due to its high cost because it involves extensive distances, such as the Pacific DC Intertie where power is sent where it is needed according to the operator's commands.Figures 4(c) and 4(d) depict one of the transmission lines with various series-type FACTS Controllers as alternate FACTS Controllers. Through the use of impedance regulation [Figure 4(c)] a FACTS or phase angle [Figure 4(d)], or serial injection of the necessary voltage the power flow can be controlled by the controller as needed. Under contingency circumstances, where this line is anticipated to transport greater power as a result of the loss of a parallel line, the maximum power flow may in fact be constrained to its rated limit.

**Power flow in the meshed system:** Consider a highly simplified scenario where power is being sent from generators at two distinct locations to a load center via a network made up of three lines in a meshed connection (Figure 5) to better comprehend the free flow of power. Assume that the lines AB, BC, and AC have emergency ratings of double those numbers for a long enough period of time to allow rescheduling of electricity in the event that one of these lines fails. The continuous ratings for these lines are 1000 Mw, 1250 MW, and 2000 MW, respectively. A total of 3000 MW would be sent to the load center if just one of the generators is producing 2000 MW and the other is producing 1000 MW. According to Figure 5(a), the three lines would be able to transport 600, 1600, and L400 Mw, respectively, for the impedances depicted. In order to meet the load without overloading line BC, generation would need to be increased at A and decreased at B, respectively. In short, power flows according to transmission line series impedances, which are 907o inductive and have no direct relationship to transmission ownership, contracts, thermal limits, or transmission losses.

However, if a capacitor with a reactance of -5 ohms (O) at the synchronous frequency is added to one line [Figure 5(b)], the line's impedance will be reduced from L0 o to j,f, ro, resulting in a power flow of 250,1250, and 1750 MW across the lines AB, BC, and AC, respectively. It is obvious that alternative power-flow levels may be reached if the series capacitor is adjustable, depending on the ownership, contract, thermal constraints, transmission losses, and a variety of load and generating schedules. The number of operations would be significantly constrained by wear on the mechanical parts because the line loads fluctuate continuously with load circumstances, generating schedules, and line outages. Despite the fact that this capacitor could be modular and physically switched, the number of operations would be severely limited. If the series capacitor is mechanically controlled, more issues might occur.

Sub synchronous resonance may result from a series capacitor in a line; for an OOgzsystem, this resonance commonly occurs at 10–50 Hz. This resonance happens when the inductive impedance of the line coincides with one of the mechanical resonance frequencies of the shaft of a multiple-turbine generator unit, which is 60 Hz less than that frequency. Such resonance will eventually cause shaft damage if it continues. In addition, power flow oscillations at low frequencies (usually 0.3-3 Hz) may cause generators to lose synchronism, potentially leading to the system's collapse, while the failure of one line compels other lines to operate at their emergency ratings and bear heavier loads. However, it can be changed as frequently as necessary if the series capacitor is thyristor-controlled in whole or in part. Low-frequency fluctuations in the power flow can be dampened quickly, as well as any subsynchronous resonance circumstances.

In addition to lowering the possibility of system collapse, this would enable the transmission system to transition from one steady-state condition to another without endangering a generator shaft. In other words, a series capacitor regulated by a thyristor can significantly improve network stability. In order to overcome system limits at the lowest possible cost, it is usually practical for some of the series compensation to be mechanically regulated and some to be thyristor controlled. Similar outcomes can be achieved by adding a 7 A reactor (inductor) in series with line AB to one of the lines in the same mesh structure to increase its impedance [Figure 5(c)]. Again, a series inductor that is partially mechanical and partially thyristor controlled may be used to dampen undesirable oscillations as well as regulate steady-state power flows.

In any of the three lines, a series reactor or capacitor could be substituted with a thyristor-controlled phase-angle regulator to get the same result. In order to lower the overall phase-angle difference along the line from 8.5 degrees to 4.26 degrees in Figure 5(d), the regulator is fitted in the third line. The phase-angle regulator may once again be controlled mechanically and by a thyristor to cut costs. Alternatively, by injecting a variable voltage in one of the lines, the same results could be obtained. It should be noted that in the example above, balancing the power flow only required one FACTS Controller, while there are other possibilities for different controllers and in separate lines.A choice can be taken solely based on overall economics if there is just one owner of the transmission system. On the other side, if there are several owners, a decision-making system about the investment and ownership is required[10].

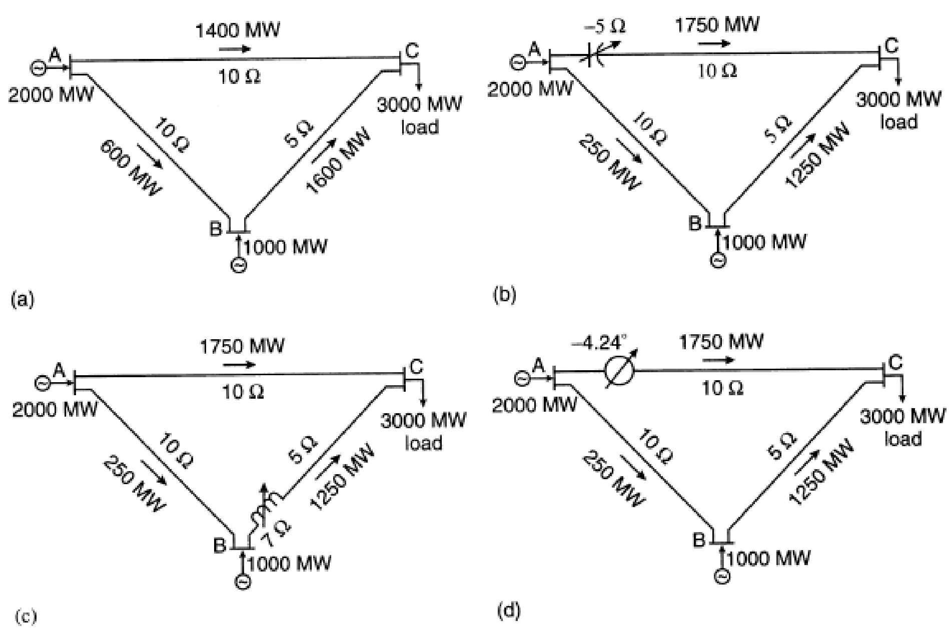



**Figure 5: Power flow in a meshed network**

## CONCLUSION

In conclusion, flexible AC transmission system (FACTS) technology has emerged as a game-changer in the power transmission and control industry. The enhanced control capabilities of FACTS devices, such as SVCs, STATCOMs, and UPFCs, allow for the control of reactive power and dynamic voltage as well as the capacity to dampen oscillations in the power system. The use of FACTS technology has many advantages, including greater power transfer efficiency, decreased power losses, and improved power system stability. Despite the difficulties connected to the cost-effectiveness and integration of FACTS devices, current research and development efforts are concentrated on removing these barriers. FACTS technology can revolutionize how electricity is transferred and controlled, opening the door for a more effective and dependable power grid as power systems continue to change and must meet rising needs.

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CHAPTER 2

# INTRODUCTION TO FACT'S CONTROLLER

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**ABSTRACT:**

The FACT Controller is a cutting-edge technology created to effectively manage and regulate FACT (Flexible AC Transmission technology) components in power systems. It functions as a centralized platform for controlling and monitoring FACT device performance, improving grid stability, and maximizing power flow. This introduction gives a summary of FACT's Controller while emphasizing its main advantages.The Controller from FACT is a crucial part of industrial automation and control systems. An overview of the main characteristics and features of FACT's Controller is given in this abstract. The Controller from FACT is a cutting-edge tool for reliable and effective control of industrial processes. It acts as a central center for managing and watching over numerous pieces of machinery and systems in a production or manufacturing setting. The Controller serves as a conduit for communication and control between input devices like sensors and switches and output devices like actuators and motors. The Controller's sophisticated capabilities, such as its capacity to process real-time data and carry out intricate control algorithms, are highlighted in the abstract. This makes it possible for it to precisely monitor and control factors in industrial processes including temperature, pressure, flow rate, and speed. The development of specialized control techniques is made possible by the programming abilities of the Controller, ensuring top performance and productivity.

**KEYWORDS::**

Facts Controller, Shunt Controller, Series Controller, Series Capacitor, Reactive Power, Real Power.

## INTRODUCTION

The massive, interconnected transmission networks, which are primarily made up of overhead transmission lines, are prone to insulating clearance reductions brought on by overgrowth as well as problems brought on by lightning discharges. Kirchhoff's laws for a certain power injection (both active and reactive) at various nodes govern the power flow in a transmission line. In addition to fluctuations brought on by the weather (ambient temperature) and other uncontrollable factors, loads in a power system are generally affected by the time of day. In a deregulated economy, the generation pattern also tends to be unpredictable. Thus, even under typical, steady-state conditions, the power flow in a transmission line might change. A contingency that occurs (because a line or generator trips) may cause an abrupt rise or fall in the flow of power. This may overload some lines, endangering the security of the system as a result[1]–[3].

A significant disturbance can also cause generator rotors to swing, which contributes to power fluctuations in transmission lines. As separate components (such as lines and generators) trip as a result of protective relays, the system may experience transient instability and cascading outages. Even a little disturbance can cause big power fluctuations and blackouts if the system is operating close to the edge of the small signal stability region.Voltage collapse can occasionally result from increased transmission line loading because of a lack of reactive power delivered to the load centers. Due to the nature of the load (such as induction motors producing constant torque), as well as the higher consumption of reactive power in the transmission network, this is the case.

The factors highlighted in the preceding paragraphs highlight the difficulties in maintaining massive interconnected systems' economical and secure operation. If sufficient margins (in power transfer) can be maintained, the issues are alleviated. Due to difficulties in expanding the transmission network brought on by economic and environmental factors, this is not practical. Fast dynamic control of reactive and active power by high-power electronic controllers can significantly lower the necessary safe operating margin. As a result, the AC transmission network may be more flexible' to adjust to the shifting circumstances brought on by contingencies and load changes. Alternating current transmission systems that incorporate power electronic-based and other static controllers to improve controllability and expand power transfer capabilities are known as Flexible AC Transmission Systems (FACTS). "A power electronic based system and other static equipment that provide control of one or more AC transmission system parameters" is how the FACTS controller is defined.

The FACTS controllers can be classified as

1. Shunt-connected controllers
2. Controllers connected in series
3. Controllers with combined series-series
4. Controllers for combined shunt series

The FACTS controllers can be classified as

(A) Variable impedance type (B) Voltage Source Converter (VSC) based, depending on the power electronic devices employed in the control.

The controllers for variable impedance include

i. Static Vary Compensator (SVC), which is coupled to a shunt.
ii. A series-connected Thermistor Controlled Series Capacitor (TCSC).
iii. Static PST (mixed shunt and series) Thermistor Controlled Phase Shifting Transformer (TCPST)

These are the VSC-based FACTS controllers:

i. Static Synchronous Compensator (STATCOM) (coupled with a shunt)
ii. A series-connected static synchronized series compensator
iii. Combining series-series Interline Power Flow Controller (IPFC)
iv. Combined Shunt Series Unified Power Flow Controller (UPFC)

Thermistor Controller Braking Resistor (TCBR) is one of the special-purpose FACTS controllers.

a) Thermistor Controller Braking Resistor (TCBR)
b) Thermistor Controlled Voltage Limiter (TCVL)
c) Thermistor Controlled Voltage Regulator (TCVR)
d) Interphase Power Controller (IPC)
e) NGH-SSR damping

The VSC-based FACTS controllers provide many benefits over the variable impedance variety. For instance, a STATCOM is technically superior and much more compact than an SVC for a similar rating. Even at low bus voltage levels, it can provide the necessary reactive current, and it can be provided with an internal short-term overload capacity. A STATCOM can also provide active power if its DC terminals house an energy source or a sizable energy store.

The requirement to use self-commutating power semiconductor devices like Gate Turn- o® (GTO) thyristors, Insulated Gate Bipolar Transistors (IGBT), and Integrated Gate Commutated Thyristors (IGCT) is the only downside of VSC-based controllers. Despite being available at higher voltage ratings, thyristors lack this capacity and cannot be employed, despite generally being more affordable and having lower losses. However, the technical benefits of VSC-based controllers combined with newly developed silicon carbide-based power semiconductor devices are anticipated to result in the widespread adoption of VSC-based controllers in the future.It is noteworthy that while SVC was the first FACTS controller (using the thyristor valves created in connection with HVDC line commutated convertors), various other FACTS controllers based on VSC have been developed. Due to this, VSC has been implemented in HVDC transmission with ratings up to 300 MW[4]–[6].

## DISCUSSION

### Loading capability limits

What restricts the loading capability, and what can be done about it, assuming ownership is not a concern and the goal is to optimize the loading capability (taking into account contingency conditions) and make the greatest use of the transmission asset?

There are three different types of limitations:

1. Thermal
2. Dielectric
3. Stability

Thermal ambient temperature, wind speed, conductor condition, and ground clearance all affect an overhead line's thermal capacity. Due to the changing environment and loading history, it may vary by a factor of 2 to 1. The nominal rating of a line is typically determined on a cautious basis, assuming the worst possible statistical case for the ambient environment. However, because this case is so uncommon, there is typically much more real-time capacity available than is thought. Some utilities give ratings for the winter and the summer, however. This still leaves a sizable window of opportunity. Additionally, there are offline software tools that may determine a line's carrying capacity depending on the ambientEnvironment and recent history of loading. Then there are the online monitoring tools, which serve as the foundation for online real-time loading. These techniques have developed over many years, and it makes sense to take into account reasonable, day-to-day, hour-to-hour, or even real-time capability information in the age of automation (typified by GPS systems and inexpensive advanced communication services). Having the ability to establish the line's real rating may be helpful because the ambient conditions occasionally turn out to be worse than anticipated. Normal line loading is frequently determined during the planning and design phases based on loss evaluation assumptions that may have altered for many reasons; however, losses can be taken into account on the real-time value basis of additional loading capabilities[7]–[9].

The real-time ratings of the transformers and other equipment must also be taken into account when raising the rating of a transmission circuit, some of which may need to be modified to raise the burden on the lines. The ambient temperature, the age of the transformer, and recent loading history are all factors that affect the real-time loading capacity of transformers. Transformer loading capability can also be determined in real-time using online and offline loading capability monitors. Additionally, the transformer is well-suited for improved cooling.

Then there is the chance to upgrade a line by switching to a conductor with a higher current rating, which can also call for structural improvement. The option of turning a single-circuit line into a double-circuit line is the last one. The question of how to employ the increased current capability then emerges once it is accessible. Will the additional power genuinely exist and be in control? When the load suddenly drops, etc., will the voltage conditions be acceptable? Making the most of this newly discovered capacity is possible with the aid of FACTS technology. Dielectric Many lines are very sparingly built from an insulating perspective.It is frequently possible to enhance normal operation by +10Vo voltage (i.e., 500–550 kV) or even higher with a given nominal voltage rating. Then, it's important to take precautions to keep dynamic and transient overvoltage within acceptable bounds. The line and substation voltage capability can be significantly increased with the help of modern gapless arresters, line insulators with inbuilt gapless arresters, or potent thyristor-controlled overvoltage suppressors at the substations. To guarantee suitable over-voltage and power flow circumstances, the FACTS technology could be applied. The transmission capacity is constrained by a number of stability problems.

The following are some of them: Transient stability, Dynamic stability, Steady-state stability, Voltage collapse, Frequency collapse, and Low-frequency resonance. There are some excellent books on the subject. As a result, the treatment of these subjects in this book will be condensed and limited to what is actually necessary for understanding FACTS Controllers. The ultimate stability restrictions would then be thermal and dielectric, which the FACTS technique can unquestionably exceed.

**Basic types of facts controller:**

Series Controllers: [Figure 1(b)] To meet the required need, the series controller could be a variable source of main frequency, subsynchronous, and harmonic frequencies (or a mix of these), depending on power electronics, such as a capacitor, reactor, etc. In theory, all series controllers inject voltage into the line in series. Even a changing impedance represents an injected series voltage in the line when the current flowing through it is doubled. Only variable reactive power is supplied or consumed by the series controller as long as the voltage is in the quadrature phase with the line current. Real power handling will be necessary for any other phase relationship.

Shunt Control/ers: [Figure 1.(c)] Shunt controllers can be variable impedance, variable source, or a combination of these, just like series controllers. The point of connection is where all shunt Controllers, in theory, inject current into the system. Even a variable shunt impedance coupled to the line voltage produces a variable current flow, which is what is meant when it is said that current injection into the line has occurred. The shunt Controller only produces or consumes variable reactive power as long as the injected current is in phase quadrature with the line voltage. Real power handling will be necessary for any other phase relationship.

Combined series-series Controllers: [Figure 1(d)] In a multiline transmission system, this could be a mix of different series controllers that are coordinately controlled. Or it might be a unified controller, as shown in Figure 1(d), in which series controllers transfer real power between the lines via the power tint while simultaneously providing independent series reactive compensation for each line. Real and reactive power flow in the lines can be balanced to enhance transmission system efficiency. This is made possible by the unified series-series controller, also known as the interline power flow controller. The term "unified" in this context refers to the connection of the dc terminals of all Controller converters for actual power transfer.

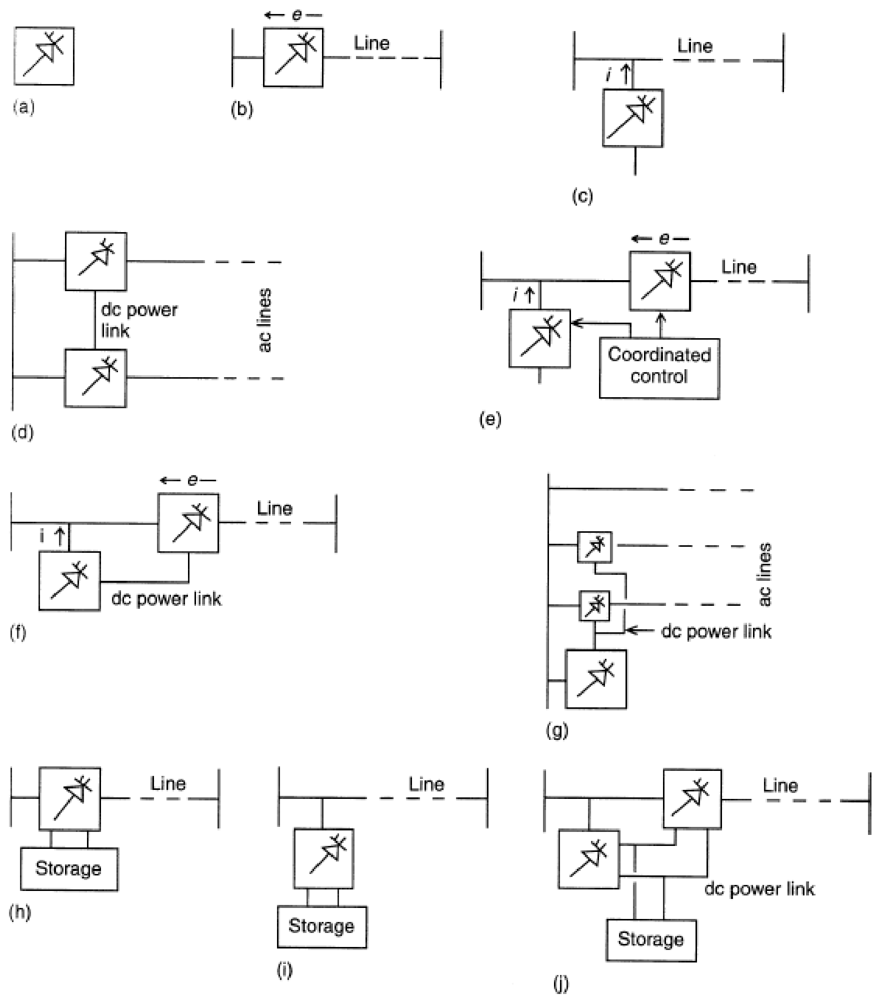


**Figure 1: Basic types of fact controller (research gate)**

Combined series-shunt Controllers: Illustrations 1(e) and 1(f) A unified power flow controller with series and shunt parts [Figure 1(f)] or a mix of independent shunt and series controllers that are regulated in concert could be used for this. Combination shunt-series controllers, in theory, pump current into the system through the shunt portion and voltage through the series portion into the line. The series and shunt Controllers, however, can actually exchange power via the power link when the shunt and series Controllers are combined.

**The relative importance of Different Types of Controllers:**

It is crucial to understand that the series-connected Controller directly affects the driving voltage, which in turn affects the flow of current and power. The series controller is therefore significantly more potent than the shunt controller for a given MVA size if the application's goal is to manage the current/power flow and dampen oscillations as stated. In contrast, the shunt Controller functions as a source of current that either draws from or injects current into the line. Therefore, using a shunt controller to inject reactive current (leading or lagging), either by itself or in combination with an active current for more effective voltage control and dampening of voltage oscillations, is a useful technique to control voltage at and near the point of connection.The series Controller can still be used to maintain the line voltage within the desired range, notwithstanding what has been said. As a result of the voltage drop in the series impedances of the lines, transformers, and g" or" tutor, the voltage fluctuations are, in large part, an "on."qo"n" of these.

Therefore, the most cost-effective way to improve the voltage profile is to add or subtract the FACTS Controller voltage in series (main frequency, subsynchronous or harmonic voltage, or a combination thereof). The needed voltage profile at a substation bus can be maintained much more effectively with a shunt controller. The shunt controller has the significant benefit of serving the bus node regardless of the individual lines connected to the bus.

In particular, if the application requires for contingency outage of any one line, a series controller solution may require, but may not always require, a separate series controller for each line linked to the substation. This should not, however, be the deciding factor when selecting a shunt-conn"t"d Controller as the needed MVA size of the series Controller is lower than that of the shunt Controller, and the shunt Controller, in any event, does not control the power flow in the lines.'On the other hand, series-connected Controllers must be built to ride through contingency and dynamic overloads, as well as to ride through or bypass short circuits "orr".

When the fault current is too large, it can be protected by metal-oxide arresters or momentarily bypassed by solid-state devices, but they must be rated to manage dynamic and contingency overload. The aforementioned reasoning implies that a series and shunt controller combination [Figures 1(e) and 1(f] can offer the best of both worlds, i.e., efficient power/current flow and line voltage regulation. Shunt controllers can work together with individual line controllers when series and shunt controllers are used together [Figure l: a(g)]. With unified Controllers, this architecture may offer additional advantages (reactive power flow control).FACTS controllers can be built using either power devices having gate turn-off functionality or thyristor devices with no gate turn-off (just gate turn-on). Additionally, as will be covered in other chapters, the main controllers with gate-off devices generally rely on dc-to-ac converters, which can exchange active and/or reactive power with the ac system. When the exchange only involves reactive power, they are only given a minimal amount of storage on the dc side.

However, the converter's dc storage can be increased beyond what is necessary for the converter to operate as a source of just reactive power if the generated ac voltage or current has to vary from 90 degrees concerning the line current or voltage, respectively. To meet the needs for short-term storage (a few tens of main frequency cycles), this can be done at the converter level. Additionally, a battery, superconducting magnet, or any other energy source can be added in tandem with the first storage source. to refuel the converter's dc store through an electronic interface. any of the converter-based, series, shunt, or shunt-series hybrid designs Controllers typically accommodate storage, such as superconducting magnets, batteries, and capacitors, which give FACTS technology a new dimension [Figures 1. (h), 1. (i), and 1. (j)].

The Controller would greatly benefit from an additional storage system, such as massive dc capacitors, storage batteries, or superconducting magnets. In comparison to a controller without storage, a controller with storage is significantly more effective at controlling the dynamics of the system.

This has to do with actual power being dynamically pumped into or out of the system as opposed to just having an impact on real power being transferred within the system, as is the situation with controllers without storage. Engineers must reconsider the function of storage in this case as well, especially that which is capable of delivering or absorbing huge amounts of actual power in brief bursts.To significantly lower the low-order harmonic generation, a converter-based Controller can alternatively be constructed with so-called high pulse order or pulse width modulation. In reality, an active filter can be created in a converter by designing it to produce the right waveform. It can also be managed and operated in a method that involves energy transfer between phasis and balances the unbalanced voltages. If the converter is made in such a way, it can accomplish all of these advantageous things at once.

Given the overlap of advantages and characteristics, it may be argued that when comparing series versus shunt and combination Controllers and storage versus no storage, one should have an open mind.

**Series Controllers:**

**Static Synchronous Series Compensator (SSSC)**

SSSC, or Static Synchronous Series Compensator To increase or decrease the overall reactive voltage drop across the line and thereby regulate the transmitted electric power, a static synchronous generator is used as a series compensator without the use of an external electric energy source. Its output voltage is in quadrature and controllable independently of the line current. To improve the dynamic behavior of the power system by extra temporary real power compensation, the SSSC may include transiently rated energy storage or energy-absorbing devices. These devices can temporarily raise or decrease the overall real (resistive) voltage drop across the line.

One of the most significant FACTS Controllers is SSSC. Similar to a STATCOM, but with the output ac voltage connected to the line in series. It can have a current-sourced converter or a converter that draws power from a voltage source [Figure 2(a)]. The insulation to the ground is often rather high, and the injected voltage in series is quite low compared to the line voltage. The converter equipment is positioned at the ground potential when the transformer's primary and secondary are properly insulated from one another unless the entire converter equipment is set up on a platform that is properly isolated from the ground. The transformer ratio is adjusted to the converter design with the lowest cost. SSSC can only inject a variable voltage that is 90 degrees leading or lagging the current in the absence of an additional energy source. Unless the converter is momentarily bypassed during severe line faults, the primary of the transformer and consequently the secondary as well as the converter must carry the entire line current, including the fault current. A series controller [Figure 2(b)] can also be coupled to superconducting magnetic storage or batterystorage to inject a voltage vector with a changeable angle in series with the line.

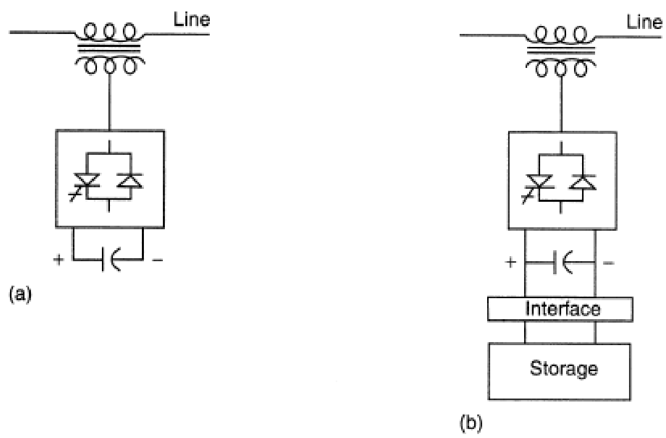


**Figure 2: Static Synchronous Series Compensator (SSSC)**

**Interline Power Flow Controller (IPFC)**

Because the IPFC is a new controller, there isn't an IEEE definition for it yet. The combination of two or more Static Synchronous Series Compensators that are connected via a common dc link to enable the bi-directional flow of real power between the SSSCs, and that is controlled to provide independent reactive compensation for the adjustment of real power flow in each line and maintain the desired distribution of reactive power flow along the lines, is one possible definition. A STATCOM connected to the IFC's common dc connection may also be included in the IPFC configuration to provide shunt reaction compensation and provide or absorb the overall real power deficit for all SSSCs combined.

**Thyristor-Controlled Series Capacitor (TCSC)**

A series capacitor bank is switched by a thyristor-controlled reactor to provide a smoothly variable series capacitive reactance in a capacitive reactance compensator known as a thyristor-controlled series capacitor (TCSC).

The TCSC [Figure 3] is built using thyristors that cannot turn off the gate. It serves as an alternative to the SSSC mentioned above and, like an SSSC, is a crucial FACTS Controller. A series capacitor is connected across a variable reactor, such as a Thyristor-Controlled Reactor (TCR). The TCR reactor stops conducting when the firing angle is 180 degrees, and the series capacitor's impedance returns to normal. The capacitive impedance rises as the firing angle is advanced from L80 degrees to less than 180 degrees. On the other hand, because the reactor impedance is intended to be significantly lower than the series capacitor impedance when the TCR firing angle reaches 90 degrees, the reactor fully conducts, and the overall impedance changes to inductive. The TCSC assists in minimizing fault current with a firing angle of 90 degrees. To achieve a better performance, the TCSC may be a single, huge unit or may be made up of multiple smaller capacitors of equal or various sizes.

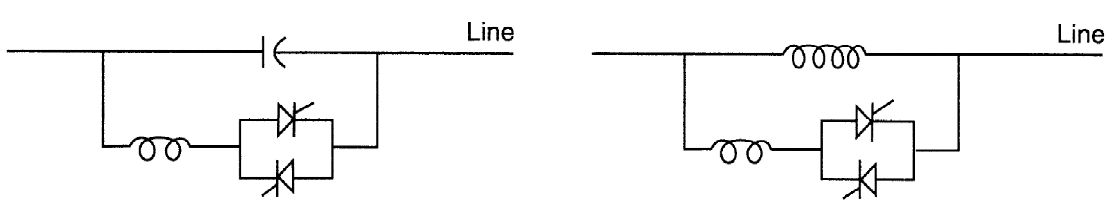


**Figure 3: Thermistor Controlled Series Capacitor (TCSC)**

## CONCLUSION

In conclusion, the FACT Controller is essential to the efficient administration and control of FACT devices in power systems. It improves grid stability and maximizes power flow by offering centralized monitoring and regulation.A series capacitor is connected across a variable reactor, such as a Thermistor-Controlled Reactor (TCR). The TCR reactor stops conducting when the firing angle is 180 degrees, and the series capacitor's impedance returns to normal. The capacitive impedance rises as the firing angle is advanced from L80 degrees to less than 180 degrees. Because of the system's increased capabilities, power systems are more reliable and efficient overall, resulting in a more reliable and sustainable energy infrastructure. Implementing FACT's Controller can boost operational effectiveness and reduce costs. It is a significant advancement in the field of power system control.

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**CHAPTER 3**

# APPLICATION OF THE POWER SEMICONDUCTOR DEVICES

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## ABSTRACT:

Modern power electronics systems must have components called power semiconductor devices. They are essential for the management and conversion of electrical power, which enables the efficient and dependable functioning of a variety of applications, such as electric vehicles, renewable energy systems, and industrial automation. An overview of power semiconductor devices is given in this chapter along with information on their many varieties, traits, and uses.Modern power electronics applications depend heavily on power semiconductor devices because they make it possible to convert and transmit electrical power in an effective and controlled manner. The main characteristics and purposes of power semiconductor devices are highlighted in this abstract. Electronic components known as power semiconductor devices are created specifically to handle high voltages and currents. They are used in numerous applications, including electric vehicles, renewable energy systems, motor drives, power supplies, and industrial automation. Their significance in enabling these systems to run dependably and efficiently is emphasized in the abstract.

## KEYWORDS:

Facts Controller, Forward Voltage Drop, Power Electronics, Power Semiconductor, Semiconductor Devices.

## INTRODUCTION

Only generic information regarding power semiconductor devices appropriate for FACTS Controllers is intended to be provided in this section. Power systems engineers can grasp the alternatives and how they apply to FACTS applications using the information that is supplied. For people who are interested in the specifics of a device, books are readily available and offer comprehensive information. Typically, three-phase power ratings for FACTS applications range from tens to hundreds of megawatts. FACTS Controllers essentially consist of a combination of ac/dc converters, high-power ac switches, and/or ac/dc converters. Each valve in a converter is an assembly of power devices along with any necessary snubber circuits (damping circuits), turn-on/turn-off gate drive circuits, and other equipment. A converter is an assembly of valves. Similar to this, each ac switch is made up of a pair of back-to-back linked power devices, as well as their snubber and gate drive circuits for turning on and off the device. The practical circuit rating of large power devices may only be 25 to 50Vo of their nominal rating. The nominal ratings of large power devices are in the range of 1-5 kA and 5-10 kV per device. The converters and ac switches would be an assembly of numerous power devices, as this is implied. To achieve the appropriate FACTS Controller rating and performance, converters, ac switches, and devices are linked in series and/or parallel. In some circumstances, a controller may also be divided into single-phase assemblies. These factors offer a fascinating opportunity and, in fact, a requirement for a supplier to adapt modularity for the efficient use of the power devices.

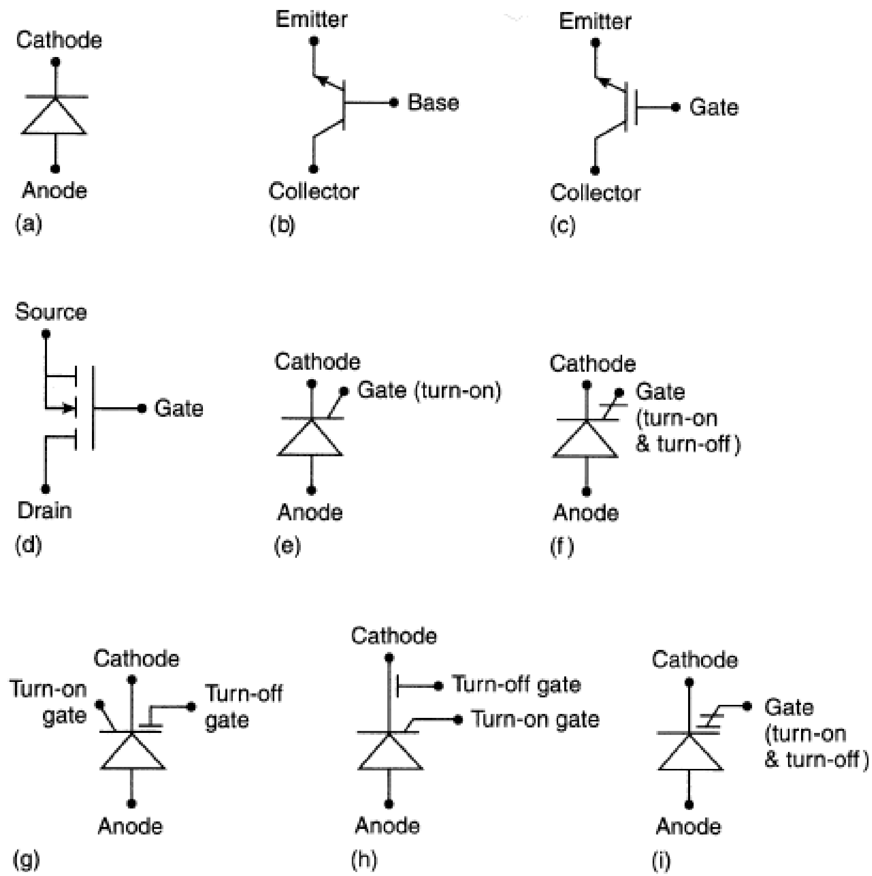


**Figure 1: Power semiconductor devices: (a) Diode, (b) Transistor, (c) Integrated Gate Bipolar Transistor (IGBT), (d) MOS Field Effect Transistor (MOSFET), (e) Thermistor, (0 Gate Turn-Off (GTO) Thermistor- and Gate-Controlled Thermistor (GCT), (g) MOS Turn-Off Thermistor (MTO), (h) Emitter Turn-Off (ETO) Thermistor, and (i) MOs-Controlled Thermistor (MTO).**

If used correctly, modularity can decrease costs by standardizing modules and submodules, but it can also be advantageous from the user's point of view in terms of dependability, redundancy, and staged investment[1]–[3]. The cost, performance, size, weight, and losses of FACTS Controllersor, for that matter, all power device applicationsare significantly influenced by the device ratings and characteristics and how they are used. The cost of everything used to support the devices, such as snubber circuits, gate-drive circuits, transformers and other magnetic equipment, filters, cooling equipment, losses, operating performance, and maintenance needs, is included in the leverage. For instance, faster switching capability enables concepts that create fewer harmonics and faster FACTS Controller reaction, as well as fewer snubber components and lower snubber losses. They are crucial for the effective implementation of specific FACTS Controllers principles, such as engaged filters. Low-power industrial applications require a variety of sophisticated circuit principles.

The economic use of first cost at a high-power level is mostly a function of device advancements, which are primarily driven by first cost. These ideas include choppers, resonant converters, soft switching, pulse width modulation (PWM), and others. As a result, even at higher prices, the design of FACTS Controller equipment would typically be based on the devices with the best available features. The availability of devices with better characteristics gives the FACTS options an important leverage and a competitive edge for a supplier of FACTS technology, enabling them to meet a certain specified performance at the lowest evaluated cost, even though device cost is a factor. As a result, advancements in power semiconductor devices and their packaging have a significant impact on the price, performance, and commercial success of FACTS Controllers.

In actuality, the FACTS Controller designer has a lot to gain from negotiating the device specifications, including packaging and subassemblies, with the device supplier rather than using those specifications as the foundation for the Controller design. Therefore, a user of FACTS technology must have a general understanding of the available power semiconductors, the current state of device technology, emerging developments, as well as circuit principles utilized in utility and industrial applications. High-power electrical devices are, generally speaking, quick switches built on high-purity single-crystal silicon wafers and intended for a range of switching characteristics. The devices may be able to control the current flow in their forward-conducting direction by being instructed to do so using gate control. Some power devices aren't built with the ability to block in the reverse direction, in which case another reverse blocking diode is placed in series with them or another parallel diode is used to bypass them in the reverse direction. Power semiconductor components are mostly made up of several types of diodes, transistors, and thyristors. Figure 1 depicts the fundamental gadgets in these groups symbolically. These symbols are frequently illustrated in a different way than Figure 1.These three kinds are briefly defined in the paragraphs that follow, and then more particular devices are detailed.

## DISCUSSION

### Diodes:

A two-layer device family with unidirectional conduction, diodes. When a diode's anode is positive relative to the cathode, the diode conducts (conducts) in a forward manner from the anode to the cathode. It doesn't have a gate to regulate conduction moving ahead. When a diode's cathode is made positive concerning its anode, the diode prevents conduction in the opposite direction. A crucial part of many FACTS Controllers is the diode.

### Transistors:

Transistors are a group of three-layer electronic components. When one of a transistor's electrodes, known as a collector, is positive relative to another electrode, known as an emitter, and when a turn-on voltage or current signal is provided to the third electrode, known as the base, a transistor conducts in its forward direction. When the base voltage or current is not enough to fully turn on the device, it will continue to conduct while maintaining a partial anode-to-cathode voltage. In applications requiring low to medium power, transistors are frequently utilized. Insulated Gate Bipolar Transistor (IGBT) transistors are one form of transistor that has advanced to become a choice in a variety of low and medium-power applications that can reach several megawatts and even a few tens of megawatts. IGBT is hence quite significant to FACTS Controllers. Another form of a transistor, the MOS Field Effect Transistor (MOSFET), is only appropriate for low voltages but has extremely quick turn-on and turn-off speeds and is frequently employed as a thermistor pilot gate device[4]–[6].

**High-Power Thermistor Device Types:**

The words "thermistor" and "silicon-controlled rectifier" refer, technically, to a basic family of four-layer controlled semiconductor devices, where turn-on and turn-off depend on pnpn regenerative feedback. The inventors chose the moniker Silicon Controlled Rectifier (SCR), which GE commercially popularized. Later, the word SCR was modified to thermistor by others to refer to a device that can be turned on but not off. The term "conventional thyristor" or simply "thermistor" started to be used for the device with just the turn-on capability after the development of a device known as the Gate Turn-Off Thyristor, or GTO. There are other acronym-based names for other members of the thermistor or SCR family. The traditional thyristor is commonly intended when the term "thyristor" is used in this text.

When a trigger current pulse is applied from the gate to the cathode, the thyristor begins to conduct forward and quickly latches on to full conduction with a little forward voltage drop (between 1.5 and 3 V, depending on the thyristor type and the current). As was already established, the typical thyristor depends on the circuit for the current to reach zero rather than being able to compel it to do so. The thyristor recovers in a few tens of microseconds of,66" blocking voltage when the current reaches zero, after which it can block the forward voltage until the next turn-on pulse is applied.When circuit configuration and cost-effective applications do not require a turn-off capability, conventional thyristors are frequently utilized due to their low cost, high efficacy, robustness, and high voltage and current capability. The turnoff feature frequently does not provide enough benefits to offset the devices' higher costs and losses. For practically all HVDC projects, some FACTS Controllers, and a sizable portion of industrial applications, the conventional thyristor has been the preferred technology. It is frequently referred to as the power electronics industry's workhorse.

The most important of them, and those that are pertinent to the FACTS technology, are the following variants of thyristors with turn-off capability: The GE-developed Gate Turn-Off Thyristor is today known as a GTO thyristor or just a GTO. When a turn-on current pulse is supplied to the gate concerning the cathode, it operates similarly to a typical thyristor by turning on in a complete ion conducting mode (latched mode) with a low forward voltage drop. The GTO can turn off when a turn-off pulse is applied to the gate in the opposite direction, just like a normal thyristor does when the current naturally drops to zero. The CfO quickly turns off with a suitable turn-off pulse, recovers to withstand the forward voltage, and is prepared for the subsequent turn-on pulse. Although the GTO is a popular component for FACTS Controllers, it is likely to be replaced in the upcoming years by more sophisticated GTos and thyristors due to its large gate drivers, delayed turn-off, and expensive snubbers. These modern GTOs, in turn, are a component of the thyristor family, each of which has its own acronyms that are listed below and further defined in this chapter.

MOs running off Silicon Power Corporation is where the thyristor was developed. Transistors are used in Harshad Mehta's (sPCo) to help turn devices off quickly and with little switching losses. The medium- to high-power industrial and FACTS Controllers have a good potential for using this device, which has just recently been commercially introduced. Another variant of the GTO, the Emitter Turn-off Thyristor, was created at the Virginia Power Electronics Center in partnership with SPCO and uses low-voltage transistors in series with a high-voltage GTO to produce quick turn-off and minimal turn-off switching losses. The Mitsubishi and ABB-created Integrated Gate-commutated thyristor (GCT and IGCT, Section 2.10) is essentially a GTo with a hard turn-off, which when combined with other packaging advancements results in a quick turn-off and minimal turn-off switching losses. These device slaves, which have just lately been commercially released, have good potential for use in

FACTS Controllers and industrial settings. Victor Temple at GE developed the MOs-controlled thyristor (MCT, Section 2.r2), which is almost the pinnacle of thyristor devices and has an integrated MbS structure for both quick turn-on and turn-off. It features very little conduction loss in addition to very little switching loss. These products have a fair chance of being used in FACTS Controllers and have been commercially released for low-power applications. The following devices are briefly described in this essay due to their significance in terms of FACTS Controllers: the diode, transistor, MOSFET, thyristor, GTO, MTO, ETO, IGCT, IGF|4, and the MCT.

**Principal High-Power Device Characteristics and Requirements:**

Voltage and Current Rating: Single crystal silicon wafers with a diameter of 75 to 125 mm or even closer to 150 mm are typically used as device cells for high-power applications. For higher voltage and lower current, the same diameter device can be produced, and vice versa. Potentially, silicon crystal has a resistivity that falls between that of metals and insulators and a very high voltage breakdown strength of 200 kV/cm. Impurities can change the conduction properties of Dipping. Doping increases the number of circuits, which lowers the withstand voltage and raises the current carrying capacity of the device. Lower doping results in higher forward voltage drop, and higher voltage capability, but also lower current capability. As was already established, there are certain similarities between the current and voltage capacities. Higher current capability naturally results from a greater diameter. A 125 mm device might be able to tolerate voltages between OOOO and 10,000 volts and transport currents between 3000 and 4000 amperes. Although a full description of different trade-offs is not relevant to this book, it is vital to note the key characteristics of various devices. The overall number of devices as well as the cost of all the additional components reduce as device ratings rise. The highest blocking capacity as well asother desired properties for thyristors, GTOs, and IGBTs fall between 8 and 10 kV, 5 g kV, and 3 to 5 kV, respectively. After allowing for numerous factors in a circuit.

The useful device voltage will be around half the blocking voltage capability to account for overvoltages and redundancy. For high-voltage valves, it is frequently required to link devices in series. For a valve designer, choosing the ideal combination of several approaches and weighing trade-offs among them becomes a key exercise in ensuring equitable voltage sharing during turn-on, turn-off, and dynamic voltage fluctuations. Device matching, particularly the traits that allow for device swapping, is one of these methods. Large power devices often don't need to be connected in parallel because they can be built to accommodate several thousand amperes of load current.

However, the needed current capacity is frequently determined by the short-circuit current duty; in this case, connecting two matching devices directly in parallel on the same heat sink is a viable solution. In the application circuit, devices must typically ride through a blocked condition after one cycle of offset fault current. Although using fuses in industrial power electronics is standard procedure, doing so is not recommended for high-voltage applications like FACTS Controllers. Therefore, to choose the current and voltage margins and redundancy, the device selection must consider all plausible failure and protection scenarios. The thyristor family of devices can withstand very high single-cycle fault currents and high overload currents for brief periods without failing. If the circuit's remaining components are capable of carrying out the required task, it may continue to operate even after the thyristor and diode family of components fails in a short circuit with low voltage drop.

As determined by the converters' market requirements (covered in Chapter 3: The majority of devices having turn-off functionality are manufactured with oo,qlu" or" blocking capabilities, according to Voltage-Sourced Conuerteri. As a result, they are also known as asymmetric turn-off devices, or simply turn-off devices. The device's thickness, forward conduction losses, and switching losses can all be reduced if the reverse voltage capability requirement is not present. Conversely, asymmetric devices can produce a greater forward withstand voltage. It turns out that each main component of the voltage-sourced converters must be connected in parallel with a reverse diode. Due to their effect on the primary devices' turn-on needs, these diodes are often specialized diodes with the lowest possible reverse leakage current. However, the current-sourced converters that were proposed require equipment that can tolerate reversing voltage. Despite this, many industrial applications with a focus on the first cost frequently contemplate using a diode in series with the asymmetric primary device to acquire reverse blocking capabilities. This is due to the enormous volume of asymmetric power devices.

**Losses and Switching Speed:**

The characteristics that are significant to the devices go beyond their ability to withstand voltage and carry current. The forward-voltage drop and ensuing losses during the full conducting state (on-state losses) are the most significant of these. It costs a lot of money to remove the heat that must be quickly transferred from the wafer through the package and into the cooling medium.

Switchover time: After turning off, there is a transition from a fully conducting to a fully no conducting state (with a matching high DLT), and from I The transition from a fully no conducting to a fully conducting state (turn-on) and a high dildt value during the turn-off are crucial characteristics. They determine the device's usable current and voltage rating as well as the size, price, and losses of the snubber circuits required to soften excessive duldt and dildt.

Changing losses: When a device is turned on, the forward current increases before the forward voltage drops, and when a device is turned off, the forward voltage increases before the current drops. High voltage and current present simultaneously in the device represent power losses. Due to their recurring nature, they account for a sizable portion of the losses and frequently outweigh the on-state conduction losses.

The trade-off between switching losses and forward voltage drop (on-state losses) in a power semiconductor design also means that the optimization of device design depends on the architecture of the application circuit. As will be seen later in chapters 3 and 4, even though the typical system frequency is 50 or 60 Hz, there is a class of converters known as "pulse-width modulation (PWM)" converters that have a high internal frequency of hundreds of H4 to even a few kilo-llz for high-power applications. The switching losses can dominate the total losses in PWM converters with many times more switching events.

A significant portion of the losses and overall equipment cost is related to the power and energy requirements of the gatedriver. In addition to being significant relative to the overall losses when big and prolonged current pulses are required for turn-on and turn-off, the cost of the driver circuit and power supply may also be more than the price of the device. The stray inductance and capacitance rise with the size of every component that surrounds a power device, which in turn affects the pressures on the devices, switching time, and snubber losses. The future trend is to buy the device and the driver together from the device supplier since it is crucial to coordinate the design and packaging of the device and the driver[7]–[10].

**It's critical to pay close attention to losses for two reasons:**

1. For the obvious cause that losses are the user's financial responsibility. Utility companies and industrial clients always evaluate losses on a lifetime present value basis, and this value might range from $1,000 to $5,000 per kilowatt of losses for purchase price evaluation. If a FACTS Converter has losses of 2vo (0.02 kw loss per kw rating) and costs $100 per kilowatt, the losses for a converter with an evaluated value of $2,000 per kilowatt will be $40 per kilowatt, or 40Vo of the converter's purchasing price. As a result, a complete FACTS controller with a rating of several hundred MW must have an efficiency of better than 98vo and converter valve losses of less than 1-7o.
2. The device losses from the inside of the wafer to the outside of the sealed, high-voltage, insulating package and onto the external cooling medium must be removed effectively. In order to maintain safe switching characteristics, appropriate margin for overload and short circuit currents, and a water temperature of no more than roughly 100oC, it is a tough challenge to package and cool the devices. Most of the time useful rating of the devices is determined by the not, Fault current. Greater losses translate into greater packaging costs, more losses, and disposal costs. The equipment's size and weight, as well as its thermal losses to water or air.

**Parameter Trade'Off of Devices:**

The cost of devices is also tied to the production yield of high-quality devices, which are subsequently rated according to a range of criteria. As a result, this necessitates thorough quality control from the raw materials to the finished product, including the quality of the electric supply.Uppty in the manufacturing facility. Like with HVDC converters, all power components for high-power controllers are individually tested, and a record of their results is preserved for replacement services in the future.

In addition to the trade-off between voltage and current capability, there are other trade-off factors, such as the gate's power requirements.

**Capability Of Dildt Du Ldt Capability**

Turn-on and turn-off capabilities (also known as the "Safe Operating Area [SOA]") Uniformity of attributes, such as the quantity and quality of starting silicon wafers and the cleanliness of the manufacturing environment, etc. Innovative design and processing techniques have been created and are still being created. A device maker separates the market into numerous types of devices adapted to the application and market size based on a wide range of characteristics. Additionally, it is "o-*on for device makers to customize their products for certain large clients and even for specific major project orders, such as HVDC and FACTS Projects.

The fact that the power semiconductor devices are sold separately from the gate-drive circuits and the snubber circuits is substantially to blame for the switching, size, cost, and other losses that are universally attributed to the power semiconductor devices. The discussion further in this chapter should make it evident that the circuit-bus design for tying the devicemodules into a converter, in that order of importance, is entwined with the gate driver, snubber, and device performance. If the device, the gate driver, the snubber, and the accompanying buswork very close to the devices were assembled and sold by the device supplier as a building block, significant reductions in the application cost may be achieved. In actuality, the device wafer's electrical-mechanical integration with its gate-drive circuit offers significant advantages up to the application. It has become more common practice to sell assemblies of many devices in a mold or package that represents a circuit or a portion of a circuit for low- and medium-power industrial applications. The demand for integration, which should begin with the device wafer and its gate driver, is not fully met by this method, although it lowers the cost of packaging. The U.S. Office of Naval Research (oNR) launched the Power Electronics Building Block (PEBB) initiative with this goal in mind, addressing all integration-related issues such as the device, gate driver, packaging, and bus-work, which have an impact on reduction in conversion losses, costs overall, weight, and dimension. Significant improvements have been made as a result of this initiative, which also enabled them. In fact, this tendency has already started and it is increasingly acknowledged that there may be benefits. Pre-packaged gate drivers and snubber circuits are sold with devices under many trade names, not always the moniker PEBB.

**Power Device Material:**

High-purity, single-crystal silicon is the basis for power semiconductor devices. In the so-called Float Zone finances, single crystals up to 150 mm in diameter and many meters in length are generated. Then, after undergoing many processing procedures, this enormous crystal is divided into thin wafers for use in power devices. In the lattice, each pure silicon atom has four electron bonds with its neighbors. It has a very high dielectric strength of over 200 kV/ cm and high resistance. By implanting particular impurities (doping), it is possible to modify, layer, and grade its resistivity as well as the charge carriers that are available for conduction. Large finished devices are manufactured using various impurities, levels, and forms of doping, as well as cutting-edge photolithography, laser cutting, etching, insulating, and packaging techniques.

Donor and acceptor impurities are the two different types of impurities used during silicon wafer implantation. Because it has five electrons as opposed to silicon's four, phosphorus is a donor. So a phosphorous atom becomes a fixed atom site with an additional electron when it is inserted into a silicon lattice. With the help of an electric field, this additional electron is easily displaced. A hole is created when one electron leaves the site of the phosphorus atom and waits to be filled by an electron from another site, which then also creates a hole. With an applied electric field, there are therefore electrons and holes available for the conduction process in a directed conduction. To contribute negative particles (electrons) to the conduction process, phosphorus doping is referred to as n doping. Phosphorus doping of silicon is referred to as n- doping when it occurs mildly, and n+ doping when it occurs heavily.

The antithesis of phosphorus is boron, another doping substance. It has three electrons per atom, and when a boron atom is inserted into the structure of silicon, it leaves one empty spot (a hole that can be filled by an incoming electron). When a hole at a boron atom site is filled, it leaves a negatively charged site that must wait for a hole from another site to neutralize it before it too becomes negatively charged, creating the illusion of moving holes. For introducing positive holes to aid in the conduction process, borax is referred to as p doping. P- or p+ can be either mildly or strongly doped in silicon.

Thus, in a directed conduction with an applied electric field, n-doped silicon has electrons available for the conduction process while p-doped silicon has holes available. The majority carriers and minority carriers in p-doped silicon are the holes and any electrons, respectively. Electrons are referred to as the majority carriers and holes as the minority carriers in the n-doped layer. In addition to the carriers added by doping in a power device, there are also the so-called intrinsic carriers, produced by thermal excitation, which have an equal amount of electrons and holes. According to their lifespan, these carriers are continually created and recombined until they reach an equilibrium density of 1010–1013/cm3 over a temperature range of approximately 0°C to 100°C. Low doping (fewer carriers) is needed to achieve high withstand voltage, which makes intrinsic carriers more prevalent and important for the conduction process. The inherent carriers, which are temperature-dependent, become substantial, and even the dominating carriers with high current levels. Slices of silicon are blasted with neutrons in a reactor to serve as the raw material for high-voltage, high-power semiconductor devices. N-doped silicon is created, but it has a modest and consistent doping concentration in the range of 5 X I012lcm3, which is comparable to the intrinsic carrier concentration. This is because the proper number of silicon atoms is changed to phosphorous atoms depending on the radiation. This thin slice with extremely low n doping is changed by diffusion in high-temperature furnaces and other techniques to have different doping profiles in the layers, channels, etc. needed for particular devices. This book does not explain doping procedures.

## CONCLUSION

In conclusion, power semiconductor devices are essential parts of power electronics systems that make it possible to regulate and convert electrical power reliably and efficiently. They have a wide range of uses in many industries, such as industrial automation, electric vehicles, and renewable energy systems. Power semiconductor devices come in a variety of forms, including diodes, transistors, and thermistors, each with special qualities and abilities to satisfy particular needs. Power semiconductor technology is always improving, which leads to lower power losses, better energy efficiency, and better system performance. Power semiconductor devices are crucial in determining how future energy systems will develop, easing the shift to efficient and sustainable power use.

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CHAPTER 4

# FEATURES OF THE POWER ELECTRONICS FACTS CONTROLLER

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**ABSTRACT:**

A sophisticated system called the Power Electronics FACTs (Flexible AC Transmission Systems) Controller makes use of power electronics components to improve the control and stability of AC power systems. To control power flow, adjust voltage, and minimize grid disturbances, it integrates a variety of power semiconductor devices and control algorithms. An overview of the Power Electronics FACTs Controller's features uses, and advantages are given in this chapter.Modern power electronics applications depend heavily on power semiconductor devices because they make it possible to convert and transmit electrical power in an effective and controlled manner. The main characteristics and purposes of power semiconductor devices are highlighted in this abstract. Electronic components known as power semiconductor devices are created specifically to handle high voltages and currents. They are used in numerous applications, including electric vehicles, renewable energy systems, motor drives, power supplies, and industrial automation. Their significance in enabling these systems to run dependably and efficiently is emphasized in the abstract.

**KEYWORDS:**

Electronics Facts Controller, Forward Voltage, NPN Transistor, Reverse Voltage, Voltage Drop, Voltage-Sourced Converters.

## INTRODUCTION

Diode (Pn Junction): The diode is conceptually represented in Figure 1(b) together with the cross-sectional structure of its wafer junction. The prospect that:

1. A diode converter can be employed as a straightforward, low-cost, and efficient converter, to supply active power in a FACTS Controller, highlighting the significance of diodes for FACTS Controllers.
2. In voltage-sourced converters and multilevel voltage-sourced converters, a diode is connected across each turn-off thyristor in addition to connections of intermediate levels.
3. For reverse voltage blocking, a diode may be connected in series with each turn-off thyristor.
4. Gate-drive and snubber circuits both require diodes.

In actuality, diodes might be a good starting point or general foundation. Nearly half of the devices utilized in FACTS of the p and n layers on a silicon wafer are diodes, which are single-junction devices [Figure 1(b)].

Similar to layer n, which has excess electrons as the dominant carriers, layer p is electron-deficient (has holes as the majority carriers). These p and n layers are created by doping impurities in a silicon slice, as was previously explained. The generation of carriers and their participation in conduction at a p-n junction (a diode) are explained by the introduction of voltage that makes the p side positive and the n side negative unfavorable side. Due to this external force, holes from the p side cross over to the n side, and electrons from the n side cross over to the p side. If the voltage is switched around, though, the holes and electrons leave the junction and form an internal centerfield that prevents the current from moving. To better understand the principles of many junctions for other devices, a detailed description of a diode is required[1]–[3].

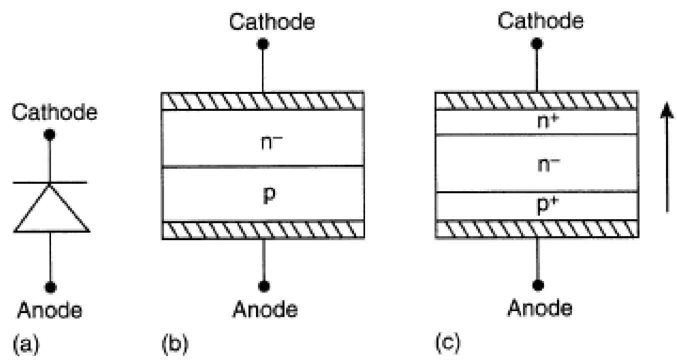


**Figure 1: Diode: (a) diode symbol, (b) diode structure, and (c) diode structure.**

There are two physical ways by which these electrons and holes can move:

1. Through diffusion brought on by variations in carrier density
2. By drifting in the direction directed by an applied voltage from the outside

The pn junction only develops a very modest electric field (less than 1 V) in the absence of any external voltage. This happens as a result of some holes diffusing from the p side into the n side and some electrons diffusing from the n side into the p side. A counter force (opposite electric field) is produced by the sites vacated by the diffused holes and electrons, and it closely confines the boundary of this space charge on both sides of the junction. The p and n sides of this tiny electric field are both positive. Electrons are drawn from the n side to the p side and holes from the p side to the n side when the anode is turned positive to the cathode. Once the diffusion-induced tiny electric flow barrier is broken with a low voltage of less than L V, a large current can easily flow by drift with a high driving voltage. Due to the silicon's resistance, the voltage drop will increase with the current, reaching roughly 1.5-3.0 V at the maximum permitted current.

When the cathode becomes positive with the anode, electrons, and holes are drawn away from that side of the junction in the n layer and that side of the junction in the player, respectively. In an ideal diode, no conduction occurs because of the strong electric field that is produced near the junction, which is positive on the cathode side and negative on the anode side to counter the externally applied voltage. The depletion region refers to the area of the electric field that was created at the connection. The depletion region is thinner for higher doping and vice versa; the field is more intense for higher doping. The field is greatest at the junction in the depletion region.

The depletion layer expands as the reverse voltage rises, mainly on the nside, and the diode will fail if the reverse voltage is high enough to cause the depletion layer to spread out to the full width of the n- region. The holes turn into the minority carriers when they cross the boundary and enter the n layer during the conductionstate. The electrons likewise change from being the majority carriers as they move from the n to the p regions. As long as carriers from the doping sites dominate the conduction, the device is referred to be a minority carrier device.

In n-type power diodes, the n side is weakly doped (n-) at the junction, resulting in a wide depletion area on the n- side, while the p side is extensively doped (p*), resulting in a very narrow depletion region on the p* side. The nside expands significantly more than the pside when a reverse voltage is applied (making the cathode positive with the anode). To support the majority (nearly all) of the reverse voltage, the n-side is thickened. The n-layer might be only slightly doped, making the intrinsic carriers a sizable portion of the n-side carriers. The device's thickness is raised to support the larger depletion layer and provide a higher reverse voltage capability. The resistance and consequent on-state losses will rise as the thickness does as well. Because it extends past the depletion layer itself and corresponds to the applied field, the n-side is referred to as the drift zone. The reverse voltage causes a small number of heat carriers to diffuse and conduct electricity throughout the remaining thickness of the n-layer. Nearly all silicon-based products are designed for the device's biggest area to be of the n kind.

Although it is far from the junction and close to the end, where the cathode plate is linked, the n layer is likewise strongly doped (n*) in power diodes [Figure 1(c)]. The purpose of the ends' p+ and n* areas, which both contain a significant number of doping-based carriers, is to prevent the metal from being exposed to the depletion region during reverse voltage. The n* layer also plays the crucial role of starting to balance out the stress throughout the n- layer so that a larger voltage can be applied after the depletion layer approaches the n+ boundary. For the same "u" or" Doug" rating, this "punch-through" procedure allows for a reduction in the thickness of the layer, which in turn reduces on-state losses. The availability of carriers from the n* layer during forward conduction significantly reduces the on-state losses.

Several additional devices, which will be explored later, also employ this high doping on the n side right near the anode plate. The edge is contoured (physically and with a doping profile) and insulated for high-power diodes as well as other high-power silicon power devices to prevent edge flashover. The breakdown level of the environment at a device's edge is substantially lower (about 1/10th) than the voltage stress throughout the device's thickness, which explains why this is true. The device is packaged to provide sealed and robust wafer containment with adequate external insulation between the anode and cathode and good thermal contact between the wafer and outside for efficient heat removal from inside to outside. This Uoot does not discuss passivation, which is the transition from the silicon wafer edge to the atmosphere outside the edge. For all power electronics devices, packaging that successfully tackles a combination of electrical, thermal, and mechanical pressures is a significant challenge.'

In application circuits, the voltage across the diode often increases to a negative value as the current reaches zero after conduction. For a short time (microseconds or tens of microseconds), some reverse "u.r" it flows as a result, drawing out any excess internal charges and restoring the depletion layer corresponding to the applied reverse voltage. In voltage-sourced converters, these reverses current flow in diodes and causes an increase in the current required to turn on the turn-off devices, which in turn raises their turn-on losses. The diodes used in voltage-sourced converters in tandem with turn-off devices must therefore have a very quick turn-off and little stored charge. To attain greater speed and less stored charge, advanced diodes have been developed in terms of doping profiles, although they are not discussed here. Diodes that have been improved to have low reverse turn-off current will significantly reduce the price of voltage-sourced converters.

## DISCUSSION

### Transistor:

The transistor is a family, and by studying it, we can better understand it. Devices with three layers and two joints. Here are some fundamentals to understand the principles of high-power devices. The transistor functions similarly to one another. There are two different types of transistors with two p-n diode junctions stacked against each other:

The PNP transistor [Figure 2(a,b)], which is a stack of pn (diode) over np (reversed diode), results in a device with two players and an n layer in the middle. The cathode (collector) side p layer is narrow and strongly doped, while the anode (emitter) side p layer is formed of *id" material.

NPN transistor, which is a stack of an np (reverse diode) over a pn (diode) to create a device with a player in between two n layers (Figure 2(c,d)).If we only look at the NPN transistor, which is the favored kind for power transistors, the central player becomes the base, the other n layer is termed the collector, and one of the outside n layers is built with heavy doping (n*) to serve as the emitter.

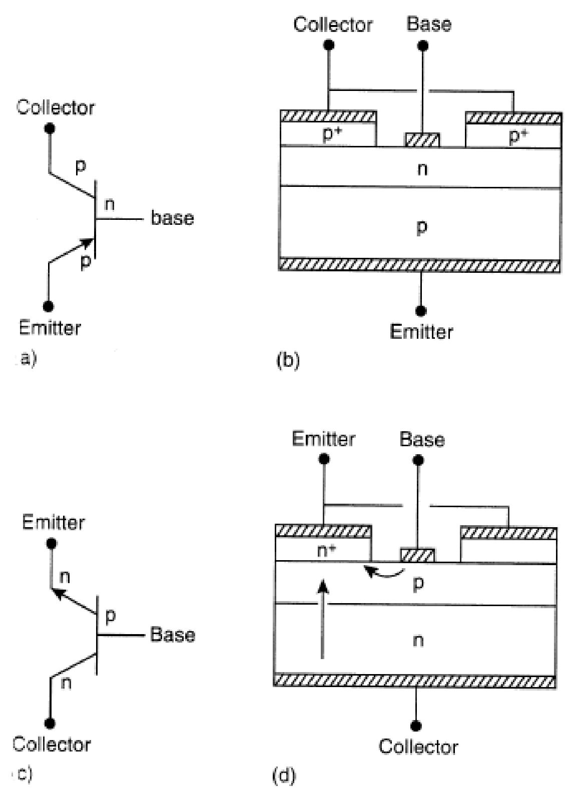


**Figure 2: Transistor: (a) transistor symbol (pnp), (b) pnp structure, (c) transistor symbol (npn), and (d) npn structure**.

No current flows when the collector is made positive concerning the emitter by an external driving voltage because the depletion layer created at the n-p junction on the collector side blocks the flow of current. By now doping the player, this junction is made to endure high voltage. Electrons now flow from the n+ "-itt" to the p 6'ur" (current from the gate to the emitter) if a further minor external voltage is supplied to the gate with the "gut" positive concerning the emitter. The electric field of the depletion layer accelerates electrons to the collector as they move from the n+ emitter to the base, causing current to flow through the device as indicated by the arrow in Figure 2(d).

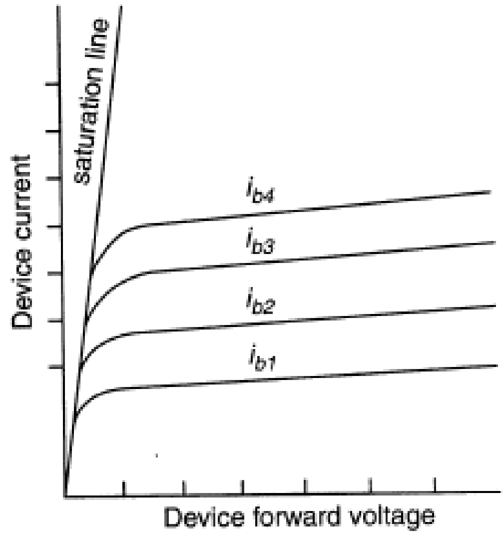


**Figure 3: Transistor voltage-current characteristic for different values of base current.**

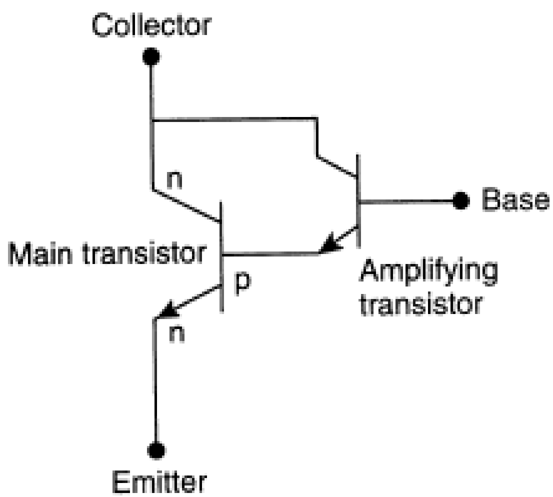


**Figure 4: Transistor with amplifying stage.**

The depletion layer voltage limits the current flow because the injected electron from the n+ layer is a function of the base current. For various base current values, Figure 3 displays the forward-conducting properties of device current vs device voltage. Device saturation is determined by the base current. The device current and forward voltage drop in a power device will be confined along the steep line on the left side of the curves in typical operation with a high base current, and the voltage drop and consequently the losses will be modest.

The device will be able to hold some of the voltage if the base current is restricted, but the device current will be constrained at the saturation line for the corresponding base current. In fact, this characteristic is employed in low-power converters to limit current during an external fault, after which the devices are quickly and safely turned off. It should be noted that the wafer is constructed for power devices in such a way that several gate connection lines are brought out through the top layer. As a result, a power transistor may actually have a lot of tiny devices connected in parallel. The devices are manufactured using an amplifying stage or stages due to the comparatively low gain (base-to-device current ratio) as seen in Figure 4. Darlin GTO n transistors are the name given to such transistors.

**MOSFET**

Transistors come in a variety of varieties. The so-called Metal-Oxide Semiconductor Field Effect Transistor (MOSFET), which is gate driven by the electric field (voltage) rather than current, is a type of transistor capable of quick switching speed and low switching losses. Capacitive coupling between the gate and the device is used to achieve this. Its construction and corresponding circuit are depicted in Figure 5. MOSFET is frequently utilized for applications requiring modest power (kilowatts) and is inappropriate for large power. However, as will be discussed later under, they are helpful tools when used in conjunction with sophisticated GTOs. Here is a basic explanation of MOSFET.

MOSFETs can be pnp or npn devices; Figure 5 exclusively depicts anNPN configuration. The n+ and p junction are separated from the gate metal by a silicon-oxide (SiO) dielectric layer. The main benefit of a MOS gate is that space charge is created around the small gate sections by applying voltage rather than current to the gate concerning the source to completely or partially block the device. Electrons from the n* layer are drawn into the p layer when the gate is given a suitably positive voltage concerning the emitter. This allows the current to move from the drain (collector) to the source (emitter) by opening the channel nearest to the gate.

To produce an n+ buffer behind the n- drift layer, the drain side of the MOSFET is severely doped. This buffer prevents the depletion layer from reaching the metal, balances the voltage stress across the n-layer, and lessens the forward voltage drop during conduction, as was covered in Section 2.4 on diodes. It is an asymmetrical device with a relatively poor reverse voltage capacity due to the buffer layer's inclusion. Low switching losses, high switching speed, and low gate energy requirements are all characteristics of MOSFETs. MOSFETs are great gate amplifying devices but unfortunately have high forward on-state resistance and high on-state losses, making them unsuitable for power applications[4]–[6]. The forward current-voltage characteristics of MOSFETs are identical to those of the transistor in Figure 4; the base current is substituted by the gate voltage, though.

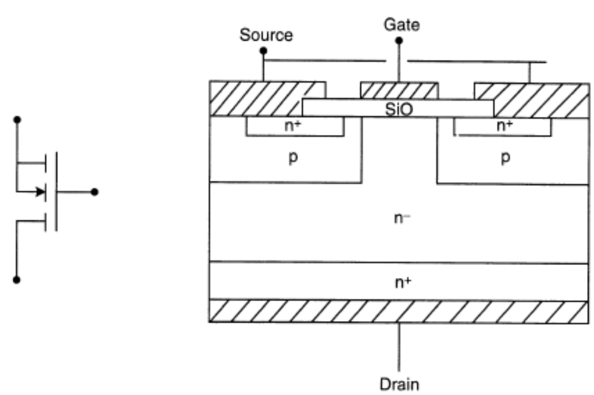


**Figure 5: MOSFET**

**Thermistor without turn-off capability**

The thermistor, Figure 6, is a four-layer, three-junction device. Its symbol is shown in Figure 6(a), and its structure is depicted in Figure 6(b). The thermistor is a unidirectional switch that latches into conduction with the lowest forward voltage drop of 1.5 to 3 V at its continuous rated current once activated by a trigger pulse. It cannot turn off its current; therefore, it can only return to its turned-off condition when an external circuit causes the current to flow to Zero. One of the workhorses of power electronics is the thermistor. Turn-off capability is not required in a vast number of applications. In comparison to a device with turnoff capability, the resulting device can have higher voltage and/or rating, cost less than half as much, require a simpler control circuit, have lower losses, etc. Therefore, where there is a clear application advantage, which is frequently the case with FACTS Controllers, as would be seen in earlier chapters, the decision will be made in favour of a more expensive and greater loss device with turn-of capabilities.

The thyristor is identical to the integration of two transistors, pnp, and npn, as seen in Figures 6(c) and (d). The upper NPN transistor begins to conduct when a positive gate trigger is applied to the p-gate concerning the n* emitter [cathode Figure 6(d)l. As seen by the arrows, a current flowing through the NPN transistor transforms into the gate current of the PNP transistor, causing it to conduct as well. The current flowing through this pnp transistor transforms into the gate current of the neighboring npn transistor, creating a regenerative effect that results in latching conduction with a minimal forward voltage drop, with the current flow effectively constrained by the surrounding circuit. What matters is that when the thyristor is turned on, the internal p and n layers get saturated with electrons and holes and behave like a short circuit in the forward direction due to the internal regenerative process into saturation. The entire gadget functions like a single pn junction gadget (a diode). Thus, although having three junctions, its forward on-state voltage drop is only one junction, as opposed to two junctions in transistor-type devices like the MOSFET and IGBT.

The diagram makes it clear that the n base of the lower transistor can also be used as the gate for turn-on, but the n base requires more current, hence the p base is typically used instead in thyristors. The thyristor is still loaded with electron and hole carriers in the center pn region when the current falls to zero (due to an external circuit), which must be eliminated or merged for the device to recover and be prepared to block the voltage when the current rises again. Fortunately, this stored charge is dissipated in real-world thyristor-based circuits by applying a negative voltage across the component right after the current zero, in addition to the slower process of charge carrier recombination until the point of thermal equilibrium. As a result, the turn-off time, which depends on the reverse voltage after current zero and can range from a few to a few tens of microseconds, must be carefully addressed for a given application. Before any positive power may be securely applied, this turn-off period must have passed.

The device can also be turned on by applying a positive anode to cathode voltage with a rapid rising time (du/dt). This occurs because the cathode's capacitive coupling to the gate's high Duldt and the resulting current is just sufficient to turn the device on.This is a risky approach to turning on a thyristor since it may happen at a weak point, spread slowly, and harm the component. If the forward voltage is too high, internal charge carriers will accelerate and create charge carriers in a weak area, leading to unsafe turn-on. This implies that a gadget may be developed with a purposefully created weak point from which a safe turn-on could be incorporated. Recent HVDC projects have featured such self-protecting and optional triggering mechanisms. Another crucial factor is that the anode-to-cathode forward voltagealso known as the rate of rise of voltagemust be sufficient to trigger a quick turn-on when a turn-on pulse is applied. Insufficient voltage can result in a gentle turn-on, where the voltage of the device steadily decreases as the current increases.

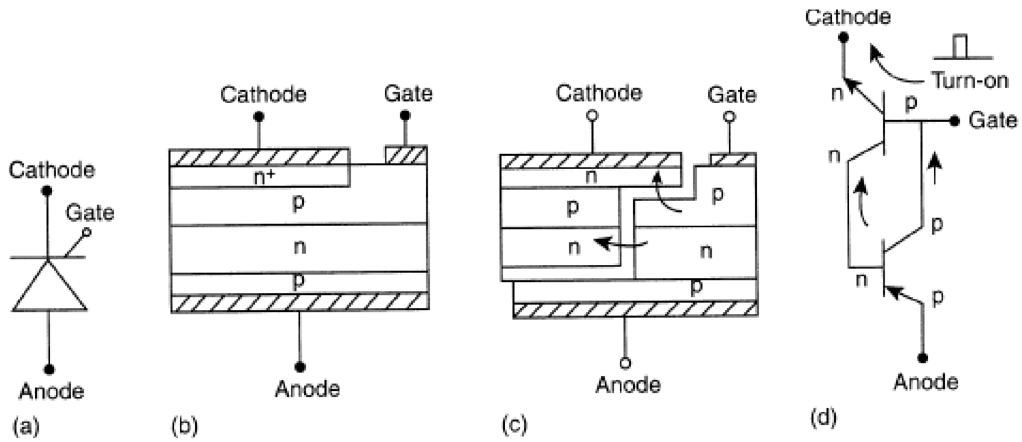


**Figure 6: Thermistor without turn-off capability (research gate)**

In some regions of the gadget, this can result in a high turn-on loss and potential damage. Depending on the application, the device must be built for the required minimum turn-on voltage, and if the forward voltage is insufficient, the turn-on pulse is suppressed. The thyristor has a negative temperature coefficient at high temperatures. Therefore, it needs to be built to guarantee a consistent internal turn-on and turn-off. Being a high-voltage device, it has both a significant number of intrinsic carriers and doping-based carriers. Higher temperatures result in more thermal carriers and therefore more total carriers, which reduces the forward voltage loss. A minimum anode-cathode current must be maintained once a thyristor is turned on in order to keep the device operational. This minimal current typically represents a small portion of the rated current. Typically, the gate drive is set up to send an additional turn-on pulse when necessary. Thyristors often have a high overload capacity. They may have 50 times fully offset short-circuit current for one cycle, two times typical over-current capability for several seconds, and ten times for numerous cycles.

**Gate Turn-Off Thermistor (GTO)**

The gate turn-off (GTO) thermistor is essentially comparable to the conventional thyristor, and the majority of the topics covered in Section 2.6 above also apply to GTOs. The GTO (Figure 7) is a latch-on and latch-off device, just like the thyristor. The typical GTO without the most current device advancements developed under various acronyms, which are covered in later parts, is the GTO that is discussed in this section. Consider the equivalent circuit, Figure 7(c), which is the same as the thyristor's circuit in Figure 6(c), with the exception that the turn-off has been added in parallel with the gate turn-on (the equivalent circuit merely shows arrows to indicate this). The npn transistor will be pulled out of the regenerative action if a high pulse current is sent from the cathode to the gate to remove enough charge carriers from the cathode, or from the emitter of the upper PNP transistor.

The device returns to a nonconducting state as the lower transistor is left with an open gate as the higher transistor goes off. However, a sizable amount of gate current is needed for the turn-off. For a L000 A device, the gate current pulse needed for turn-on may be as low as 3-5Vo, or 30 A, for just L0 ;r,sec, whereas the gate current needed for turn-off would be more along the lines of 30-50Vo, or 300 A or more, for 20–50 g.sec. Being a pulse of high current, the high-current pulse requires a low voltage to drive it (about 10–20 V).

The energy needed for turn-off is only 20 to 50 psec long. However, the losses are substantial enough to represent a substantial economic obligation in terms of cooling and losses. When taking into account the number of valves and turn-off occasions in a converter. The energy needed to turn on a GTO is 10 to 20 times greater than the energy needed to put it off, and vice versa for a thyristor. Turn-off circuits for GTO are comparable in price and size to the price of the actual device.

Another factor to take into account is that the gadget must be completely turned off for the turn-off to be effective. In contrast to thyristors, which have a single cathode and gate structure distributed over the entire device, successful GTO turn-off necessitates the division of the cathode into thousands of islands, each of which has its own gateline. A GTO is made up of a lot of thyristor cathodes that share a gate, drift area, and anode. Modern GTOs lack amplifying gates because of their complicated structural design. As a result, compared to a thyristor, the overall area on the device that may accommodate a cathode is reduced to around 50Vo. The forward voltage drop of a GTO is therefore around 50Vo higher than that of a thyristor but still 50Vo lower than that of an IGBT transistor with the same rating.

Although the general manufacturing method for GTOs is similar to that of thyristors, it necessitates a cleaner environment, may result in lower yields, and may cost up to twice as much for converters with the same ratings due to cathode and grid distribution issues. In the case of a thyristor, a GTO design involves trade-offs including voltage, current, di/dt, du/dt, switching times, forward losses, switching losses, etc. A fast recovery diode is linked in reverse across each GTO in voltage-sourced converters, which makes it unnecessary for GTOs to have reverse voltage capability. Other characteristics, particularly the voltage drop and higher voltage and current ratings, benefit from the tradeoffs that are also provided by this. This is accomplished by an n+ layer at the end of the nlayer known as a "buffer layer," which is strongly doped Asymmetric GTOs are these kinds of GTOs.

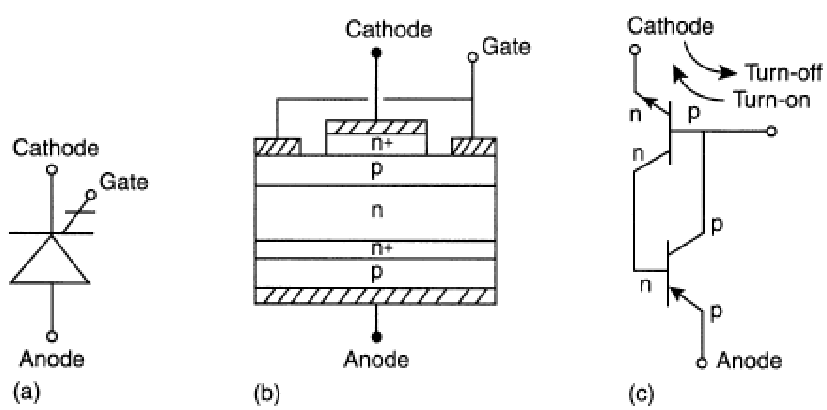


**Figure 7: Gate turn-off (GTO) thermistor (research gate)**

After accounting for the fault current requirements, the continuous operating junction temperature limit is similar to a thyristor at roughly 100oC. Similar to a thyristor, a GTO can withstand a high, brief overcurrent (10 times for one offset cycle) as long as it doesn't need to shut off the current. In order to prevent a flashover near the edge and reduce voltage stress, the edge needs to be passivated. Failure mechanisms are likewise comparable. Since the external system causes the current zero in a thyristor, the voltage across the device automatically shifts from positive to negative following the current zero. Contrarily, a GTO is turned off while the circuit is moving ahead when a GTO is present. Therefore, a dampening circuit is required to lower the rate-of-rise of forward voltage in order to achieve a successful turn-off. In a GTO, the pn- junction on the anode side is just mildly doped and built to support nearly all of the blocking voltage, mostly on the n- side. The cathode side pn junction, on the other hand, has significant doping on both sides, and its breakdown voltage may be around 20 V.

**Mos Turn-Off Thyristor (MTO)**

Power Semiconductor Devices MOS TURN-OFF THYRISTOR (MTO) the gate-drive power, snubber circuits, and dv/dt constraints of the GTO have all been addressed by SPCO by creating the MTO thyristor, a combination of a GTO and MOSFETs. To avoid the necessity for high-current GTO turn-off pulses, unlike IGBT (Section 2.I2), the MOS structure is not implanted on the entire device surface. Instead, the MOSFETs are placed all around the GTO on the silicon. For its benefits of high voltage (up to 10 kV), high current (up to 4000 A), and lower forward conduction losses than IGBTs, the GTO structure is virtually kept. The MTO becomes significantly more efficient than conventional GTO with the aid of these MOSFETs and tight packaging to reduce stray inductance in the gate-cathode loop. This results in smaller gate drives and shorter charge storage times on turn-off, improving performance and lowering system costs. The GTO continues to receive double-sided cooling as previously, and thin packaging technology makes it possible to remove heat from the GTO even more effectively.Figure 8 depicts the analogous circuit, its symbol, structure, and two gate structures—one for turn-on and the other for turn-off. The metal is directly connected to the p-layer for both gates. The same as in GTO, a turn-on current pulse that lasts for 5-L0 psec and is about one-tenth the size of the main current is followed by a short back-porch current to achieve turn-on. Turn on The upper npn transistor is turned on by a pulse, and the bottom PNP transistor is then turned on as well, resulting in a latched turn-on.

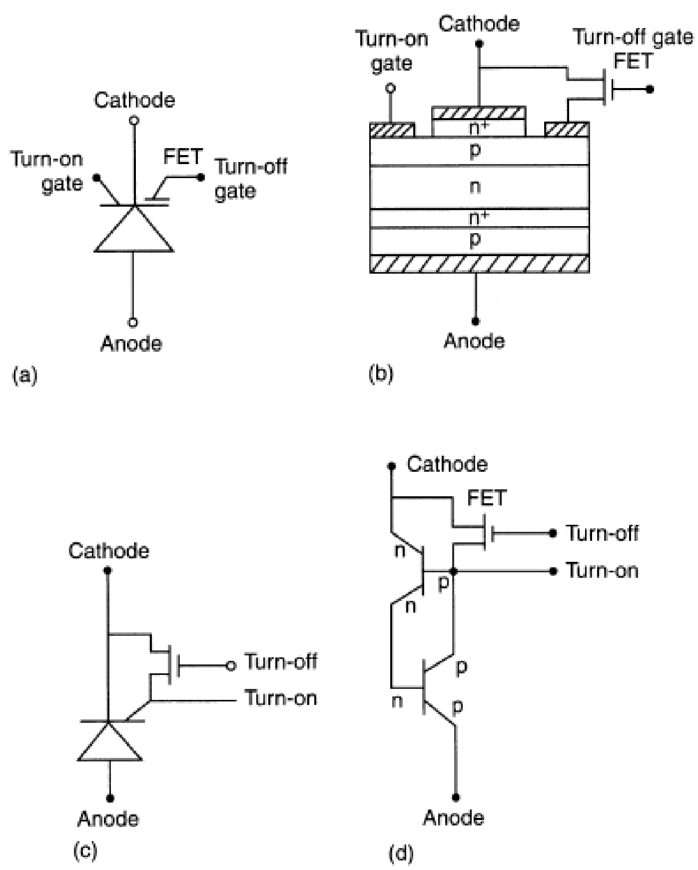

**Figure 8: MOS Turn-Off (MTO) thermistor (research gate).**

The MOSFETs are turned off by applying a single voltage pulse of roughly L5 V to their gates. This turns the MOSFETs on and shorts the NPN transistor's base and emitter, shunting off the latching process. Contrarily, as was previously discussed, the traditional GTO turn-off is accomplished by sweeping enough current from the upper NPN transistor's emitterbase with a strong negative pulse to cease the regenerative latching action. The turn-off can happen significantly faster with the new method (l-2 psec as opposed to 20-30 psec), and losses related to storage time are nearly completely avoided. Additionally, this entails high-duty, considerably smaller snubber capacitors, and the removal of the snubber resistor.

Small turn-off times allow MTOs to be linked in series without the need for device matching because almost all devices shut off at the same time, allowing each to use its fair share of the current. MOSFETs with a very low forward voltage drop are necessary for the quick turn-off because they are basically turned on in parallel to the GTO's gate cathode. MOSFETs are compact, reasonably priced, and extensively produced commercially. Fast turn-off of MTO and other high-tech GTOs can virtually make up for GTOs' lack of IGBT-like over-current protection, which will be covered on IGBTs.

**Insulated Gate Bipolar Transistor (IGBT)**

The Insulated Gate Bipolar Transistor (IGBT) is a contemporary power transistor. It functions as a transistor with a moderate forward voltage drop during conduction and high voltage and high current capabilities.The IGBT is a device that is halfway between being a transistor and a thyristor, but it is not intended to latch into full conduction, which would result in a voltage drop of one junction. Instead, it stays halfway between latching and becoming a transistor. A MOSFET-like integrated MOS structure with an insulated gate is also present. Figure 9 displays its structural cross-section and corresponding circuit. It features a two-transistor structure, just like the thyristor and the GTO. However, a MOSFET structure across its npn transistor controls the turn-on and turn-off instead of the upper NPN transistor's np gate emitter. The base and emitter of the NPN transistor flow current when it is turned on, similar to a thyristor, but not enough for the device to avalanche into latched conduction. As seen in Figure 9, a resistance that is incorporated into the design of the device shunts the base-emitter connection. Part of the cathode current is bypassed by this resistance rather than the entire current.

In the structural cross-section, the upper n+ is the MOS source of n carriers, p is the base, the lower p* is the buffer layer, and finally, the upper n+ is the substrate. The n-layer is the drift zone. Similar to a MOSFET, the NPN transistor comes on when the gate is biased positively concerning the emitter. This is accomplished by drawing n carriers into the p channel close to the gate area, which forward biases the base. The driver circuit for the IGBT is fairly straightforward because it only requires adding a positive base voltage to open the channel for n carriers and withdrawing it to close the channel in order to turn it off. Basically, if MOSFETs were also added for the turn-on, this could be accomplished in MTOs and ETOs. IGBTs are produced in sizes of approximately 1 cm2 due to the intricate MOS technology on the whole surface of the device. Several IGBTs are used to create high-power devices. In order to make them appear as one unit, they are wire-bonded, connected in parallel, and potted inside a bigger box.

The IGBT's advantage is its quick turn-on and turn-off since it functions more like an electronic device with a majority carrier (electrons). As a result, it can be utilized in high-frequency Pulse Width Modulation (PWM) Converters. However, because it is a transistor, it has a larger forward voltage drop than thyristor-type devices like GTOs. Nevertheless, the

IGBT has established itself as a workhorse for industrial applications and has grown to sizes that can support applications of at least 10 MW. By adjusting the gate voltage, transistor devices like MOSFETs and IGBTs may be able to limit the flow of current. Device losses are quite severe in this current-limiting mode, and current-limiting action can only be used for very brief durations of a few microseconds in high-power applications. However, this window of time may be sufficient to allow for the safe turn-off of the devices by enabling other preventative measures.

As a result of the existence of a sizable dc capacitor across the converter, fault current in voltage-sourced converters can grow to high levels very quickly. On the other hand, a quick turn-off can be accomplished in 2-3 microseconds thanks to quick sensing and the quick turn-off of improved GTOs. Additionally, this approach will prevent the devices from losing their usable capacity due to high-power dissipation. For high-speed protective turn-off, the traditional GTOs' turn-off time is too long. As the ratings of viable packed parallel-IGBTs rise, IGBT, which originates from a low-power end, has been displacing the traditional GTO. This is due to the major drawbacks of conventional GTOs, such as their high switching losses, slow switching, and high gate-drive needs. The evolution of the GTo into the MTo, ETo, and IGCT/GCT has demonstrated that these are the results of unresolved gate-drive packaging issues and stray inductance of the gate cathode loop[7]–[10].

IGBTs are subject to many general restrictions, such as a larger forward voltage drop, difficulties in supplying double-sided cooling, limitations imposed by the repeating MOS on the chip, and the necessity for a cleaner production facility. IGBTs have a lot going for them when it comes to high-power applications, including low switching losses, quick switching, and current-limiting ability. However, there is a chance for significant advancements for devices appropriate for a variety of FACTS Controllers with the upgraded GTOs and MCTs (described in the next section). The market dynamics of volume manufacturing, on the other hand, frequently determine future results, which is advantageous for IGBTs as they continue to push their applications to higher power levels.

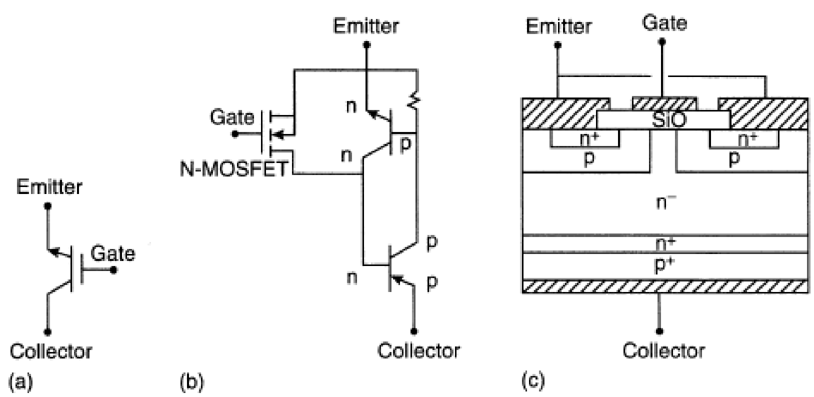


**Figure 9: Insulated Gate Bipolar Transistor (IGBT)**

MOS-Controlled Thyristor (MCT): A MOSFETlike structure is included in a MOS Controlled Thyristor (MCT) to enable both turn-on and turn-off of the device.An n-type MCT is shown in Figure 10. The equivalent circuit for the n-MCT demonstrates that similar to an IGBT, an n-type MOSFET (represented as an n-FET) is connected across the cathode side npn transistor for turn-on. Similar to an MTO, a second p-type MOSFET (depicted as a p-FET) is linked across the cathode side npn transistor's gate cathode for the turn-off. Current flows as the n-FET is turned on concerning the cathode the identical gate voltage is provided to the transistor that turns on p-FET remains off. The n-FET is turned off and the p-FET is turned on when the gate voltage is made negative. Bypassing the gate cathode in this way, the p-FET unlocks the thyristor. Because the MOS structure covers the full device surface, the device has a quick turn-on and turn-off with little switching losses. Both the delay time (storage time) and the amount of power/energy needed for the turn-on and turn-off are extremely minimal. Additionally, because it is a latching device, the on-state voltage loss is lower than that of a thyristor. Its processing technology is nearly identical to IGBT's.

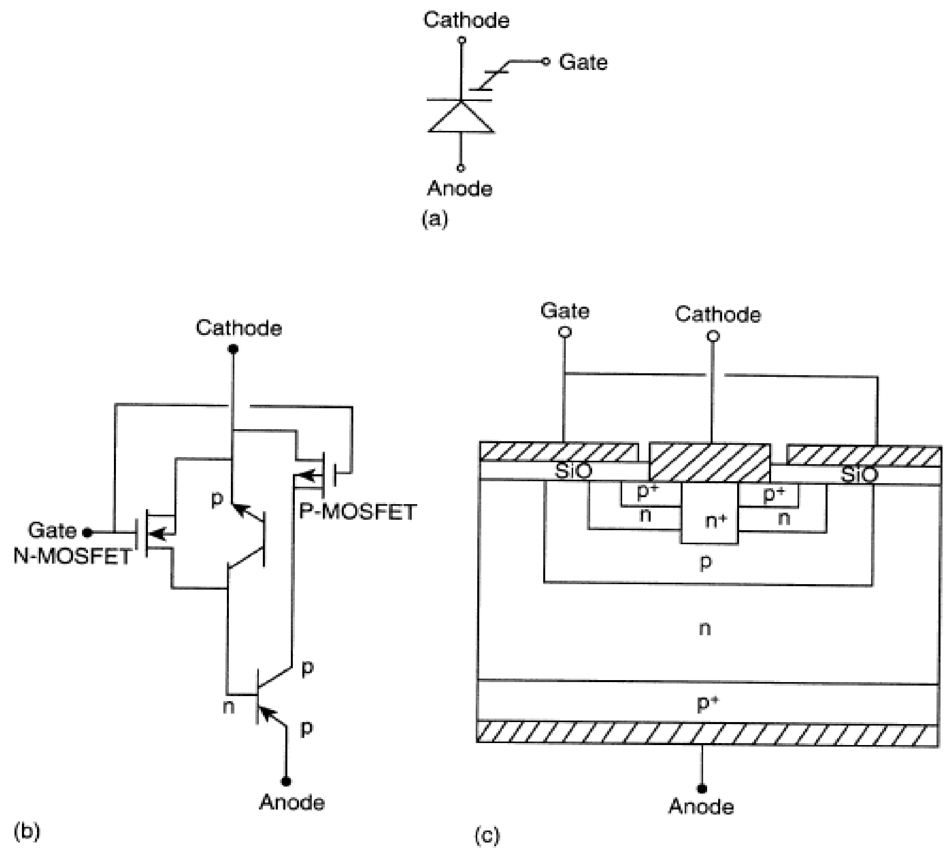


**Figure 10: MOS Controlled Thyristor (MCT)**

The main benefit of MCT over other turn-off thyristors is that it places distributed MOS gates, which are used for both turn-on and turn-off, extremely close to the distributed cathodes, enabling quick switching and minimal switching losses for a thyristor device. As a result, MCT is the almost perfect turn-off thyristor with the low on-state and switching losses, quick switching, and high-power advanced converters with active filtering capability that is required.

## CONCLUSION

The Power Electronics FACTs Controller, in summary, represents a major improvement in power system control and stability. It offers effective grid disturbance reduction, power flow control, and voltage regulation in AC power systems by utilizing power semiconductor devices and sophisticated control algorithms. The controller has several uses in transmission and distribution networks, the integration of renewable energy sources, and industrial power systems. As a result of its deployment, the grid is more stable, there is more capacity for transmission, there are fewer power losses, and the power quality is better. By easing the integration of renewable energy sources and enhancing overall system reliability and performance, the Power Electronics FACTs Controller significantly influences the future of power systems.

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CHAPTER 5

# APPLICATION OF THE VOLTAGE SOURCE CONVERTER

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**ABSTRACT:**

An essential part of power electronics systems, a voltage source converter (VSC) transforms electrical power between alternating current (AC) and direct current (DC) forms. It works by controlling the current flow while keeping a steady output voltage. An overview of voltage source converters is given in this chapter, along with information on how they function, how to manage them, and where they are used.The Voltage Source Converter (VSC), a vital part of contemporary power electronic systems, is essential for a number of applications, including flexible AC transmission systems (FACTS), the integration of renewable energy sources, and high-voltage direct current (HVDC) transmission. The Voltage Source Converter's key attributes and features are highlighted in this abstract, which gives a general understanding of the device. A power electronic device called the Voltage Source Converter transforms electrical energy between various voltage levels and waveforms. It is made out of bridge-shaped semiconductor switches, usually insulated gate bipolar transistors (IGBTs). The capacity of the VSC to deliver a high-quality output voltage waveform with adjustable amplitude, frequency, and phase is highlighted in the abstract. The main principle of operation of the VSC as a controlled voltage source is highlighted in the abstract. By synthesizing the required voltage waveform, it may convert direct current (DC) to alternating current (AC), allowing for effective power transmission and the grid integration of renewable energy sources. The VSC may also work in reverse, converting AC to DC, which is useful for systems like energy storage or power supplies.

**KEYWORDS:**

Full Wave Bridge Converter, Square Wave Voltage, Single Phase Full Wave Converter, Three Phase Full Wave Converter, Voltage Source Converter.

## INTRODUCTION

The voltage-sourced converter is the fundamental component of several controllers, including STATCOM, SSSC, UPFC, and IPFC, according to discussions on FACTS Controller ideas. Consequently, this converter is covered generally in this chapter. The so-called conventional thyristor device only has a turn-on control, as was stated, and its turn-off is dependent on the circuit and system conditions for the current to reach zero. Devices with the capacity to switch on and off include the Gate switch-Off Thyristor (GTO), Integrated Gate Bipolar Transistor (IGBT), MOS Turn-off thyristor (MTo), Integrated Gate-Commutated Thyristors (IGCT), and similar devices. However, turn-off devices enable converter concepts that can have considerable overall system cost and performance advantages. These devices, also known as turn-off devices, are more expensive and have higher losses than thyristors without turn-off capabilities. In contrast to line-commutating converters, self-commutating converters have these advantages in theory. The line-commutating converter differs from the self-commutating converter in that it requires an ac source to be attached, uses reactive power, and occasionally experiences commutation failures when operating as an inverter. Therefore, converters relevant to FACTS Controllers would be of the self-commutating type unless a converter is required to operate in only the two lagging-current quadrants (spending reactive power while converting active power). The two most common types of self-commutating converters are Current-sourced converters that reverse the polarity of the dc voltage and perform direct and power reversal through voltage-sourced converters that reverse the polarity of the dc voltage and perform direct and power reversal through current. The polarity of voltage, which is reversed from that of DC, is constant. Traditional thyristor-based converters can only be current-sourced since they cannot switch off, whereas turn-off device-based converters can be either type[1]–[3].

Voltage-sourced converters are frequently chosen over current-sourced converters for FACTS applications due to their efficiency and performance. In this chapter, several self-commutating voltage-sourced converter principles that are the foundation of multiple FACTS Controllers will be described. Asymmetric turn-off devices are those that do not require reverse voltage capability because the direct current in a converter with a voltage source can flow in either direction and the converter valves must be bidirectional because the dc voltage does not reverse. An asymmetric turn-off device, such as a GTO [as shown in Figure 1(a)], is combined with a parallel diode that is connected in reverse to provide a voltage-sourced converter valve. A parallel reverse diode may be included as part of some turn-off devices, such as IGBTs and IGCTs, making them suitable for voltage-sourced converters. However, having different diodes available is helpful for high-power converters. For high-voltage applications, numerous turn-off device-diode units would be connected in series.

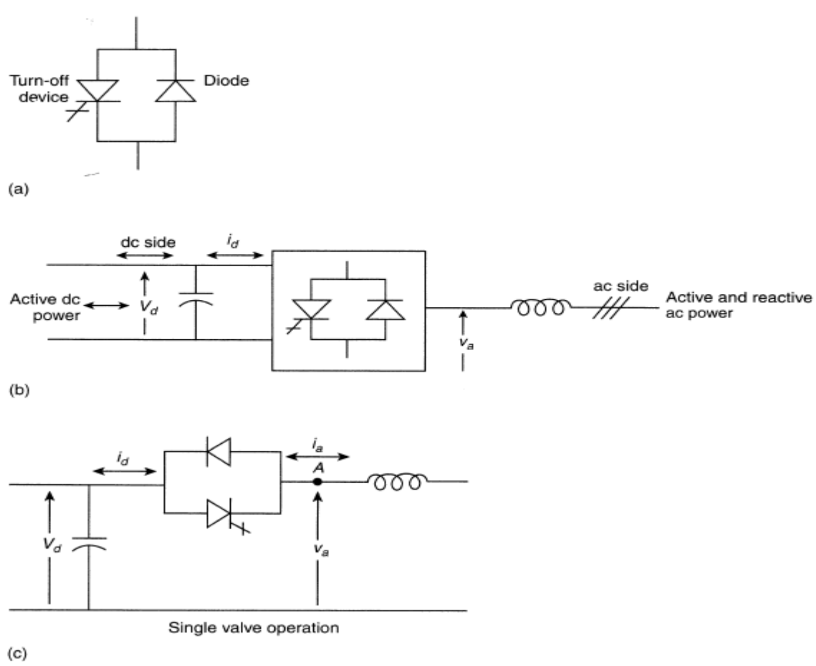


**Figure 1: Basic principles of voltage-sourced converters**

In general, a valve with the proper voltage and current rating needed for the converter will be represented by the symbol of one turn-off device with one parallel diode, as shown in Figure 1(a).Numerous different converter concepts fall under the heading of voltage-sourced converters. This chapter describes the ones that are pertinent to FACTS Controllers. Some converter topologies can only supply and consume reactive power and cannot convert active power; these converter topologies are not covered in this chapter.

The fundamental operation of a voltage-sourced converter is depicted in Figure 1(b). Converter valves' internal architecture is shown as a box with a valve symbol inside. Voltage is unipolar and sustained by a capacitor on the dc side. The switching sequence of the converter valves and changes in the phase angle of the switching valves provide sustained charge/discharge current, which may be handled by this capacitor, without a substantial change in the dc voltage. This chapter's explanation will assume that the dc capacitor voltage is constant. Additionally, it is demonstrated on the dc side that dc power can be exchanged with the connected dc system in either direction and that DC can flow in either direction. The generated ac voltage is shown connected to the ac system by an inductor on the ac side. Since the dc capacitor has a low internal impedance and is an ac voltage source, it requires a series inductive interface with the ac system (typically through a series inductor and/or a transformer) to prevent short-circuiting and rapid discharge into a capacitive load like a transmission line. To prevent additional current harmonics from entering the system side after the series inductive contact, an ac filter (not illustrated) may also be required.

A voltage-sourced converter essentially converts a dc voltage to an ac voltage. Despite having the ability to transfer electricity in either direction, it is frequently called an inverter due to historical reasons. The output voltage's magnitude, phase angle, and frequency can all be adjusted with a voltage-sourced converter.A sizable capacitor, with its positive polarity side linked to the anode side of the turnoff device, supports the DC voltage, v6, which is believed to remain constant. The positive dc terminal is linked to the ac terminal, A, when turn-off device 1 is turned on, causing the ac voltage to increase to +vd. If the current were to accidentally travel from +V to A (through device 1), power would invert from dc to ac (inverter action). Even if the device L is turned on, the current will still flow via diode 1' if it happens to flow from,4 to +Vd, causing power to transfer from the ac side to the dc side (rectifier action). Because the turn-off device can manage inverter action and the diode can handle rectifier action, a valve that combines both can handle power flow in either direction. Voltage-sourced converter notions start with this valve combination and its capacity to function as a rectifier or an inverter with the instantaneous current flowing in a positive (ac to dc side) or negative direction, respectively.

## DISCUSSION

**Single-Phase Full-Wave Bridge Converter:**

A popular power electronic circuit for converting from AC to DC is the single-phase full-wave bridge converter. It frequently appears in many uses, such as power supply, motor drives, and renewable energy systems. The single-phase full-wave bridge converter will be thoroughly explained in this article, along with its circuit design, modes of operation, voltage, and current waveforms, analysis, and control strategies. Configuration of the circuit: Four diodes are stacked in a bridge configuration to make up the single-phase full-wave bridge converter. The D1, D2, D3, and D4 diodes are linked together to create a bridge spanning the input terminals. The bridge's two input terminals are subjected to the AC input voltage, Vin. The load resistor (RL), which is linked in series with the output capacitor (C), is where the output voltage is measured.

Operation Modes: Two different operating modesthe positive half-cycle and the negative half-cyclecan be distinguished in the single-phase full-wave bridge converter's operation. Positive Half-Cycle Operation: The diodes D1 and D3 are forward biased while the diodes D2 and D4 are reverse biased during the positive half-cycle of the input voltage. As a result, the load resistor RL and diode D1 can both conduct current, causing a positive half-cycle voltage across the load. Negative Half-Cycle Operation: When the input voltage is negative, the diodes D2 and D4 move from being reverse-biased to being forward-biased. As a result, the load resistor RL and diode D4 can both conduct current, causing a negative half-cycle voltage across the load.

Voltage and Current Waveforms: The single-phase full-wave bridge converter's voltage and current waveforms are dependent on the input voltage and the characteristics of the load. The output voltage across the load resistor is positive during the positive half-cycle and negative during the negative half-cycle. However, the relationship between the input and output voltages is always proportional. Analysis of the Converter: Several parameters and equations can be obtained to examine the single-phase full-wave bridge converter's operation. These include the load current ripple, the output voltage ripple, the RMS output current, and the average output voltage. The calculations assume constant current flow via the load resistor while taking ideal diode behavior into account. Average Output Voltage: The instantaneous output voltage can be integrated over a half-cycle and divided by the duration of the input voltage waveform to determine the single-phase full-wave bridge converter's average output voltage. The output is inversely proportional to the input voltage's peak value.

RMS Output Current: By examining the current passing through the load resistor, the converter's RMS output current can be ascertained. It is based on the input voltage, the diodes' conduction angle, and the load resistance. Output Voltage Ripple: The output voltage ripple is the change in output voltage's magnitude brought on by the converter's pulsing behavior. The output voltage waveform's peak-to-peak value can be used to calculate it.

Load Current Ripple: The variation in load current magnitude brought on by the diode current's discontinuous nature during switching transitions is known as load current ripple. Analyzing the current passing through the load resistor will reveal it.

Control methods: Control techniques such as pulse width modulation (PWM) can be used to generate a regulated DC output voltage. PWM control regulates the output voltage by altering the duty cycle of the switching signal applied to the converter. The average output voltage can be changed, allowing for precise regulation, by altering the duty cycle[4]–[6].

One of the most important circuits for converting AC to DC is the single-phase full-wave bridge converter. Four diodes are used in a bridge configuration during operation to rectify the AC input voltage. A pulsing DC output voltage from the converter can be further controlled using methods like PWM. For building and executing effective power electronic systems in a variety of applications, it is essential to comprehend the single-phase full-wave bridge converter's features and mode of operation.

Single-phase leg pole operation: Now observe how Figure 2's single-pole (single-leg) circuit functions. In this circuit, the capacitor is divided into two series-connected halves, with the ac side's neutral point linked to the dc capacitor's midway N. The ac voltage waveform is a square wave with Val2 as the peak voltage as the two turn-off devices alternately close and open. The ac square wave is the sum of the two halves of Figure 2 (b) when two phase-legs are operated in a full-wave bridge mode, providing a peak voltage of Va.The neutral connection is no longer required in a full-wave circuit because the other phaseleg serves as the current's return channel.

The phase relationship between the voltage and the current in an AC converter can be in any of the four quadrants, acting as an inverter or a rectifier with leading or lagging reactive power. To exchange real power, it is assumed that a dc and an ac system are connected on both sides of the converter, as shown in Figure 2(b). Should the converter be used exclusively for reactive power, in which case the dc system is not required, and the converter will end at the dc capacitor. With control over the magnitude and angle of the converter-generated ac voltage concerning the AC, the active and reactive power can be independently adjusted. The immediate rectifier function is performed by diodes, while the instantaneous inverter function is performed by turn-off devices.

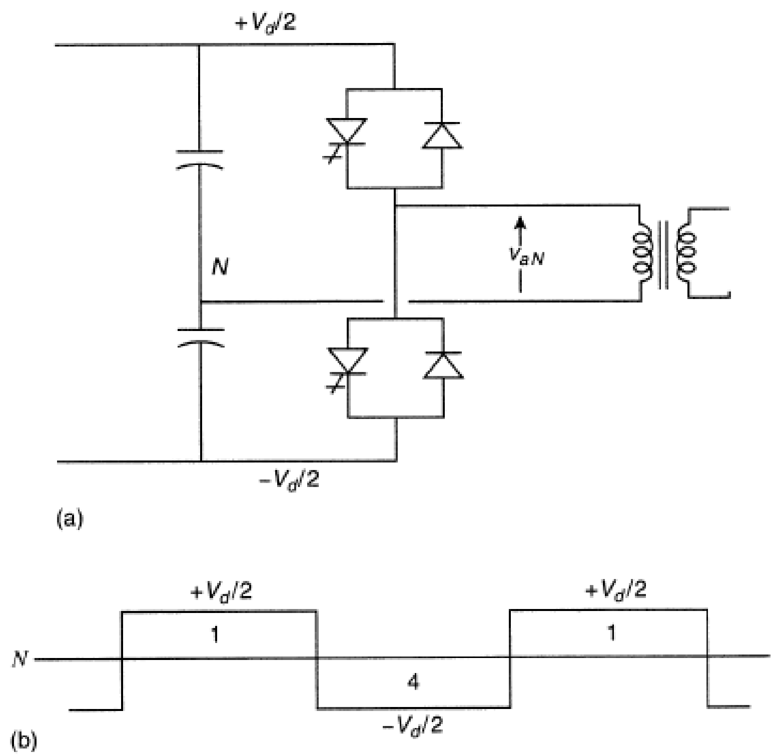


**Figure 2: (a) One-phase-leg circuit; (b) Output ac voltage.**

The average current controls the net power flow and, consequently, the net rectifier or inverter operation. Each ac cycle is made up of periods of rectifier and inverter activities in line with the phase angle. Only diodes are engaged in conduction when the converter operates as a rectifier with a unity power factor, and only turn-off devices are involved in conduction when the converter operates as an inverter with a unity power factor. The ac bus current is not directly interrupted when any turn-off device shuts down but rather is moved from one turn-off device to a diode when the power factor is less than unity, and from one turn-off device to another when the power factor is greater than unity. switch-off devices 1 and 4 (or 2 and 3) in the same phaseleg do not switch on at the same time. The devices in that phase-leg would be destroyed if this didn't happen because it would result in a "shoot-through" (short circuit) of the dc side and a very quick discharge of the dc capacitor through the shorted phase-leg. When one turn-off device in a phaseeg is on, the other is off. The gate control is set up to guarantee that only one of the two devices in a phaseleg receives a turn-on pulse and that the other device's current was zero. In any case, sensing and protection mechanisms are included, often to guarantee the converter's safe shutdown. With the two valves in each phase-leg flipping back and forth, each phase-leg is individually capable of working at any frequency or timing. Although being linked to the ac system, any number of phase-legs can theoretically be connected in parallel and each operated independently, there is a requirement for proper sequence and system interface through transformers to obtain the requisite converter performance. It is crucial to remember that switching on and off turn-off devices only establishes the voltage waveform of the ac bus voltage concerning the dc voltage and does not necessarily conduct current if the current flow results in a corresponding diode to carry the current.

**Square wave voltage harmonics for a single-phase bridge:**A common power electronic circuit for converting AC (alternating current) to DC (direct current) is a single-phase bridge. For the purpose of evaluating the circuit's performance, it is essential to comprehend the harmonics that are present in the output voltage waveform. The analysis of square wave voltage harmonics in a single-phase bridge circuit is the main topic of this article. We will look into harmonic content, calculating techniques, and their importance in real-world scenarios.

Voltage in a square wave: The output voltage waveform in a single-phase bridge circuit is not a smooth sinusoidal waveform but rather a series of pulses. These pulses are separated by a brief period of time and have equal positive and negative amplitudes. As a result, a square wave voltage with a period equal to the input frequency is produced. Square Wave Voltage Harmonics Harmonics are frequency components that are integer multiples of the fundamental frequency present in a square wave voltage. The fundamental frequency of a single-phase bridge is the same as the input AC frequency. The square wave waveform's jagged edges and discontinuities are what cause the harmonics to arise.

Calculation of Harmonic Components: Fourier analysis is frequently used to identify the harmonic components in a square wave voltage. We can separate a complex waveform into its distinct sinusoidal components using the Fourier analysis. The Fourier series expansion offers a mathematical representation of the waveform in terms of its harmonics for a square wave voltage.

$$V(t) = (4/pi) * [\sin(wt) + (1/3)\sin(3wt) + (1/5)\sin(5wt)]$$

where V(t) is the instantaneous voltage at time t, w is the fundamental angular frequency, and the terms inside the brackets represent the harmonic components.

Harmonics' Importance: In practical applications, the existence of harmonics in a square wave voltage can have a big impact. Several crucial considerations include: Harmonics cause the output voltage waveform to deviate from a clean square wave and cause distortion. The performance of connected devices may be impacted by this distortion, increasing losses.

Electromagnetic Interference (EMI): Harmonics can produce high-frequency components known as electromagnetic interference (EMI), which can impair the performance of other delicate electronic devices.

Filter design: To reduce the impacts of harmonics, the right filtering methods must be used. Filters are used to reduce undesirable harmonics and make sure the output voltage adheres to the necessary standards.

Efficiency and Power Losses: Harmonics cause an increase in the voltage waveform's RMS (root mean square) value, which increases power losses in the converter circuit and lowers overall efficiency.

Voltage Regulation: Harmonics have an impact on how the output voltage is regulated. Higher-order harmonics can cause voltage levels to deviate from the required range, which can affect the performance of associated loads.

A single-phase bridge circuit's performance and effects on linked devices must be understood by analyzing the harmonics in the output voltage waveform. The existence of harmonics in a square wave voltage generates distortion, EMI, and power losses, which must be mitigated by proper filter design and voltage regulation techniques to guarantee the circuit's dependable performance. Engineers may develop effective and reliable power electronic systems for a variety of applications by knowing the harmonics.

**Three phase full wave converter:** A power electronic circuit used to transform three-phase AC power into DC power is called a three-phase full-wave bridge converter. It is extensively utilized in many different applications, such as motor drives, renewable energy sources, and industrial power supply. In this explanation, we'll go over how a three-phase full-wave bridge converter works and its essential parts. In contemporary electrical systems, power electronic converters are crucial components for effective power conversion. To satisfy particular power needs, they are utilized to transform one type of electrical energy into another. A particular kind of power electronic converter that transforms three-phase AC power into DC power is called a three-phase full-wave bridge converter. It is renowned for its excellent effectiveness, small size, and capacity for handling large amounts of power.

Components: A three-phase full-wave bridge converter is made up of a number of essential parts. These include load resistors, smoothing capacitors, and three-phase diode rectifiers.

Three-Phase Diode Rectifiers: The major power electronic switches in the converter are made up of a bridge configuration of diode rectifiers. The conversion of AC power to DC power is made possible by the single-direction current flow that each diode permits. The bridge structure of the diodes allows them to accommodate three-phase AC input power. With this setup, a path for current flow is always there, resulting in constant DC output voltage.

Smoothing Capacitors: To the output of the diode rectifiers, smoothing capacitors are connected in parallel. These capacitors aid in lowering the output DC voltage's ripple content. The smoothing capacitors are charged to the peak voltage of the input AC waveform as the diode rectifiers conduct. A smoother DC output is produced as a result of the capacitors' stored energy being used to power the load during the non-conduction phase.

Load Resistors: The load resistors serve to represent the load attached to the converter's output. A DC motor, an industrial drive, or any other device requiring DC power can serve as the load. In the case of a motor, the load resistors transform the electrical energy into mechanical energy. The load resistors' value controls the output voltage level and the current that flows through the converter.

Operation: A three-phase full-wave bridge converter's functioning can be broken down into two different modes: the positive half-cycle and the negative half-cycle. First, let's think about the positive half-cycle:

Positive Half-Cycle: One of the three diode pairs conducts electricity during the positive half-cycle of the AC input waveform. The load resistors and the smoothing capacitors can both conduct current thanks to the conducting diodes. As a result, the capacitors are charged to the peak voltage of the AC waveform and the load receives power from the AC source. Throughout this half-cycle, the other two pairs of diodes are kept in a non-conducting state.

Negative Half-Cycle: During the AC input waveform's negative half-cycle, the conducting diode pairs go from conducting to non-conducting while the previously non-conducting pairs begin to conduct. By switching the diodes, a conduit for current passage is always present. A continuous DC output voltage is produced by the load resistors and smoothing capacitors continuing to power the load. During the times when the diodes are not conducting, power is provided by the energy stored in the smoothing capacitors.

Advantages: The full-wave bridge converter for three phases has the following benefits:

High Efficiency: The converter has a high overall efficiency due to the low power losses of the diode rectifiers it uses.

Compact Size: Because the compact bridge design has a lower physical footprint, it is appropriate for applications where space is at a premium.

High Power Handling Capability: Due to the converter's high power handling capacity, it is appropriate for industrial applications.

Simplified Control: Compared to other power electronic converters, the converter does not require complex control techniques, which makes it inexpensive and simple to use.

Applications: The three-phase full-wave bridge converter is used in a variety of situations, such as:

Motor Drives: To convert three-phase AC power to DC power for driving DC motors, converters are frequently employed in motor drive systems.

Renewable Energy Systems: The converter is used to transform the AC electricity produced by renewable energy sources, such as wind turbines and solar power plants, into DC power for grid connection or battery charging.

Industrial Power Supplies: To power industrial machinery and equipment, industrial power supplies use the converter to transform three-phase AC electricity to DC power.

A power electronic circuit known as a three-phase full-wave bridge converter transforms three-phase AC power into DC power. It is made up of load resistors, smoothing capacitors, and diode rectifiers. When the AC input waveform is in its positive and negative half-cycles, the converter conducts current through its diodes. It has benefits like high efficiency, small size, great capacity for handling power, and straightforward control. The converter is used, among other things, in industrial power supplies, renewable energy systems, and motor drives.

**Fundamental and harmonics for a Three phase bridge converter:**A power electronic circuit called a three-phase bridge converter is used to transform three-phase AC power into DC power. It produces both fundamental and harmonic components while in operation. In this discussion, we'll go through the features and consequences of the fundamental and harmonic parts of a three-phase bridge converter.

Essential Element: The output of a three-phase bridge converter's base frequency component is referred to as the fundamental component. The fundamental frequency of a three-phase system is commonly either 50 Hz or 60 Hz, depending on the location. To supply the necessary DC power to the load, the main converter output component is crucial.

Characteristics:

Magnitude: The converter's input voltage or current as well as the load it is linked to determine the magnitude of the fundamental component. The magnitude of the primary component depends on the DC output voltage or current that the converter is intended to deliver.

Frequency: The fundamental component's frequency, which is commonly 50 Hz or 60 Hz, matches that of the incoming AC power source. At this frequency, the converter sends energy from the input source to the load.

Power: The fundamental component's ability to transfer power from the AC source to the DC load is what makes this possible. It is essential for the converter and related load to operate properly.

Effects: A three-phase bridge converter's core part has the following effects:

Electricity conversion: The key element transforms three-phase AC electricity into DC power, giving the load the necessary power. It is in charge of the converter's main power transfer.

Load Operation: Operating a connected load, such as a motor or industrial device, at the specified voltage or current level is made possible by the basic component. It supplies the energy required for the load to operate properly[7]–[10].

Harmonic Components: In the output of a three-phase bridge converter, harmonic components are non-fundamental frequency components. These integer multiples of the fundamental frequency can have a big impact on the converter and the system it's linked to.

Characteristics:

Frequency: The frequencies of harmonic components are multiples of the fundamental frequency. The multiple of the fundamental frequency is represented by the harmonic order (e.g., second harmonic, third harmonic, etc.).

Amplitude: The converter design, the characteristics of the load, and the caliber of the AC power source used as the input all affect the harmonic components' amplitude. Current or voltage distortions may be caused by harmonics.

Power: Harmonic components transfer power, but in comparison to the fundamental component, their share of the total power transmission is quite modest. Harmonics, however, can result in power losses, lower system effectiveness, and more heating of the converter and other linked equipment.

Affects: A three-phase bridge converter's harmonic components have a number of affects.

Voltage and Current Distortion: Harmonic distortion of the output voltage and current waveforms might cause them to deviate from their ideal sinusoidal shape. Increased line losses, decreased system efficiency, and interference with other electrical equipment are just a few issues that might result from this distortion.

Electromagnetic Interference (EMI): Harmonics produce additional electromagnetic emissions that can interfere with neighboring electronic devices or other systems due to electromagnetic interference (EMI). To reduce EMI problems, electromagnetic compatibility (EMC) standards compliance becomes essential.

Overloading and Resonance: In some circumstances, harmonics can result in resonances in the system, overloading and harming specific components. When the harmonic frequencies and the natural frequencies of the system or its elements coincide, resonance results.

Issues with power quality: Harmonics have an impact on the system's overall power quality. It may result in worse power factor, voltage flicker, and greater harmonic distortion. Power quality issues can interfere with the functioning of delicate machinery and increase the cost of system maintenance and corrective actions.

Mitigation: Several steps can be done to reduce the effects of harmonic components in a three-phase bridge converter system:

Filtering: By lowering the harmonic content of the output waveform, filters such as passive harmonic filters or active power filters can enhance power quality and lessen distortions.

Harmonic Principles: Harmonic content in the system is kept within acceptable bounds by adhering to harmonic standards, such as IEEE 519 or IEC 61000-3-2, reducing its effects on the system and other connected equipment.

Load Design: Designing the load properly can assist reduce harmonic effects when it comes to the converter. System performance can be increased by reducing harmonic generation by choosing equipment with strong harmonic tolerance and putting power factor correction procedures into practice.

System Design: Harmonic effects can be reduced by using an ideal system design that takes into account component sizing, grounding, and careful layout. Harmonic variables are taken into account throughout the design phase to help guarantee the system runs effectively and consistently.

The output of a three-phase bridge converter produces both fundamental and harmonic components. While harmonic components can result in interference, power quality problems, and distortions, the fundamental component is responsible for the majority of the power transmission from the AC source to the DC load. For building and running effective and dependable three-phase bridge converter systems, it is essential to comprehend the properties and impacts of the fundamental and harmonic components. Harmonics' negative effects on the system and related equipment are lessened by mitigation methods such filtering, standard compliance, load considerations, and system design considerations.

**Three level voltage source converters:** An example of a power electronic equipment used to convert electrical energy between AC and DC systems is a three-level voltage source converter (VSC). In comparison to conventional two-level converters, it has a number of benefits, including better performance, fewer switching losses, and lower harmonics. We will go into detail about a three-level voltage source converter's operation, essential parts, control schemes, benefits, and applications in this explanation.

Operation: A three-level VSC's operation entails switching between three levels of voltage across its output terminals: positive, zero, and negative. Power semiconductor components, such as integrated gate-commutated thyristors (IGCTs) or insulated gate bipolar transistors (IGBTs), are used in conjunction with the right control techniques to achieve this.

**Key Elements: Among the Essential Elements of a Three-Level VSC Are**:

**Power Semiconductor Devices:** To regulate the current and voltage flows in the VSC, power semiconductor devices are used as the switching elements. To produce the desired voltage waveform, certain components, such as IGBTs or IGCTs, are stacked in a particular way.

**DC Capacitors:** Parallel connections are made between DC capacitors and the VSC's DC terminals. They contribute to the DC voltage's averaging and give the converter a reliable voltage supply.

**Control System:** The VSC's control system is essential in regulating how the power semiconductor devices are switched on and off. To accomplish the intended performance, it regulates the control settings, guarantees proper synchronization with the AC grid, and watches the output voltage or current waveform.

**Control Strategies:** In order to attain optimal performance, a three-level VSC employs a variety of control mechanisms. Among the often-employed control methods are:

**Pulse Width Modulation (PWM):** To create the desired output voltage waveform in three-level VSCs, PWM is frequently utilized. To regulate the average output voltage, switching pulses that are supplied to power semiconductor devices are varied in width. PWM methods can vary, including carrier-based PWM and space vector modulation.

**Phase-Shifted PWM:** This control method involves changing the phase of the switching pulses that are applied to the various converter legs. This method lessens the harmonic content of the output waveform and assists in balancing the voltage across the various levels.

**Advantages:** Comparing the three-level VSC to conventional two-level converters, there are various benefits to be had:

**Reduced Harmonics:** The three-level VSC's additional voltage levels lead to a reduction in the amplitude of harmonics in the output waveform. Improved power quality, lower losses, and less strain on linked equipment are the results of this.

**Lower Switching Losses:** In a three-level VSC, switching losses are minimized due to the reduced voltage stress across the power semiconductor devices. As a result, there is less of a need for elaborate cooling systems and the converter's overall efficiency is increased.

**Performance Improvement:** The three-level VSC's improved control over output voltage waveform enables improved performance. It makes it possible to have less voltage sag, a better power factor, and better voltage management. This qualifies it for uses that call for high-quality power conversion.

Applications: The three-level VSC is used in a variety of contexts, such as:

**Renewable Energy Systems:** The three-level VSC is used to connect the generators' AC output to the grid in renewable energy systems like wind farms and solar power plants. It makes grid synchronization, power quality control, and efficient power transfer possible.

High-Voltage Direct Current (HVDC) Transmission: For long-distance transmission, HVDC transmission systems use three-level VSCs to transform AC power into high-voltage DC power. The use of three-level VSCs enhances system stability, reduces losses, and provides for better management of power flow.

**Motor Drives:** To provide variable speed control and effective power conversion for AC motors, three-level VSCs are employed in motor drive applications. They facilitate harmonic distortion reduction, smooth torque management, and enhanced motor performance.

**Active Filters:** Three-level VSCs can be used as active power filters to reduce harmonics and enhance the quality of the power in commercial or industrial power systems. In order to actively reduce harmonic distortions in the system, they actively inject counteracting currents to cancel out harmonics produced by nonlinear loads.

A power electronic device that offers three voltage levels in its output waveform is known as a three-level voltage source converter, and it has benefits like lowered switching losses, lowered harmonics, and increased performance. It works by varying the voltage between positive, zero, and negative levels between its output terminals. Three-level VSCs are suited for a variety of applications, including renewable energy systems, HVDC transmission, motor drives, and active power filters thanks to their control techniques, essential components, and advantages. In contemporary electrical systems, these converters are crucial to delivering effective and dependable power conversion.

**Pulse width modulation converter:**A common power electronic circuit is the Pulse Width Modulation (PWM) Converter, which regulates output voltage or current by changing the width of the pulses sent to the load. It is used in many different applications, such as power supplies, renewable energy systems, and motor drives. The workings of PWM converters, modulation methods, control schemes, benefits, and applications will all be covered in this discussion.

Working Theory: The average output voltage or current of a PWM converter is controlled by the creation of a train of pulses of varying widths. The duty cycle of the pulses can be changed by modifying the pulse width, giving rise to the appropriate average value.

Three components make up the PWM converter:

**Modulator:** Depending on the intended output waveform, the modulator generates pulses with varied widths. The modulated output pulses are produced by comparing a reference signal with a high-frequency carrier signal, such as a sinusoidal waveform or a voltage reference.

**Comparators:** To calculate the on and off periods of the pulses, the comparators compare the carrier signal and the reference signal. The breadth of each pulse is represented by a digital signal that they produce.

**Power Switches:** The output of the comparators is used to operate power switches, such as transistors or IGBTs. The required average output voltage or current is produced by controlling the connection and disconnection of the load from the source of the input voltage.

Modulation Methods The modulated output pulses are produced by PWM converters using a variety of modulation schemes. Some approaches that are frequently used are:

**Carrier-Based PWM:** In carrier-based PWM, the reference signal is contrasted with a high-frequency carrier signal that has a set amplitude and frequency. By contrasting the reference signal's instantaneous value with the carrier signal, the pulse width is calculated. The modulated pulses that are produced have varied widths that match the reference signal.

**Sinusoidal PWM:** This approach uses a sinusoidal waveform as the reference signal. Typically, the carrier signal has a triangle waveform. The carrier signal is compared to the reference signal, and the pulse width is modified as necessary. Comparing sinusoidal PWM to carrier-based PWM, the former offers higher harmonic performance.

**Space Vector Modulation (SVM):** Space vector modulation is a more sophisticated approach that offers better resolution and less harmonic distortion. In a two-dimensional vector space, the three-phase reference signals are represented. The modulation procedure determines the power switches' ideal switching states to produce the required output waveform.

**Control Strategies:** PWM converters use a number of different control algorithms to precisely control the output voltage or current. Among the often employed control methods are:

**Voltage Mode Control:** By comparing the output voltage to a reference value and modifying the duty cycle of the pulses as necessary, voltage mode control controls the output voltage. Even when the load or input voltage varies, it keeps the desired voltage level. In order to continuously monitor the output voltage and modify the modulation as necessary, feedback loops are required.

**Current Mode Control:** By comparing the output current to a reference current, current mode control controls the output current. In motor drives and power supplies where accurate current control is necessary, this control method is frequently employed. It offers quick response times and strong dynamic performance.

**Advantages:** PWM converters have a number of benefits over alternative control strategies in power electronic systems.

**Precise Control:** PWM converters give the output voltage or current a precise amount of control. The average value may be precisely controlled by altering the pulse width, enabling precision load regulation.

Efficiency: Because PWM converters may switch power devices between completely on and totally off states, they provide excellent efficiency. By doing this, power losses are reduced and total system efficiency is raised.

**Reduced Harmonics:** When compared to other control techniques, PWM converters create output waveforms with less harmonic distortion. The harmonic content can be reduced, resulting in better power quality, by choosing the right carrier frequency and modulation method.

**Flexibility:** PWM converters allow for the flexible control of a variety of parameters, including voltage, current, and power factor. They provide control over a wide variety of operating points and can adjust to different load circumstances.

Applications: PWM converters are widely used in a number of industries, such as:

Motor Drives: To regulate the speed and torque of electric motors, PWM converters are frequently employed in motor drive systems. The average voltage or current applied to the motor can be changed by varying the duty cycle of the pulses, allowing for fine speed and torque control.

Power Supplies: PWM converters are employed in power supplies, such as AC-DC rectifiers and DC-DC converters, to deliver regulated and stable output voltage or current.

Renewable Energy Systems: PWM converters are essential components of renewable energy systems, such as solar photovoltaic (PV) inverters or wind turbine converters, since they provide high efficiency and accurate voltage regulation. They transform the renewable energy source's DC output into AC power that can be utilized locally or sent into the grid. Uninterruptible Power Supplies (UPS): PWM converters are used in UPS systems to supply backup power during utility outages. UPS stands for Uninterruptible Power Supplies. To power essential loads, they transform DC electricity from batteries into AC power.

Pulse width modulation (PWM) converters are common power electronic circuits that adjust the width of the pulses applied to the load to change the average value of the output voltage or current. They provide flexible operation, decreased harmonics, great efficiency, and accurate control. PWM converters are used, among other things, in motor drives, power supply, solar energy systems, and UPS systems. Power electronic systems may be accurately regulated and operated with great efficiency thanks to the numerous modulation techniques and control schemes. Modern power electronics rely heavily on PWM converters to provide dependable and effective power conversion.

**Converter rating:**

A six-valve converter with one turn-off device/diode per valve would appear to be the cheapest and most straightforward controllable three-phase converter, assuming that the needed converter rating is relatively modest. Since a transformer would typically be required in FACTS applications to connect the converter valves to the ac system, the transformer turn ratio offers some flexibility in order to meet the current and voltage ratings of the available devices. One device per valve in a six-pulse converter may result in a maximum rating of, say, 5 MVA. A basic six-pulse converter is probably not the best option for connection to the ac system, even at this low rating, due to harmonic distortion restrictions. Aside from the flexibility needed for the control, complex judgments must be taken regarding the usage of big filters against higher pulse-order, PWM or quasi-PWM converter topologies, etc.

The effects of a device failure are one area that needs study for single-device per valve converters. It would not be advisable to utilize fuses. Although it is not unreasonable to detect a fault occurrence, such as a shoot-through, in a few microseconds and shut off other connected converter valves for a safe protection plan, given the advancements in sensing and digital protection technologies. Converters with a rating substantially higher than 5 MVA will be used in the majority of FACTS applications. Now that the higher grade is available, the designer has a wide range of alternatives.

1. By increasing the pulse order to 12, 24, or 48, one can more effectively increase the overall converter rating to a maximum of 10, 20, or 40 MVA, while maintaining one turn-off device per valve, and minimize harmonics to an acceptable level with 2, 4, or 8 six-pulse converters that have been properly phase-shifted. In this situation, one must decide between series and parallel connections on the dc side, various transformer configurations, phase shift between converters, and series and parallel connections on the ac side. These strategies must be weighed against other methods, such as three-level, PWM, specific notches, and combinations of the aforementioned, for lowering harmonics and gaining flexibility in dynamic and steady state management.
2. By adopting a three-level converter topology, the converter voltage is also doubled, resulting in a potential increase in the single-device per valve converter's maximum capacity to, for example, L0 MVA per six-pulse, 20 MVA each L2-pulse, and so on. The flexibility of a constrained range of independent ac voltage regulation is offered by the three-level structure. To accomplish independent ac voltage control, this must be weighed against low frequency PWM or notch-based topologies, though. Thus, it can be seen that a FACTS converter rating of a modest size can be obtained without using devices connected in series.
3. For high-power converters, connecting components in series is the most popular configuration. Here, ensuring that all of the devices receive an equal amount of voltage is the problem. Although the series connection approach is well known, voltage dividers or snubbers must be provided, and the device voltage rating must be adjusted in some way. To guarantee ongoing operation in the case of a device failure, it is also common practice to add an additional device or diode in series to each valve. With the exception of the possibility that the failure of a second device or diode in the same valve could result in a catastrophic failure, it should be noted that when a power semiconductor device fails, it must fail into a short circuit and continue to carry current forever without experiencing any negative effects.
4. Increase the number of phase-legs by two and connect them in parallel, where the two phase-legs are linked together in parallel by a center-tapped inductor. These phase-legs could be two- or three-level structures.

5. Parallelize converter group connections. In actuality, many more groups than may be required to increase the pulse number can be connected in parallel. With converters connected in parallel, a protective strategy is required to isolate a problematic converter while having the least possible influence on the performance of the remaining converters. 24 phase legs are involved in a 48-pulse converter with all six-pulse converters connected to the same dc bus.
1. The ability to quickly turn off devices and high-speed sensing make it possible to link many phase legs in simultaneously. However, taking into account fault currents and high-current bus operations frequently results in a mix of series and parallel connections.
6. Combine two or more of the aforementioned options, or any other option not specified above, to create the necessary converter Performance and evaluation. There is a strong motivation to develop a platform-based design, and even a transformer-less design, especially when a tiny converter is required in a high-power transmission, given the high relative expense of high-voltage isolation using transformers.A designer (provider) has a lot of options to consider, as is clear. The chances of two design teams working independently and coming up with diverse ideas are relatively high. Therefore, it's crucial that the buyer of FACTS technology focus more on the performance requirements than on the specifics of the technical design.

## CONCLUSION

In conclusion, by enabling effective AC/DC power conversion and control, voltage source converters (VSCs) play a significant role in contemporary power electronics systems. They are extensively utilized in many different fields and applications, including the integration of renewable energy sources, high-voltage direct current (HVDC) transmission, electric car production, and industrial motor drives. Fast response times, excellent controllability, and little harmonic distortion are among the benefits of VSCs. Power quality, system stability, and energy efficiency are all improved by their capacity to control voltage and current flow. Power electronics innovation is being fueled by the continual developments in VSC technology, which has made it possible to create more dependable, effective, and sustainable energy systems.

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## CHAPTER 6

# SELF AND LINE-COMMUTATED CURRENT SOURCE CONVERTER

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**ABSTRACT:**

Power electronic converters come in two varieties: self-commutated current source converters (CSC) and line-commutated current source converters. These converters are utilized in a variety of applications, including motor drives, reactive power compensation, and high-voltage direct current (HVDC) transmission. An overview of the functions, traits, and uses of these converters is provided in this chapter. While the line-commutated CSC uses the power grid to manage the flow of current, the self-commutated CSC operates with the aid of semiconductor devices. Each converter's benefits, drawbacks, and important factors are explained. The contrast between the two types of converters draws attention to their unique qualities and applicability for various uses. Finally, prospective future study directions and CSC technological advancements are discussed.

**KEYWORDS:**

Current Source Converter, Full Wave Diode Rectifier, Line Commutated Current Source, Power Electronics Converter, Reactive Power Compensation.

## INTRODUCTION

Power electronic converters come in two varieties: self-commutated current source converters (CSC) and line-commutated current source converters. These converters are utilized in a variety of applications, including motor drives, reactive power compensation, and high-voltage direct current (HVDC) transmission. An overview of the functions, traits, and uses of these converters is provided in this study. While the line-commutated CSC uses the power grid to manage the flow of current, the self-commutated CSC operates with the aid of semiconductor devices. Each converter's benefits, drawbacks, and important factors are explained. The contrast between the two types of converters draws attention to their unique qualities and applicability for various uses. Finally, prospective future study directions and CSC technological advancements are discussed. Power electronic converters are essential in many applications because they make efficient energy conversion and control possible. The self-commutated current source converter (CSC) and line-commutated current source converter are two of these converters that are frequently utilized in a variety of industries and sectors. These converters offer crucial features like motor control, reactive power correction, and power transmission. For constructing and putting into practice effective power electronic systems, it is crucial to comprehend their operating principles, characteristics, and applications. In-depth comparisons of self-commutated and line-commutated CSCs will be given in this study, with special attention paid to the differences, benefits, and drawbacks of each[1]–[3].

**Self-Commutated Current Source Converter:** Through the employment of semiconductor components, the self-commutated CSC regulates current flow to carry out its operation. Insulated gate bipolar transistors (IGBTs) and integrated gate-commutated thyristors (IGCTs) are the most often utilized components. To control the current, these devices are controlled y turned on and off. Because it receives its energy from a voltage source, the self-commutated CSC is also referred to as a voltage-fed CSC. It has a number of benefits, including greater power quality, decreased harmonic distortion, and better controllability.

**Working Theory:** A load, a current source inverter (CSI), and a DC link capacitor are the main parts of a self-commutated CSC. The capacitor in the DC connection smooths the DC voltage that is obtained from the voltage source. In order to supply the load, the CSI transforms the DC voltage into a controlled AC current. Pulse width modulation (PWM) techniques are used to control the semiconductor devices in the CSI to control the current flow. The switching frequency, the appearance of the output current waveform, and the degree of harmonic distortion are all influenced by the modulation technique.

**Advantages and Qualities:**

**Improved Controllability:** Enhancing Controllability The output current can be fully controlled by the self-commutated CSC. The average output current may be precisely controlled by modifying switching patterns and modulation strategies, enabling accurate control of motor drives and power flow in HVDC transmission systems.

**Lessened Harmonic Distortion:** In self-commutated CSCs, the PWM techniques used help reduce the harmonic content in the output current waveform. This is accomplished by carefully regulating the switching patterns to modify the current waveform. Self-commutated CSCs, in contrast to other converter topologies, result in cleaner and more sinusoidal current waveforms.

**Enhanced Power Quality:** higher Current Waveform and Less Harmonic Distortion Together, these factors lead to higher power quality. Self-commutated CSCs aid in reducing problems with reactive power usage, power factor, and voltage distortion. They are frequently employed in situations where sensitive industrial loads and renewable energy systems require high-quality electricity.

**Applications:** Self-commutated CSCs are widely used in a variety of fields and spheres, including:

**Direct current at high voltage (HVDC) transfer:** For effective and controlled power transfer over long distances, self-commutated CSCs are widely employed in HVDC transmission systems. Reactive power compensation and accurate power flow control are made possible by the exact regulation of the current.

**Motor Drives:** Self-commutated CSCs are suited for motor drive applications due to their controllability and low harmonic distortion. They allow for accurate motor speed and torque control, which enhances motor performance and energy economy.

Renewable Energy Systems: For effective power conversion and grid integration, self-commutated CSCs are used in renewable energy systems like wind turbines and solar photovoltaic (PV) systems. The increased power quality and lower harmonic distortion help these systems operate steadily and consistently.

**Line-Commutated Current Source Converter:** The power grid is used to regulate the current flow in a line-commutated current source converter. It is also referred to as a synchronous CSC or a grid-commutated CSC. In this converter, the power grid's natural commutation is used to switch the current from one phase to another. In high-power applications, where grid compatibility and fault tolerance are crucial, the line-commutated CSC is frequently utilized.

**Working Principle:** The current source rectifier (CSR), the DC link capacitor, and the current source inverter (CSI) make up the line-commutated CSC. The DC link capacitor stores the DC current that the CSR created by converting the AC grid power to a DC current. The CSI transforms the DC current into a regulated AC current that is given to the load, much like the self-commutated CSC. The grid's natural voltage reversal is used to commutate the current from one phase to another.

**Advantages and Qualities:**

Due to their reliance on grid commutation for current flow management, Grid Compatibility: line-commutated CSCs are naturally compatible with the electrical grid. Since the grid's intrinsic commutation provides synchronization with its frequency and voltage, large-scale power transmission systems can use them.

**Fault Ride-Through Capability:** Line-commutated CSCs provide a high level of fault tolerance and fault ride-through capability. Without experiencing significant disruption, they can survive and navigate grid failures and disturbances like power dips or short circuits. Because system stability and reliability are crucial in high-power applications, this attribute is particularly significant.

**Low Harmonic Distortion:** Despite the fact that line-commutated CSCs have a larger amount of harmonic distortion than self-commutated CSCs, they nonetheless provide an output current waveform with a comparatively low harmonic content. Natural commutation reduces harmonics, allowing them to be used in applications where a small amount of harmonic distortion is acceptable.

Applications: Line-commutated CSCs are used in a variety of fields and professions, such as:

**Direct current at high voltage (HVDC) Transmission:** Line-commutated CSCs are frequently utilized for bulk power transmission over large distances in HVDC transmission systems. They are suited for this application due to their grid synchronization features and fault ride-through capability.

**Reactive Power Compensation:** To increase power factor and voltage stability, reactive power compensation systems use line-commutated CSCs. They can control voltage and support dynamic reactive power, improving the reliability and effectiveness of the power system.

Applications in the industrial sector: Line-commutated CSCs are used in high-power conversion applications including arc furnaces, big motor drives, and train traction systems. They are ideal for these demanding applications due to their fault tolerance and grid synchronization capabilities.

**Comparison and Selection:** Depending on the application's requirements, one may choose between self-commutated and line-commutated CSCs. When choosing the right converter, the following factors should be taken into account:

**Controllability and Power Quality:** Self-commutated CSCs provide enhanced controllability and increased power quality with less harmonic distortion. They are appropriate for systems like motor drives and renewable energy sources that need precision current management and high-power quality.

**Grid Compatibility and Fault Tolerance:** Line-commutated CSCs perform exceptionally in terms of grid compatibility and fault ride-through ability. They are useful for high-power applications where grid synchronization and fault tolerance are essential, such as HVDC transmission and reactive power compensation.

**Cost and Complexity:** Due to the requirement for semiconductor devices and sophisticated control methods, self-commutated CSCs are typically more complex and expensive than line-commutated CSCs. When choosing the converter for a given application, it is important to take into account the complexity and cost variables.

**Future Research and Development:** CSC technology is a topic that is still developing, so there are a number of directions that future study and development should take. Some possible directions for the future include:

**Efficiency Improvement:** Research should concentrate on improving the efficiency of CSCs by creating cutting-edge semiconductor devices, namely wide-bandgap devices, and by tuning converter topologies and control schemes.

**Size and Cost Reduction:** By integrating small and light components and improving system design and manufacturing procedures, further progress can be achieved in decreasing the size and cost of CSCs.

**Advanced Control Strategies:** Both self-commutated and line-commutated CSCs can have their performance, controllability, and power quality improved by researching and developing advanced control strategies.

**Hybrid Converter Configurations:** Exploring hybrid converter designs, which include the benefits of both self-commutated and line-commutated CSCs, can improve performance and broaden the range of possible applications.

Current source converters that are self-commutated and line-commutated are two significant forms of power electronic converters that are utilized in several applications. The self-commutated CSC is appropriate for applications requiring precise control and good power quality because it has outstanding controllability and minimal harmonic distortion. On the other hand, line-commutated CSCs are superior for high-power applications due to their grid compatibility and fault ride-through ability. The individual needs of the application determine which of the two types to use. To further increase the performance and usability of CSC technology, future research should concentrate on efficiency improvement, size and cost reduction, sophisticated control strategies, and researching hybrid converter topologies.

## DISCUSSION

**Three phase full wave diode rectifier:**A common power electronic circuit for converting three-phase AC electricity to DC voltage is the three-phase full-wave diode rectifier. This paper gives a general overview of the three-phase full-wave diode rectifier's operation, circuit design, properties, and applications. The rectifier's operation is described, along with the diodes' conduction and non-conduction times. The rectifier's benefits and drawbacks are explored along with its use in a variety of fields, including power supply, motor drives, and renewable energy systems[4]–[6].

Power electronic rectifiers are crucial parts that transform AC electricity into DC voltage in a variety of applications. Due to its simplicity, affordability, and dependability, the three-phase full-wave diode rectifier is a frequently used rectifier topology. It is frequently used in commercial, residential, and industrial applications. The three-phase full-wave diode rectifier is the subject of this study, which seeks to provide a thorough grasp of its operation, characteristics, and applications.

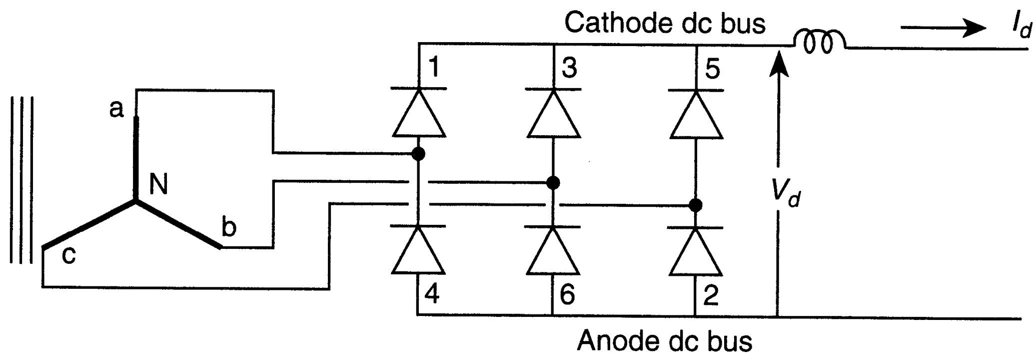


**Figure 1: Three phase full wave diode rectifier (google)**

**Working Principle:** To rectify the three-phase AC voltage, the three-phase full-wave diode rectifier uses six diodes placed in a bridge arrangement. Three input terminals, one for each phase of the AC supply, are used to connect the rectifier to the AC input. Two of the diodes conduct, allowing current to flow through the load in one direction, throughout each half-cycle of the AC voltage, while the other diodes remain non-conductive. As a result, the output has a constant DC voltage. Diodes D1, D3, and D5 conduct during the positive half-cycle of the AC voltage, but diodes D2, D4, and D6 do not. This enables the output to be rectified and merged at the positive half-cycle of each phase. Similar to this, diodes D2, D4, and D6 conduct during the negative half-cycle of the AC voltage while diodes D1, D3, and D5 do not. A constant DC voltage is produced at the output as a result of rectifying the negative half-cycle of each phase.

**Circuit Setup:** The three-phase full-wave diode rectifier features a circuit set up with six diodes grouped in a bridge configuration. Each diode has a load resistor linked in series with it. Three input terminals, one for each phase of the AC supply, are used to connect the rectifier to the AC input. A rectified DC voltage is obtained from the junction of the load resistors as the output.

**Traits and Characteristics:** The three-phase full-wave diode rectifier has the following traits and characteristics:

**Continuous Output:** Because the positive and negative half-cycles of the AC voltage overlap, the rectifier produces a continuous output voltage with little ripple.

**Voltage and Current Ratings:** To handle the highest anticipated voltage and current levels, the voltage and current ratings of the diodes and the load resistors should be carefully chosen.

**Waveforms of voltage and current**: The rectified output voltage waveform has a frequency that is identical to the input AC frequency. Harmonics can be found in the non-sinusoidal waveform of the output current.

**Ripple Voltage:** Because of the rectified waveform's pulsing nature, the output voltage has ripple components. The load current and the load resistor's value affect the ripple's amplitude.

**Benefits and Drawbacks:** The full-wave three-phase diode rectifier provides the following benefits:

**Simple and Economical:** The rectifier circuit is a simple and economical way to convert three-phase AC voltage to DC voltage. It only requires the use of six diodes.

**High Efficiency:** Because there are no switching components used in the rectifier, there are very few power losses. As a result, the rectifier has a high efficiency.

**Reliability:** The rectifier's reliability is increased by the lack of intricate control circuits and switching mechanisms.

The rectifier, however, has some restrictions:

**Nonlinear Load Current:** The rectifier's load current waveform contains harmonics, which can compromise the quality of the power and increase load losses.

**Limited Voltage Regulation:** Because the output voltage is a direct function of the input voltage's strength, the rectifier has a limited ability to regulate voltage.

**Applications:** The three-phase full-wave diode rectifier is used in many different fields and spheres, such as:

**Power Supplies:** Rectifiers are frequently utilized in power supply for electronic devices in order to provide a DC voltage source from the AC mains.

**Motor Drives:** Rectifiers are used in motor drives to change the AC input voltage into a DC voltage that powers the motor.

**Renewable Energy Systems:** The rectifier transforms the AC output from the generator into DC voltage for grid integration or battery charging in renewable energy systems like wind turbines and solar PV systems.

A common power electronic circuit for converting three-phase AC voltage into DC voltage is the three-phase full-wave diode rectifier. It offers reliability, efficiency, and simplicity. Six diodes placed in a bridge configuration are used to power the rectifier. Despite having a constant DC output, it has drawbacks such nonlinear load current and a poor ability to regulate voltage. Power supply, motor drives, and renewable energy systems all use the rectifier. The focus of future research and development can be on expanding the rectifier's ability to regulate voltage for a wider range of applications, lowering harmonic content, and improving power quality.

**Thermistor-based converter (with gate turn-on but without gate turn-off):**For effective power conversion, thermistor-based converters are widely employed in a variety of power electronic applications. The thermistor-based converter that is the subject of this study functions with gate turn-on but not gate turn-off capabilities. This converter's qualities, advantages, and limits are examined along with its operating principle and circuit setup. The converter is frequently employed in tasks requiring unidirectional power flow, like rectification and motor control. In order to guarantee the converter's safe and dependable operation, the study also emphasizes the significance of appropriate control systems. Converters based on thermistors are crucial parts of power electronic systems. In a variety of applications, they provide excellent efficiency, toughness, and dependability. This study describes a particular kind of thyristor-based converter that employs gate turn-on but is unable to do gate turn-off. The thyristor in this converter is activated to conduct, and it continues to do so until the current flowing through it naturally drops below a predetermined level. This converter can only be used in applications where unidirectional power flow is necessary because it lacks gate turn-off functionality.

**Working Principle:** One or more thyristors are connected in a specified configuration, such as a diode-rectifier bridge, in the thyristor-based converter without gate turn-off capability. The thyristor enters conduction when the gate turn-on signal is applied, allowing the current to flow in the desired direction. The thyristor cannot be turned off via a gate signal in this sort of converter, unlike other thyristor-based converters. Instead, when the current flowing through it drops below a certain holding current or when the AC voltage in an AC input passes zero, the thyristor spontaneously shuts off.

**Circuit Configuration:** A thyristor-based converter without gate turn-off functionality often has a diode-rectifier bridge as well as extra control and protective circuitry. The gate turn-on signal is used to activate the thyristor into conduction while it is coupled in series with a load. The additional bridge diodes guarantee appropriate current flow and deliver the required unidirectional power transmission.

**Characteristics:** The thyristor-based converter lacks the ability to turn off the gate, but it does have the following characteristics:

**Unidirectional Power Flow:** The converter only permits the flow of power in one way, making it ideal for applications requiring unidirectional power transfer, such as rectification and motor control.

**High Voltage and Current Handling:** Thyristors are able to handle high voltage and current levels, making this converter appropriate for high-power applications.

**High Efficiency:** Thyristors have low conduction losses, which helps to increase the efficiency of the converter as a whole.

**Advantages:** The following benefits are provided by the thyristor-based converter without gate turn-off capability:

**Simple Circuitry:** The converter's circuitry and control system are made simpler by the lack of a gate turn-off feature, which lowers complexity and costs.

**High Current and Voltage Ratings:** Thyristors are capable of handling high current and voltage levels; hence the converter is appropriate for high-power applications.

**Robustness:** The converter is capable of withstanding short-circuit situations without suffering serious harm.

The converter has some restrictions as well:

**Limited Control:** The converter's control options are constrained by the inability to turn off the gate. During normal operation, it is impossible to control the output voltage or current.

**Unidirectional Power Flow:** Unsuitable for applications requiring bidirectional power flow is the converter's ability to solely permit unidirectional power transmission.

Applications include the following for the thyristor-based converter without gate turn-off functionality:

**AC-to-DC Power Conversion:** The converter is frequently used in rectification applications, which include converting AC voltage to DC voltage.

Motor Control: When unidirectional power flow is required, such as in variable speed drives, it can be used in motor control systems.

For applications requiring unidirectional power flow, the thyristor-based converter without gate turn-off capability offers a straightforward and reliable solution. It has benefits including simplicity, high current and voltage handling, and good efficiency while not having gate turn-off functionality. Applications for the converter include rectification and motor control. To guarantee the converter operates safely and reliably, appropriate control strategies and safety precautions are essential. In order to increase the converter's usefulness in a wider range of power electronic systems, more research and development can concentrate on improving control options and overcoming the constraints brought on by the absence of gate turn-off capability.

**AC current harmonics:**In an alternating current waveform, the term "AC current harmonics" describes the presence of frequency components that are integer multiples of the fundamental frequency. The fundamental frequency is the main component of a perfect sinusoidal waveform, but in real-world systems, harmonics can appear because of a variety of things, such as non-linear loads, switching equipment, and power electronic converters. Multiples of the fundamental frequency, known as harmonic frequencies, are commonly expressed as n times the fundamental frequency (where n is an integer). The second harmonic, for instance, would be twice the fundamental frequency, the third harmonic, three times, and so on.

**Causes of AC Current Harmonics**:

**Non-Linear Loads:** Electronic equipment, power supplies, and variable speed drives are examples of non-linear loads that draw non-sinusoidal current from an AC power source. These loads' non-linear properties cause harmonic components to enter the current waveform.

Power Electronic Converters: Due to their switching action, power electronic converters such as rectifiers, inverters, and switch-mode power supply produce harmonics. In these converters, the semiconductor components are rapidly switched, resulting in non-sinusoidal current waveforms.

**Transformer Saturation:** Harmonic production is another potential consequence of transformer saturation of the magnetic core. The transformer core's non-linear magnetization properties lead to distorted current waveforms.

Effects of AC Current Harmonics: Harmonics in AC current waveforms can have a number of negative effects, including:

**Voltage Distortion:** Voltage distortion is caused by harmonic currents that pass through the electrical system's impedance. This may result in distorted voltage waveforms, greater voltage drops, and poorer power quality.

**higher Power Losses:** Due to higher resistive heating and eddy currents, harmonic currents that pass-through power system components including transformers, cables, and capacitors result in additional power losses.

Overloading of Equipment: Harmonic currents can overload electrical equipment, which can result in overheating, a shorter equipment lifespan, and a higher failure rate. Transformers, capacitors, and wires are particularly prone to overheating caused by harmonics.

**Electromagnetic Interference:** Harmonics can produce electromagnetic interference (EMI), which can impair the functionality of delicate electronic devices and cause disruptions, errors, and corrupted data.

Resonance Conditions: Harmonic frequencies have the potential to produce resonance conditions in the parts of a power system, increasing their effects and resulting in severe voltage distortion and equipment damage.

**Harmonic Standards and Mitigation:** Various actions can be taken to lessen the impact of AC current harmonics, including:

Filtering: Harmonic currents and voltage distortion can be reduced using passive and active harmonic filters, particularly in non-linear loads and power electronic converters.

**Power factor correction:** Methods to reduce harmonics brought on by non-linear loads include the use of capacitors and compensating for reactive power.

**Harmonic Standards and Guidelines:** To preserve power quality and guarantee electrical device compatibility, international standards like IEEE 519 and IEC 61000-3-2 set limits on harmonic levels.

**System Design:** Harmonic-related problems can be reduced with careful system design, which includes choosing machinery, cables, and transformers with sufficient harmonic handling capabilities.AC current harmonics are additional integer multiples of the fundamental frequency present in the current waveform. They are primarily brought on by transformer saturation, power electronic converters, and non-linear loads. Voltage distortion, higher power losses, equipment overheating, electromagnetic interference, and resonance situations can all be caused by harmonics. Filtering, power factor adjustment, adherence to harmonic standards, and appropriate system design are a few harmonic mitigation strategies that can assist lessen their negative impacts and preserve a high-quality power supply[7]–[9].

**DC voltage harmonics:**Direct current (DC) voltage harmonics are the existence of unwelcome frequency components in a DC voltage waveform. While alternating current (AC) systems are more frequently linked to harmonics, DC voltage systems can also experience harmonic introduction due to certain conditions.

**Causes of DC Voltage Harmonics:**

Switching Devices: Switching Equipment Switching elements like transistors and thyristors have the potential to introduce harmonics into the DC voltage waveform in power electronic systems like DC-DC converters and inverters. These devices' quick switching can result in voltage transients and high-frequency components.

**Ripple in DC Sources**: Even in systems with flawless DC voltage sources, ripple components may still exist as a result of issues with the input voltage or faulty filtering. These ripple elements may appear as harmonics in the waveform of the DC voltage.

**DC voltage harmonics' effects:**

**Increased Ripple:** The DC voltage waveform's harmonic elements are a factor in the phenomenon of increased ripple. Greater DC voltage level changes are caused by higher harmonic content, which can destroy delicate electrical equipment and circuits.

**Electromagnetic Interference (EMI):** Harmonics in the DC voltage waveform can produce electromagnetic interference (EMI), which can degrade the functionality of surrounding electronic devices and lead to problems including noise, distorted signals, and malfunctions.

**Stress on Components:** Harmonic elements in the DC voltage can increase the stress on capacitors, inductors, and semiconductors. These components' lifespans may be shortened and their heating may be exacerbated by high-frequency harmonics.

**Harmonic Mitigation and Standards**: Standards for harmonic mitigation are in place, despite the fact that harmonics in DC voltage are less frequent than in AC systems.

**Filtering:** To lessen the ripple and harmonic content in the DC voltage waveform, appropriate filtering techniques can be used. Depending on the application, this could include the use of capacitors, inductors, or active filtering methods.

**Component Selection:** Harmonic impact can be reduced by selecting components with appropriate voltage ratings and harmonic handling capabilities. Harmonic effects can be minimized, for instance, by using capacitors with low equivalent series resistance (ESR) and high ripple current ratings.

**Standards and Recommendations:** While there aren't any specific guidelines for reducing DC voltage harmonics, adhering to general power quality guidelines like IEEE 519 and IEC 61000-3-2 can assist guarantee the right design and operation of power electronic systems, which in turn helps to minimize harmonic problems.

The presence of harmonics in DC voltage waveforms is still possible, even if they are less common than in AC systems. This is mainly because to switching devices and ripple in the DC sources. Component stress, electromagnetic interference, and enhanced ripple are all possible effects of these harmonics. Filtering, selecting components wisely, and adhering to pertinent standards are a few mitigation strategies that can assist reduce the effects of DC voltage harmonics and guarantee the steady operation of DC power systems[10]–[12].

**Current source versus voltage source converter:**Converters that are voltage sourced versus current sourced have the following benefits and drawbacks:

1. If the converter does not need to control active power, diode-based converters are the most affordable.
2. A traditional thermistor-based converter offers a low-cost converter with active power control if the leading reactive power is not necessary. It can also function as a reactor controlled by a thermistor or as a controlled lagged reactive power load.
3. Unlike the voltage-sourced converter, the current-sourced converter does not have a high short-circuit current. The dc reactor controls the rate of rise of fault current for current-sourced converters during external or internal faults.
1. The capacitor discharge current would rise extremely quickly in the voltage-sourced converters and could harm the valves.
4. The 12-pulse converter's transformer primary do not need to be connected in series for harmonic cancellation, while the six-pulse, current-sourced converter does not produce third harmonic voltage. Using phase-shifting windings, a 24-pulse operation can likewise be achieved rather easily.
5. Because ac capacitors are present in a current-stiff converter, the valves are not exposed to excessive duty.
6. Although the size of the ac capacitors used for the current-stiff converters can be reduced by using p.m. topology, they can still be rather expensive and huge.
2. The issue of an acceptable interface between current-sourced converters and the ac system is generally more complicated.
7. Continuous losses in a current-sourced converter's dc reactor are significantly higher than losses in the dc capacitor. These losses may result in a large loss penalty.
8. Because this converter contains capacitors, which are susceptible to commutation charging and discharging, harmonic voltages will be produced at a frequency where the inductances of the ac system and the capacitors will resonate. By designing the

capacitors so that the resonance frequency does not coincide with typical harmonics, the negative impacts of this can be avoided.

9. Overvoltages on the valves and transformers may occur as a result of these harmonics and the existence of a dc reactor.
10. Voltage-sourced converters are an advantageous option when turn-off capability is required due to the widespread adoption of asymmetrical devices, such as IGBTs and GTOs, as the devices of choice for reducing on-state losses. Because high-volume industrial applications typically drive the device market, it's possible that symmetrical turn-off devices with the necessary operating characteristics, particularly the switching characteristics, won't be readily available until the FACTS market grows in size. However, as the technology advances, in particular with the development of the advanced GTOs mentioned.

## CONCLUSION

In conclusion, current source converters with both self-commutation and line-commutation play important roles in power electronic systems. Self-commutated CSCs have benefits such stronger controllability, lower harmonic distortion, and better power quality because they rely on semiconductors for current control. It is frequently utilized in applications like motor drives and renewable energy systems where precise control and excellent performance are necessary. In contrast to line-commutated CSCs, self-commutated CSCs may be more expensive and sophisticated. For high-power applications like HVDC transmission and reactive power compensation, on the other hand, the line-commutated CSC is more suited since it makes use of the power grid to manage the current flow. It works with less overall harmonic distortion and offers good fault ride-through capabilities. Line-commutated CSCs, however, are susceptible to voltage swings and grid disturbances and have a limited amount of controllability. The individual needs of the application determine which of the two types of converters is best. Line-commutated CSCs are appropriate for high-power applications that favor grid compatibility and fault tolerance, while self-commutated CSCs are chosen when precise control and enhanced power quality are crucial. Overall, current source converters that are self-commutated or line-commutated are essential parts of contemporary power electronic systems. Their special qualities and abilities make them useful for a variety of uses, advancing power transmission, motor control, and the incorporation of renewable energy sources.

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## CHAPTER 7

# AC TRANSMISSION LINE AND REACTIVE POWER COMPENSATION

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**ABSTRACT:**

The effective and dependable transfer of electrical power over vast distances depends heavily on AC transmission lines. They do, however, display traits like reactive power consumption, voltage dips, and resistive losses. Techniques for reactive power adjustment are used to address these problems and enhance the transmission system's overall performance. The significance of reactive power compensation in AC transmission lines, various compensation techniques, and their advantages are covered in this chapter. The main ideas covered in the paper are summarized in the chapter.Techniques for compensating for line and reactive power are essential for enhancing the efficiency, voltage stability, and power quality of power transmission and distribution systems. An introduction of line and reactive power compensation is given in this abstract, along with a discussion of its importance and major features. The techniques and equipment used to control the active power flow in electrical networks are referred to as line power compensation. To maintain dependable and effective functioning, it entails managing the active power transmission between connected systems or regions. The importance of line power compensation in reducing power losses, improving system stability, and preserving a balanced power flow throughout the grid is emphasized in the abstract.

**KEYWORDS:**

Power Factor Correction, Reactive Power Compensation, Reactive Power Control, Series Compensation, Shunt Compensation.

## INTRODUCTION

**Performance of line connected unity power factor load:** For effective and dependable power delivery, the performance of an electrical power transmission line linked to a unity power factor load is crucial. This essay focuses on examining the features, benefits, and difficulties of such a configuration. It talks about how a load with a unity power factor affects the stability of the entire system, power losses, and line voltage control. Additionally, techniques for compensation are investigated as means of enhancing performance. To maintain efficient operation and usage of transmission infrastructure, power system engineers and operators must have a thorough understanding of the behaviour of a line linked to a load with unity power factor. An electrical load that operates at a power factor of one, when the current and voltage are in phase, is referred to as a unity power factor load. This indicates that the load uses only real power and doesn't need the power system to supply it with reactive power. The efficiency and dependability of the system are determined by a number of performance metrics that are impacted when such a load is connected to a power transmission line.

Impact on Voltage Regulation: The voltage regulation of a transmission line is not significantly affected by a load with a unity power factor. There is no reactive power flow since the load only uses real power, reducing voltage dips and enhancing voltage stability. As a result, the voltage levels at the load end can be better regulated along the line, keeping them close to the source voltage[1]–[3].

Reduced Power Losses: A load with a unity power factor reduces power losses in the transmission line. Reactive power losses are eliminated since the line does not have a reactive power component flowing through it. As a result, the efficiency of power supply is improved and overall line losses are decreased. A shorter equipment lifespan and less heating are further benefits of lower losses.

System Stability: Connecting a load with a unity power factor to a transmission line enhances the stability of the system. A line sees less voltage swings and offers a reliable power supply when real power demand is matched. This improves the efficiency and dependability of the linked electrical loads, assuring uninterrupted operation.

Challenges and Considerations: While a load with a unity power factor has several benefits, there are some difficulties and factors to take into account:

Reactive Power Compensation: Even though a load with a unity power factor doesn't need any reactive power from the system, other neighboring loads or components might. To keep the power factor and voltage stability of the entire power system, reactive power compensation methods, like the usage of shunt capacitors or static VAR compensators, may be required.

Voltage Regulation for Variable Loads: Although a load with a unity power factor has no effect on voltage regulation, it is crucial to take this into account when the load is changing. Voltage regulation mechanisms must be put in place if the load varies significantly or if additional non-unity power factor loads are present in the system to guarantee stable and dependable operation.

Several techniques can be used to further improve the performance of a line connected to a load with a unity power factor. Compensation for Reactive Power: Using capacitor banks or synchronous condensers to compensate for reactive power can assist the system maintain the desired power factor and voltage stability.

Voltage Control: By using tap-changing transformers and automatic voltage control (AVC) systems, it is possible to keep voltage levels within reasonable ranges and reduce the voltage variations brought on by different load circumstances.

A unity power factor load connected to a power transmission line performs best because of better voltage management, lower power losses, and increased system stability. Power delivery is efficient because voltage dips and reactive power flow are reduced when the load only uses real power. However, factors like voltage regulation under shifting load situations and reactive power compensation should be taken into account. The performance of a line connected to a unity power factor load can be further improved by utilizing reactive power compensation techniques and voltage control devices. To ensure dependable and effective power transmission, it is essential for power system engineers and operators to comprehend these performance characteristics. Lines linked to unity power factor loads can operate better thanks to ongoing research and development in power system optimization approaches.

**Performance of symmetrical line:**A symmetrical transmission line is a specific kind of transmission line in which the signal and return wires are arranged symmetrically with respect to one another. Applications including telecommunications, electricity distribution, and high-speed data transmission frequently use this topology. To ensure effective and dependable signal transmission, a symmetrical transmission line's performance is essential. The main features of symmetrical transmission lines and their performance characteristics will be discussed in this discussion. The ability to provide balanced signals is one of the main benefits of symmetrical transmission lines. These lines are capable of successfully reducing common-mode noise and interference by maintaining symmetry between the signals and return conductors. Unwanted electrical disturbances that equally affect both conductors are referred to as common-mode noise. Symmetrical transmission lines guarantee good signal integrity and lower the possibility of data corruption or signal degradation by cancelling out this noise. A symmetrical transmission line's performance is affected by a number of variables. The characteristic impedance of the line is an important consideration. The transmission line's apparent impedance when it is infinitely long is represented by the characteristic impedance symbol Z0. The characteristic impedance of a symmetrical transmission line is normally the same as the impedance of the signal and return wires. For effective power transfer and signal integrity, it is crucial to match the line's characteristic impedance to the impedance of the connected devices. Impedance mismatches can result in signal reflections, which can amplify signals and degrade performance. The transmission line's attenuation or loss is another crucial performance factor. As a signal moves along the transmission line, it weakens, a process known as attenuation. Signals can be transmitted over great distances with little loss thanks to the low attenuation of symmetrical transmission lines.

The physical design of the line and the material selection are key factors in influencing the attenuation characteristics. To reduce signal loss, high-quality conductors with low resistance and dielectric materials with low loss tangents are frequently utilized. Signal delay or propagation delay can also affect symmetrical transmission lines. The amount of time it takes for a signal to move from one end of the transmission line to the other is referred to as propagation delay. The physical length of the line, the dielectric constant of the insulating material positioned between the conductors, and the speed of light in the medium all have an impact on this delay. Minimizing propagation delay is essential for maintaining the timeliness and integrity of signals during high-speed data transfer. Symmetrical transmission lines are additionally vulnerable to numerous types of noise and interference in addition to these concerns.

One such issue is crosstalk, which occurs when electromagnetic coupling causes the signals on nearby transmission lines to interfere with one another. Crosstalk can be reduced through the use of appropriate design strategies, such as shielding and keeping a suitable distance between the transmission lines. The frequency range of operation also affects how well symmetrical transmission lines perform. At higher frequencies, signal propagation and attenuation are impacted by transmission line phenomena such the skin effect and dielectric losses. To obtain best performance across the specified frequency range, the selection of transmission line parameters, such as conductor size, dielectric constant, and shielding, must be carefully addressed. In conclusion, symmetrical transmission lines must function properly for signal transmission to be effective and trustworthy. These lines enable high-speed data transmission and power distribution by offering balanced signalling, low attenuation, appropriate impedance matching, and efficient noise suppression. Symmetrical transmission lines operate optimally in a variety of applications thanks to careful consideration of variables like characteristic impedance, attenuation, propagation latency, and noise characteristics.

## DISCUSSION

**Reactive power compensation:**In order to raise the power factor and increase the general effectiveness of electrical networks, reactive power compensation is a crucial component of power systems engineering. Reactive power is the kind of power that fluctuates between the source and the load as a result of the system's inductive and capacitive components. The notion of reactive power, its effects on power systems, and the many strategies and tools employed for reactive power compensation will all be covered in this topic. In an electrical system, the interaction of inductors and capacitors results in reactive power. Reactive power is used by inductive components like motors, transformers, and generators because they store energy in magnetic fields. Capacitive parts, on the other hand, including capacitors and other kinds of loads, provide reactive power by storing energy in electric fields. In terms of providing power to the load, reactive power is ineffective; instead, it causes higher currents, voltage drops, and worse system efficiency. A lower power factor is one of the main effects of reactive power. The power factor is the ratio of perceived power (measured in volt-amperes) to real power, which is expressed in watts. A low power factor indicates that the source is drawing a large amount of reactive power, which raises the current and causes more losses in the power system. Due to the penalty utilities impose for low power factor consumption, a low power factor can also lead to voltage dips, decreased system capacity, and higher electricity costs.

Reactive power compensation methods and equipment are used to reduce the problems caused by reactive power. These methods put an emphasis on enhancing voltage stability, lowering line losses, and boosting power factor. Let's investigate a few of the often-employed techniques for reactive power compensation: One of the most often utilized tools for compensating reactive power is a Capacitor Banks: These banks, which are situated close to the inductive loads, are made up of several capacitors connected in parallel. Capacitor banks lessen the strain on the power system and increase power factor by supplying reactive power locally to counteract the reactive power drawn by the inductive loads.

**Static Var Compensators (SVC):** SVCs (Static Var Compensators) are sophisticated electronic devices that offer accurate and dynamic control of reactive power compensation. They are made up of both thyristor-switched capacitors (TSC) and thyristor-controlled reactors (TCR). When necessary, SVCs can inject or absorb reactive power, offering quick reaction and precise compensation. They are frequently utilized in activities like industrial operations and renewable energy installations that have loads that change quickly.

**Synchronous Condensers:** Synchronous condensers are rotating devices that function as synchronous motors that have been overexcited. They modify their field excitation to give reactive power correction. Systems with high fault currents, voltage control needs, and power factor correction requirements benefit most from synchronous condensers.

**Static Synchronous Compensators (STATCOM):** Another class of sophisticated power electronic device used for reactive power compensation is the static synchronized compensator (STATCOM). Voltage source converters (VSC) are used by them to inject or absorb reactive power as necessary. In addition to reactive power compensation, STATCOMs can also give voltage support, harmonic mitigation, and precise control[4]–[6].

**Active Power Factor Correction (APFC):** Power electronic-based systems that actively adjust the power factor are known as active power factor correction (APFC) systems. APFC systems detect the load's power factor and inject the required reactive power to make up for any variations from the intended power factor using the appropriate control algorithms and power electronic converters.

**Unified Power Flow Controllers (UPFC):** Unified Power Flow Controllers (UPFCs) are cutting-edge power electronics that offer thorough control over active and reactive power flow in transmission networks. Voltage, reactive power, and active power flow can all be controlled simultaneously thanks to their integration of the SVC and STATCOM functionalities. In linked power systems, UPFCs are used to increase power transfer efficiency, maintain voltage stability, and manage power flow.

These are only a few illustrations of the methods and tools employed for compensating reactive power. System needs, load characteristics, and economic considerations are only a few examples of the variables that influence the compensation technique selection. Enhancing the stability, effectiveness, and dependability of power systems requires reactive power compensation. Reactive power compensation approaches assist in minimizing losses, enhancing voltage stability, increasing system capacity, and lowering electricity costs by reducing reactive power flow, enhancing power factor, and optimizing voltage levels. It is essential to the design and operation of contemporary power systems, ensuring the effective use of electrical energy resources.

**Need of compensation:**In many facets of life and engineering, compensation in various forms is required to remedy imbalances, inefficiencies, and undesirable impacts. Compensation in electrical engineering and power systems refers to changing or correcting a few factors in order to enhance system performance. We will talk about how electrical systems need compensation, including power factor correction, voltage regulation, harmonics reduction, and reactive power control. Power factor adjustment is an essential component of compensation in electrical systems. The power factor, which measures the proportion of actual to apparent power in an AC circuit, reveals how effectively electricity is used. A low power factor indicates reactive power, which does not perform meaningful work and causes higher currents and losses, makes up a sizable amount of the energy being pulled from the source. In order to balance the reactive power and enhance the power factor, power factor correction requires adding reactive components to the system, such as capacitors. With less line losses, voltage drops, and system capacity restrictions due to this compensatory mechanism, energy efficiency and cost savings are ultimately increased.

Voltage regulation is another crucial area where compensation is necessary. Voltage changes that go above permitted ranges can harm the functionality of electrical devices. Voltage fluctuations may result in functional problems, shortened equipment lifespans, or even system breakdowns. On the other hand, overvoltage circumstances can result in equipment damage, insulation failure, and safety risks. To compensate for voltage variations and maintain the voltage within given limits, voltage regulators, tap-changing transformers, and other voltage control devices are used, assuring optimal equipment operation and reducing the danger of damage. The reduction of harmonics in electrical systems requires compensation as well. Unwanted frequencies known as harmonics are produced by nonlinear loads such as power electronics, variable speed drives, and some types of lighting. These harmonics can alter the waveforms of voltage and current, increasing losses, causing equipment to overheat, and interfering with communication systems.

To compensate for harmonics and keep the quality of the power supply within acceptable bounds, active filters, passive filters, and other harmonic mitigation techniques are used. This lowers equipment stress and ensures dependable operation. Another area that calls for compensation is reactive power regulation. Reactive power, which is produced by inductive and capacitive components in electrical systems, has an impact on the functionality of the system as a whole but does not contribute to meaningful work. Shunt capacitors or reactors are examples of reactive power control devices that enable the management and adjustment of reactive power flow. Reactive power regulation boosts voltage stability, lowers line losses, and improves the effectiveness of power transmission and distribution systems by addressing the reactive power demands of inductive or capacitive loads. Additionally, compensation is crucial in a number of specialized applications, including high-precision industrial processes, renewable energy integration, and electric traction systems. In order to maximize energy conversion, lower power losses, and boost the effectiveness of electric locomotives and railways, compensating techniques are used in electric traction. In order to handle the erratic nature of renewable energy sources and keep the grid stable, compensation is required in the integration of renewable energy. Techniques for compensation aid in managing power generation fluctuations, reactive power control, and voltage regulation. Compensation is necessary in high-precision industrial processes to reduce the effects of voltage sags, harmonics, and other disturbances on sensitive equipment and to preserve dependable and consistent operation. In conclusion, a number of elements, including power factor correction, voltage regulation, harmonics mitigation, and reactive power control, contribute to the requirement for compensation in electrical systems. In order to address these problems and enhance system performance, energy efficiency, and equipment longevity, compensation techniques and devices are used. Compensation helps electrical systems operate reliably, save money, and last longer overall by assuring the best possible use of electricity.

**Series compensation:**In order to boost power transfer capacity, voltage stability, and transmission efficiency, series compensation is a technique used in power systems. In order to account for the transmission lines' innate inductive reactance, series reactive components, such as series capacitors or reactors, are inserted into the lines. The idea of series compensation, its advantages, difficulties, and applications in power system engineering will all be covered in this talk. The reduction of reactive power flow in transmission lines is the main goal of series compensation. Real power (active power) and reactive power both contribute to the transfer of electricity in an AC transmission system. It takes reactive power, which doesn't produce any meaningful work, to keep the magnetic fields in the system's inductive components. It causes elevated line currents, voltage drops, and power losses, though. Series compensation reduces the transmission line's effective reactance by adding series reactive elements, allowing for the transmission of more active power while limiting the flow of reactive power.

The improvement in power transfer efficiency is one of the key advantages of series compensation. The compensated line's decreased effective reactance causes its impedance to drop, which in turn increases its capacity for power transfer. This makes it possible to transmit more power over greater distances without having to build new transmission lines or undertake significant infrastructure modifications. In systems with lengthy transmission lines or heavy load requirements, series compensation can also lessen voltage dips and increase voltage stability. The greater voltage stability and improved power transfer capability attained through series compensation may have a favourable effect on the general effectiveness of power systems. Series adjustment aids in maximizing energy efficiency and minimizing power waste by lowering line losses. By improving the voltage profile and lowering the possibility of voltage collapse or voltage sags during system disturbances, it also helps to ensure the stability and dependability of the grid. Series compensation has economic advantages in addition to technological ones. Series compensation can postpone or eliminate the need for expensive transmission line improvements or the building of new lines by enhancing the transmission capacity of existing lines. It aids utilities in resource allocation and investment optimization. In addition, series compensation makes it possible to transmit electricity over greater distances with less losses, which improves the exploitation of renewable energy sources that are situated in remote locations.

But there are other issues and obstacles related to series compensation that must be taken into account. The potential for sub synchronous resonance (SSR) when utilizing series capacitors is one of these difficulties. Because of the SSR phenomenon, the turbine-generators may experience unfavourable oscillations and stress due to the interaction between the series capacitors and the system's inherent features. To reduce the danger of SSR and guarantee system stability, appropriate system modelling, control techniques, and damping measures are used. The increased danger of transient overvoltage's is another factor to take into account in series compensation. Series capacitor insertion can result in higher voltage magnitudes during system transients, which can put stress on insulation and harm equipment. To solve this issue and ensure equipment reliability, protective measures like surge arresters and voltage control plans are put in place. Additionally, in order to optimize benefits while taking operating limits and system needs into account, the placement and size of series compensation installations must be properly planned. When designing and implementing series compensation, considerations such line length, load characteristics, fault levels, and system stability must be made.

Numerous power system topologies and conditions call for series compensation. In long-distance transmission lines, where the reactive power flow becomes a limiting factor, it is frequently utilized. Series adjustment increases system stability and allows for the transmission of more active power by lowering the effective line reactance. In order to enable power exchange and increase system efficiency, series compensation is also used in connections between various power systems or areas. To sum up, series compensation is a potent power system engineering technique that helps increase the ability to transfer power, improve voltage stability, and maximize the overall effectiveness of transmission systems. Series compensation permits the transmission of more power over longer distances and contributes to a dependable and sustainable power infrastructure by minimizing reactive power flow and mitigating line losses. Despite the difficulties brought on by SSR and transient overvoltage's, effective system design, control schemes, and safety precautions guarantee the implementation of series compensation in power systems.

**Shunt compensation:**Shunt compensation is a method applied to power systems to enhance reactive power control, power factor correction, and voltage regulation. Shunt reactive components, such as capacitors or reactors, are connected across the terminals of electrical loads or at key system locations. Shunt compensation helps balance the system's reactive power needs, lower line losses, increase voltage stability, and improve system performance as a whole. The idea of shunt compensation, its advantages, disadvantages, and applications in power system engineering will all be covered in this talk. Shunt compensation's main goals are to control reactive power flow and voltage in power systems. Reactive power increases line currents, voltage drops, and power losses because it is required to maintain magnetic fields in inductive components. With the ability to inject or absorb reactive power as needed, shunt compensation effectively balances reactive power needs and enhances power quality. The improvement in voltage regulation is one of the major advantages of shunt compensation. Voltage changes that go above permitted ranges can harm the functionality of electrical devices. By injecting reactive power during voltage decreases or absorbing reactive power during overvoltage scenarios, shunt compensation aids in keeping voltage levels within specified bounds. This voltage management assures the best possible equipment performance, lowers the chance of damaging voltage-sensitive equipment, and increases system dependability.

In addition, shunt compensation is essential for power factor adjustment. The efficiency of power utilization is shown by the power factor, which is the ratio of real power (active power) to apparent power in an AC circuit. A low power factor means that the source is drawing a large amount of reactive power, which results in higher line currents, voltage drops, and losses. Shunt compensation reduces reactive power required by inductive loads and raises power factor, particularly when shunt capacitors are used. Shunt compensation reduces line losses, improves system effectiveness, and lessens the penalty utilities apply for low power factor usage by adjusting the power factor. Controlling the flow of reactive power is another advantage of shunt compensation. Shunt reactors absorb reactive power, whereas shunt capacitors supply it. The reactive power flow can be adjusted to match system needs by altering the capacitive or inductive shunt devices. This control aids in preserving constant voltage profiles, lowering transmission losses, and maximizing the use of the transmission and distribution network. Shunt adjustment also improves the efficiency of energy transfer and increases system capacity. Shunt capacitors aid in boosting the system's capacity for power transfer by adding reactive power. When more reactive power is needed or in systems with heavy inductive loads or during periods of peak demand, this is very advantageous. Shunt compensation lowers line voltage drops, boosts the efficiency of power transmission, and permits the distribution of additional power across the network.

Different power system architectures and applications make use of shunt compensating strategies. Examples of typical applications include:

**Distribution Networks:** Shunt capacitors are frequently used in distribution networks to boost voltage regulation, lower line losses, and improve power factor. To account for the connected loads' need for reactive power, capacitor banks are strategically located at distribution substations or close to inductive loads. This enhances voltage stability, lowers energy losses, and boosts the distribution system's capacity.

**Industrial Plants:** To enhance power quality and lower energy costs, shunt compensation is widely employed in industrial plants. Low power factor is caused by inductive loads, such as motors and transformers, which are frequently used in industrial operations. Industrial plants can reduce the demand for reactive power, improve power factor, and save money on energy costs by using shunt capacitors[7]–[10].

**Renewable Energy Integration:** Shunt compensation is essential for integrating renewable energy sources into the grid, including solar and wind energy. These sources frequently have variable reactive power needs and varying power output. Shunt compensation aids in grid voltage stabilization, power factor control, and reactive power management to enable the effective and stable integration of renewable energy sources.

Transmission systems: Shunt compensation is used in transmission systems to increase power transfer efficiency, reduce line losses, and stabilize voltage. In high-voltage transmission networks, shunt compensation devices like static var compensators (SVCs) and static synchronized compensators (STATCOMs) are frequently utilized. To maintain system voltage stability, account for reactive power variations, and regulate system dynamics, these devices offer quick reactive power assistance.

Shunt compensation has a lot of advantages, but there are also problems and things to think about. The possibility of harmonic amplification is one such difficulty. Shunt capacitors have the potential to increase system harmonics if they are not properly protected or constructed.

Unwanted frequencies known as harmonics are produced by nonlinear loads and can lead to voltage distortion, equipment failure, and communication system interference. To reduce the risk of harmonic amplification and guarantee power quality, appropriate filtering, harmonic studies, and protective measures are required. The synchronization and control of the compensation devices is another factor in shunt compensation. To prevent an excessive amount of reactive power flow or voltage instability, deployment of shunt capacitors or reactors at various sites needs to be coordinated. Automatic voltage regulators (AVRs) and power factor controllers are used as control methods to track and modify the compensating devices according to system conditions. To ensure steady and dependable functioning, coordination and control procedures should be properly created and applied. To achieve optimal performance, the sizing and positioning of shunt compensating devices must also be properly selected. Voltage fluctuations, resonance problems, or even equipment damage might result from overcompensation or poor positioning. The system requirements are evaluated, the suitable compensation levels are established, and the ideal sites for shunt compensation devices are identified using system studies, load flow analysis, and simulation tools. Voltage regulation, power factor correction, and reactive power control are all addressed by the crucial power system engineering technique known as shunt compensation. Shunt compensation promotes power system efficiency by reducing line losses, increasing power transfer capability, and stabilizing voltage by injecting or absorbing reactive power. It has uses in transmission systems, industrial facilities, distribution networks, and the integration of renewable energy sources. The effective use of shunt compensation in power systems is ensured by adequate design, protection measures, and control techniques, despite the difficulties of harmonic amplification and coordination. This helps to create an electrical infrastructure that is dependable, stable, and energy-efficient.

**Advantages and disadvantages of reactive power compensation:**In power systems, reactive power compensation has a number of benefits but also some drawbacks. Let's look at both of them:

**Reactive power compensation benefits include:**

**Improved Power Factor:** Shunt capacitors and other reactive power compensation devices help the system's power factor. Compensation lowers the reactive power flow from the source and brings the power factor closer to unity by balancing the reactive power demand of inductive loads. As a result, electrical power is used more effectively, line losses are decreased, and utility fines for low power factor use are minimized.

**Voltage Regulation:** Voltage regulation in power systems is aided by reactive power compensation devices, both shunt and series. Capacitors and other shunt compensation devices, which inject reactive power during low voltage conditions, aid in keeping voltage levels within reasonable bounds. This guarantees the best possible performance of electrical equipment and reduces the possibility of equipment damage brought on by voltage fluctuations.

**Enhanced Power Transfer Capability:** Series compensation and other reactive power compensation methods aid in enhancing the power transfer efficiency of transmission lines. Series compensation enables the transmission of more active power over longer distances without the need for significant infrastructure changes by lowering the effective reactance of the line.

**Reduction in Line Losses:** Reactive power correction lessens line losses by cutting back on reactive power flow and related line currents. Reactive power is locally supplied by shunt compensation devices like capacitors, which lowers the amount of reactive power drawn from the source and the ensuing line losses. This lowers the system's overall electricity consumption and increases energy efficiency.

**Voltage Stability and Grid Reliability:** Reactive power compensation is essential for preserving voltage stability and making sure that power networks are dependable in their functioning. Compensation devices avoid voltage collapse, minimize voltage sags and swells that may cause equipment malfunction or system disturbances by limiting reactive power flow and adjusting voltage levels.

**Reactive Power Compensation's drawbacks:**

Cost: Equipment procurement, installation, and maintenance costs are incurred when reactive power compensation devices are used. It is necessary to assess the cost-effectiveness of compensation methods while taking into account the advantages acquired in terms of increased power quality, decreased losses, and improved system performance.

**Harmonic Amplification:** If not correctly built or safeguarded, reactive power compensation devices, in particular shunt capacitors, can magnify harmonic frequencies. Unwanted frequencies known as harmonics are produced by nonlinear loads and can lead to voltage distortion, equipment failure, and communication system interference. To lessen the possibility of harmonic amplification, proper filtering, harmonic research, and safety precautions are required.

**Control and Coordination:** Coordinating and controlling reactive power compensation devices, particularly in big power systems, can be difficult. In order to ensure that the compensation devices react to system conditions effectively and prevent excessive reactive power flow or voltage instability, proper control techniques and coordination schemes are needed.

**Considerations for Design and Installation:** To obtain best performance, the sizing and installation of reactive power compensation devices should be carefully considered. Voltage fluctuations, resonance problems, or even equipment damage might result from overcompensation or poor positioning. The system requirements are evaluated, the proper compensation levels are established, and the best locations for the compensation devices are identified using system studies, load flow analysis, and simulation tools. Reactive power compensation has a number of benefits, including better power factor, improved voltage management, improved power transfer, and decreased line losses.

## CONCLUSION

In conclusion, by addressing problems with resistive losses, voltage drops, and power factor, reactive power compensation plays a crucial role in AC transmission lines. Numerous advantages are provided, such as increased power quality, decreased power losses, higher power transfer efficiency, and improved voltage stability. Depending on the particular needs of the transmission system, the appropriate compensation mechanisms are chosen and put into practice. The performance and efficiency of AC transmission lines can continue to be improved with more research and development into reactive power compensation methods.Cost, harmonic amplification, control coordination, and design issues are some of the difficulties it also presents. Reactive power compensation in power systems must be applied with proper planning, technical analysis, and execution tactics to be effective and profitable.

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CHAPTER 8

# FEATURES OF THE STATIC SHUNT COMPENSATORS

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**ABSTRACT:**

Devices called static shunt compensators (SSCs) are used in power systems to control voltage levels and enhance the quality of the power. They support reactive power and are often connected in parallel with the power system. An overview of SSCs, their function, and advantages in improving power system performance are given in this chapter.Power electronic Static Shunt Compensators (SSCs) are used in power systems to manage reactive power, adjust voltage, and enhance system stability. The main characteristics and functions of static shunt compensators are highlighted in this abstract. Static Shunt Compensators are intended to inject or absorb reactive power as necessary. They are connected in parallel with the electrical network. They are essential for preserving acceptable voltage levels, improved power quality overall, and boosting power factor. The significance of SSCs in voltage regulation and reactive power compensation is emphasized in the abstract. The basic categories of static shunt compensators, such as static vary compensators (SVCs) and static synchronous compensators (STATCOMs), are discussed in the abstract. While STATCOMs use voltage source converters based on insulated gate bipolar transistors (IGBTs), SVCs are composed of reactors and capacitors that are controlled by thermistors. For the best system performance, both types provide fine control over reactive power flow and voltage regulation.

**KEYWORDS:**

End-Of-Line Voltage Support, FC-TCR SVC, Mid-Point Voltage Regulation, Reactive Power Flow, Reactive Power Compensation, Static Vary Compensator, TSC-TCR SVC.

## INTRODUCTION

It has long been understood that with the right reactive shunt compensation, the steady-state transmittable power may be enhanced and the voltage profile down the line can be managed. This reactive compensation's goal is to alter the transmission line's inherent electrical properties so that they are more compatible with the current load demand. As a result, reactors with shunt connections that are fixed or mechanically switched are used to reduce line overvoltage under light load conditions, while capacitors with shunt connections that are fixed or mechanically switched are used to maintain voltage levels under high load conditions. In order to lay a basis for power electronics-based compensation and control strategies to satisfy specific compensation objectives, basic considerations to increase the transmittable power by ideal shunt-connected vary compensation will be covered in this section. Increasing the transmittable power is the main goal of reactive shunt compensation in transmission systems. This might be necessary to increase the system's stability and steady-state transmission characteristics. Vary compensation is therefore used for voltage regulation at the middle (or some intermediate) to segment the transmission line, at the end of the (radial) line to prevent voltage instability, and for dynamic voltage management to improve transient stability and reduce power oscillations.

**Midpoint Voltage Regulation for Line Segmentation:**

Midpoint voltage regulation, commonly referred to as line segmentation, is a power system technology used to promote voltage stability and voltage profiles along lengthy transmission lines. The transmission line is divided into several segments, and each segment's midpoint is equipped with a voltage regulating device, such as shunt capacitors or reactors. We will explain the idea of midpoint voltage regulation, as well as its advantages, disadvantages, and applications in power system engineering. Maintaining targeted voltage levels and ensuring voltage stability in long transmission lines are the key goals of midpoint voltage regulation. Voltage drops arise as a result of line resistance and inductive reactance during long-distance power transmission.

Voltage breaches, low voltage circumstances, and impaired system performance can result from these voltage dips. Midway voltage regulation uses line segmentation to maintain stable voltage profiles while compensating for voltage decreases and controlling the flow of reactive power. Devices for voltage regulation are placed at the midway of each segment. Improved voltage regulation and control is one of the key advantages of midpoint voltage regulation. The voltage levels can be actively adjusted and kept within predetermined limits by placing voltage regulation devices at each segment's halfway. When necessary, these devices inject or absorb reactive power to make up for voltage losses and maintain the line's voltage. This makes sure that no matter the length or electrical properties of the transmission line, the receiving end will always get a stable and acceptable voltage level[1]–[3].

Improved voltage stability is another benefit of midpoint voltage regulation. Long transmission lines may experience voltage instability as a result of voltage drops and reactive power requirements. Midpoint voltage regulation increases the line's voltage stability by inserting voltage regulation devices at regular intervals. It ensures the steady and dependable operation of the power system by assisting in the prevention of voltage collapse, voltage sags, and other voltage-related issues. Improvements in power quality are also facilitated by midpoint voltage adjustment. Electrical equipment performance can be significantly impacted by voltage changes and low voltage circumstances, which can result in decreased efficiency, greater losses, and probable equipment damage. Midpoint voltage regulation aids in the optimization of equipment functioning, the reduction of losses, and the improvement of power quality for both utility providers and consumers. Midpoint voltage regulation also provides flexibility in the design and growth of power systems.

Longer power transmission distances are now possible without sacrificing voltage characteristics. Midpoint voltage regulation boosts transmission capacity and makes it possible to integrate distant production sources, such renewable energy installations, into the grid by adjusting for voltage decreases along the line. This system planning flexibility encourages the establishment of a strong and sustainable power infrastructure and supports the efficient use of resources. Midpoint voltage regulation does, however, provide several difficulties and issues. To achieve best performance, the design and positioning of voltage control devices must be carefully considered. The planning and implementation of midway voltage regulation must take into account variables including line length, load characteristics, fault levels, and system stability. The system requirements are evaluated, the proper compensation levels are established, and the best places for voltage regulation devices are identified using system studies, load flow analysis, and simulation tools.

In order to ensure correct functioning and prevent excessive reactive power flow or voltage instability, coordination and control of the voltage regulation devices are crucial. For the devices to respond to system conditions effectively and to maintain voltage stability down the line, adequate control strategies and coordination plans are required. Cost factors are also taken into account when putting middle voltage regulation into practice. The benefits gained in terms of better voltage profiles, increased voltage stability, and higher power quality must be taken into account when evaluating the installation and maintenance costs of voltage control devices. Utilities can allocate resources more efficiently and deploy midway voltage regulation by using cost-effectiveness analysis. In conclusion, line segmentation, also known as midpoint voltage regulation, is a technique used to promote voltage stability and voltage profiles along lengthy transmission lines. This method makes up for voltage losses and aids in maintaining stable voltage levels by putting voltage regulating devices at the middle of each line segment. Higher voltage control, increased voltage stability, higher power quality, and flexibility in system planning and extension are all advantages of midpoint voltage regulation. However, for the successful deployment of midway voltage regulation in power networks, rigorous planning, design, coordination, and cost considerations are required.

**End of line voltage support to prevent voltage instability:**

A method used in power systems to reduce voltage instability and maintain stable voltage levels at the far end of long transmission lines is end-of-line voltage support. Voltage drops happen because of line resistance and inductive reactance when electricity is delivered across long distances. Voltage instability, low voltage circumstances, and impaired system performance can result from these voltage drops. Techniques for end-of-line voltage support help to make up for these voltage dips and provide voltage stability. The idea of end-of-line voltage support, its advantages, disadvantages, and applications in power system engineering will all be covered in this talk. Maintaining steady and appropriate voltage levels at the far end of lengthy transmission lines is the fundamental goal of end-of-line voltage support. High power demand, line losses, reactive power demand, and system faults are only a few causes of voltage instability. Voltage sags, voltage collapses, and other voltage-related disturbances can negatively impact the functioning of electrical equipment, increase losses, and potentially result in equipment damage due to voltage instability. The use of voltage regulation equipment, such as shunt capacitors or reactors, at the transmission line's far end is a component of end-of-line voltage support systems.

When necessary, these gadgets inject or absorb reactive power to make up for voltage losses and keep the voltage stable. End-of-line voltage support ensures that the receiving end of the transmission line receives a stable and acceptable voltage level, independent of the length and electrical properties of the line, by actively managing the reactive power flow. The enhanced regulation and control of voltage is one of the major advantages of end-of-line voltage support. The voltage levels can be actively managed and kept within predetermined limits by placing voltage regulation devices at the far end of the transmission line. These devices counteract voltage drops and changes to keep the voltage steady and within allowable working ranges at the receiving end. This improves the efficiency of electrical machinery and reduces the dangers brought on by voltage instability. Support for end-of-line voltage also improves power quality and system dependability. This method ensures the dependable operation of electrical equipment and lowers the risk of equipment failure by maintaining steady voltage levels at the distant end of the transmission line. The performance of sensitive equipment improves, and losses are decreased, as voltage changes, low voltage circumstances, and voltage-related disturbances are avoided.

End-of-line voltage support also increases system flexibility by allowing the incorporation of distant generation sources. Longer power transmission distances are now possible without sacrificing voltage characteristics. End-of-line voltage support boosts transmission capacity and makes it easier to integrate distributed production or renewable energy sources at remote sites by making up for voltage losses along the line. This system planning flexibility encourages the construction of a robust and sustainable power infrastructure and supports the efficient use of resources. End-of-line voltage support, however, is not without its difficulties and limitations. To achieve best performance, the design and positioning of voltage control devices must be carefully considered. The planning and implementation of end-of-line voltage support must take into account variables such line length, load characteristics, fault levels, and system stability. The system requirements are evaluated, the proper compensation levels are established, and the best places for voltage regulation devices are identified using system studies, load flow analysis, and simulation tools. In order to ensure correct functioning and prevent excessive reactive power flow or voltage instability, coordination and control of the voltage regulation devices are crucial.

To guarantee that the devices react to system conditions effectively and maintain voltage stability at the far end of the transmission line, proper control strategies and coordination plans are required. End-of-line voltage support is implemented taking into account costs as well. It is necessary to assess the installation and upkeep costs of voltage regulation devices in light of the advantages acquired in terms of better voltage profiles, increased system reliability, and higher power quality. Utilities can allocate resources more efficiently and provide end-of-line voltage support by using cost-effectiveness analysis. Finally, end-of-line voltage support is an essential method for preventing voltage instability and maintaining constant voltage levels at the remote end of lengthy transmission lines. This method corrects for voltage losses and provides voltage stability by placing voltage regulating devices at the end of the line. Improved voltage regulation, increased system reliability, improved power quality, and increased system flexibility are all advantages of end-of-line voltage support. However, for the successful application of end-of-line voltage support in power systems, thorough planning, design, coordination, and cost considerations are crucial.

## DISCUSSION

**Static Var Compensator:**A Static Var Compensator (SVC) is a versatile and efficient method for controlling voltage and compensating reactive power in power systems. In order to maintain voltage stability, control power factor, and manage system dynamics, it is a static device that uses power electronics to inject or absorb reactive power as needed. We will examine the idea of SVC, its elements, functioning, benefits, and applications in power system engineering during this talk. A shunt-connected thyristor-controlled reactor (TCR) and a shunt-connected thyristor-switched capacitor (TSC) are two essential parts of a static var compensator (SVC), a high-speed voltage control device. These parts enable the SVC to dynamically change reactive power flow in the system and control voltage levels, together with related control and protection systems.

SVC operation: The TCR and TSC components' control provides the foundation for how an SVC functions. The firing angle of the thyristors, which controls the impedance of the reactor, is controlled by the TCR to control the flow of reactive power that is inductive or capacitive. On the other hand, the TSC uses thyristors to turn the capacitor banks on or off in order to manage the flow of capacitive reactive power. The SVC's control system continuously monitors system variables like voltage, current, and power factor and modifies the TCR and TSC's output of reactive power as necessary. With the help of this dynamic control, the SVC is able to adjust to system changes fast, make up for reactive power imbalances, and keep voltage stability within reasonable bounds.

Advantages of SVC: SVC has a number of benefits for power system operation and control, including:

a. Voltage Stability: SVC's capacity to improve voltage stability is one of its main advantages. The SVC contributes to the regulation of voltage levels and the reduction of voltage fluctuations by injecting or absorbing reactive power as necessary. This is especially crucial for systems with high reactive power demands or large load state fluctuations.

b. Power Factor Correction: By addressing reactive power imbalances, SVC makes power factor correction possible. It lessens the load on generators, transmission lines, and distribution systems and helps to increase power factor. As a result, system losses are decreased and electrical power is used more effectively.

c. Quick Response: SVC's solid-state control devices enable quick reactive power compensation. It is appropriate for applications that call for quick voltage control and power factor correction since it can react to system changes in just milliseconds. SVC's quick response is especially useful in systems with dynamic demands or fluctuating generation, like industrial facilities or the integration of renewable energy sources.

d. Versatile Operation: The SVC provides variable reactive power control. It has a wide range of reactive power output adjustment capabilities, enabling accurate voltage control and power factor correction in a variety of system scenarios. SVC is adaptive to changing load requirements and shifting grid conditions because to its controllable reactive power injection or absorption.

e. Harmonic Mitigation: SVC can reduce harmonic system disruptions. The TCR and TSC components of the SVC can filter out harmonics and lessen voltage distortion brought on by nonlinear loads thanks to thyristor-based management. This enhances power quality, lowers equipment faults, and avoids communication system interference.

Applications of SVC: SVC has a wide range of uses in power systems, including the following:

a. Transmission Systems: SVC is frequently used in high-voltage transmission networks to improve voltage stability and manage the flow of reactive power. It can be installed at key points along transmission lines to optimize power transfer efficiency, enhance voltage profiles, and make up for voltage drops. Power transmission efficiency and dependability over long distances are enhanced by SVC.

b. Distribution Networks: SVC can be used to control voltage levels and enhance power quality in distribution networks. It makes up for reactive power imbalances, voltage sags or swells, and changes in load that produce voltage swings. In locations with sensitive loads or equipment that is voltage-sensitive, SVC helps maintain voltage stability and prevents under- or overvoltage problems.

c. Industrial Applications: To reduce reactive power and enhance power factor, industrial facilities use SVC. It aids in reducing voltage fluctuations brought on by heavy and active loads like motors, drives, or arc furnaces. SVC improves the power factor and stability of voltage levels, which boosts the effectiveness and performance of industrial processes.

d. Renewable Energy Integration: SVC is essential to the grid's ability to include renewable energy sources like solar and wind power. The varied and intermittent generation that these sources frequently display can affect the stability of the voltage. SVC enables easy integration of renewable energy sources into the current grid architecture by regulating voltage levels, compensating for reactive power swings, and reducing interference[4]–[6].

**Fixed capacitor- Thyristor controlled reactor SVC:**One kind of Static Var Compensator (SVC) utilized in power systems for reactive power compensation and voltage management is a Fixed Capacitor-Thyristor Controlled Reactor (FC-TCR). It provides adaptable and effective reactive power assistance by combining the advantages of fixed capacitors and thyristor-controlled reactors. We will examine the FC-TCR SVC idea, its elements, functionality, benefits, and applications in power system engineering during this session. Fixed capacitors and thyristor-controlled reactors are the two primary parts of the FC-TCR SVC. While thyristor-controlled reactors manage the inductive reactive power flow by modifying the reactors' impedance, fixed capacitors compensate for reactive power by introducing capacitive reactive power into the system. The FC-TCR SVC may efficiently control reactive power and uphold voltage stability in power systems by combining these elements.

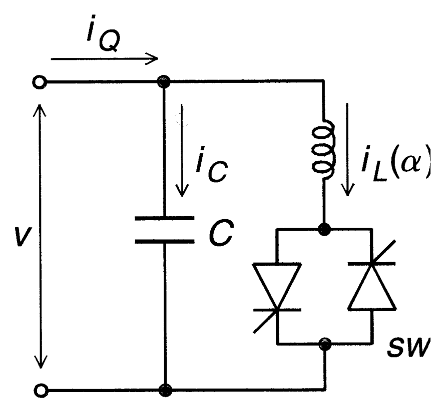


**Figure 1: Fixed capacitor- Thyristor controlled reactor SVC**

Operation of FC-TCR SVC: The thyristor-controlled reactors are used to operate the FC-TCR SVC. The firing angle, which affects the reactors' impedance, is managed by the thyristors. The FC-TCR SVC may change the amount of inductive reactive power injected into the system by varying the firing angle, so correcting for the reactive power demand or supply. Parallel to the thyristor-controlled reactors, the fixed capacitors in the FC-TCR SVC offer capacitive reactive power correction. To balance the inductive reactive power injected by the thyristor-controlled reactors, they inject capacitive reactive power. Reactive power from both inductive and capacitive sources permits the system's power factor and voltage levels to be controlled. Voltage, current, and power factor are all constantly monitored by the FC-TCR SVC's control system. In order to maintain the necessary amount of reactive power compensation and voltage stability, the control system modifies the firing angle of the thyristor-controlled reactors based on these readings.

Advantages of FC-TCR SVC: The FC-TCR SVC has a number of benefits for power system management and control, including:

a. Reactive Power Compensation: By combining fixed capacitors and thyristor-controlled reactors, FC-TCR SVC offers efficient reactive power compensation. To maintain the desired power factor and regulate voltage levels, it can inject or absorb reactive power as necessary. This enhances power quality and optimizes the use of system resources.

b. Voltage Stability: By controlling system voltage levels, FC-TCR SVC improves voltage stability. It corrects voltage fluctuations brought on by changes in load, unbalanced reactive power, or system disturbances. The FC-TCR SVC helps maintain a consistent and dependable power supply by offering dynamic voltage management.

c. Power Factor Correction: By making up for reactive power imbalances, the FC-TCR SVC raises power factor. It lessens the strain on generators, transformers, and other system components by assisting in keeping the power factor within specified bounds. As a result, system efficiency is increased, and losses are decreased.

d. Quick Response: Because the reactors are controlled by thyristors, FC-TCR SVC provides quick reactive power correction. It is appropriate for applications that call for quick voltage control and power factor correction since it can react to system changes in just milliseconds. The power system operates steadily and reliably because to FC-TCR SVC's quick response time.

e. Flexible Operation: Reactive power can be controlled with flexibility thanks to FC-TCR SVC. Under various system situations, it can precisely regulate voltage and rectify power factor by adjusting the reactive power output over a wide range. Due to its adaptability, FC-TCR SVC can handle a range of load requirements and shifting grid conditions.

Applications of FC-TCR SVC: There are numerous power system instances where FC-TCR SVC is applied:

a. System of Transmission: High-voltage transmission networks frequently employ FC-TCR SVC to improve voltage stability and manage reactive power flow. It can be used to make up for voltage losses, voltage oscillations, and reactive power imbalances at key points along transmission lines. Power flow is improved by FC-TCR SVC, which also contributes to reliable power transmission over long distances.

b. Distribution Networks: To maintain voltage stability and manage reactive power flow, FC-TCR SVC is essential in distribution networks. It ensures a steady supply of electricity to users by adjusting for voltage changes brought on by shifting loads and reactive power imbalances. Distribution network performance is improved, power losses are decreased, and voltage control is improved with FC-TCR SVC.

c. FC-TCR SVC is used in industrial facilities to control reactive power flow, enhance power factor, and regulate voltage levels. In the presence of dynamic and variable loads, such as motors, drives, and large machinery, it aids in maintaining ideal power factor and voltage stability. Industrial operations are operated effectively and with less power usage thanks to FC-TCR SVC.

d. Renewable Energy Integration: FC-TCR SVC helps the grid incorporate renewable energy sources like solar and wind. The varied and intermittent generation that these sources frequently display can affect the stability of the voltage. The FC-TCR SVC contributes to the smooth integration of renewable energy sources into the current grid architecture by regulating voltage levels, compensating for reactive power fluctuations, and ensuring power quality.

e. Voltage Support: In the event of emergencies or voltage dips in the power supply, FC-TCR SVC can offer voltage support. The FC-TCR SVC helps restore and maintain voltage levels by injecting capacitive reactive power, providing continuous power delivery to vital loads.

In summary, the Fixed Capacitor-Thyristor Controlled Reactor (FC-TCR) SVC is a flexible method for voltage regulation and reactive power compensation in power systems. The FC-TCR SVC provides advantages such reactive power compensation, voltage stability augmentation, power factor correction, quick reaction, and flexible operation by integrating fixed capacitors with thyristor-controlled reactors. It has uses in scenarios including voltage support, industrial facilities, renewable energy integration, distribution networks, and transmission systems. The use of FC-TCR SVC contributes to the improvement of power quality, performance optimization of power systems, and dependable and efficient operation of electrical networks.

e. trains and Traction Systems: To maintain voltage stability and manage reactive power flow, SVC is used in traction systems, such as electrified trains. Regenerative braking, fluctuating load circumstances, several trains running on the same track, or other factors are all taken into account. SVC contributes to the effective and dependable functioning of traction systems while preserving constant voltage levels.

Considerations and Challenges: Despite the fact that SVC has many benefits, there are a few things to keep in mind and difficulties with implementation.

a. System Modeling and Analysis: System modeling, load flow analysis, and dynamic simulations are essential for the precise sizing and positioning of SVC in the power system. Enhancing the system's performance and achieving the required control goals requires an understanding of the system dynamics and the identification of key areas for SVC implementation.

b. Control and Coordination: Control and coordination are crucial for the efficient operation of SVC in conjunction with other voltage control devices and protection systems. The SVC responds to system conditions appropriately, maintains voltage stability, and prevents any negative interactions with other system components thanks to proper control strategies and coordination plans.

c. Harmonic Considerations: The performance of SVC may be impacted by the presence of harmonics in the system. To make sure that SVC performs effectively and does not introduce or intensify harmonic distortions, harmonic filters or additional harmonic mitigation methods may be needed.

d. Cost Factors: The installation and upkeep expenses of SVC should be carefully weighed against the benefits realized in terms of improved power quality, voltage stability, and power factor correction. Utilities use cost-effectiveness analysis to make defensible judgments about the deployment of SVC and resource distribution.

The Static Var Compensator (SVC) is a versatile and efficient method for voltage regulation and reactive power compensation in power systems. Reactive power flow can be controlled by SVC, which also increases power factor, power stability, and dynamic control in a variety of applications such as transmission systems, distribution networks, industrial facilities, and the integration of renewable energy sources. SVC is a vital tool for power system engineers in assuring the dependable and effective functioning of electrical networks because to its benefits, including enhancement of voltage stability, rapid response, flexible operation, and harmonic mitigation. But for the successful application of SVC, extensive system analysis, control and coordination, harmonic considerations, and cost evaluations are essential.

**Thermistor switched capacitor-Thermistor controlled reactor SVC:**

A specific kind of Static Vary Compensator (SVC) utilized in power systems for reactive power compensation and voltage management is the Thermistor Switched Capacitor-Thermistor Controlled Reactor (TSC-TCR). To give accurate and effective control over reactive power flow, it combines the benefits of thermistor switched capacitors (TSCs) with thermistor-controlled reactors (TCRs). The idea of TSC-TCR SVC, its components, functionality, benefits, and applications in power system engineering will all be covered in this talk. Thyristor switched capacitors (TSCs) and thermistor-controlled reactors (TCRs) are the two primary parts of the TSC-TCR SVC. TSCs are switched capacitor banks that enable quick connections to or disconnections from the power grid in order to compensate for capacitive reactive power. The thyristor-controlled inductive reactors (TCRs), on the other hand, can change their impedance to inject or absorb inductive reactive power as necessary. The TSC-TCR SVC effectively controls reactive power flow and upholds voltage stability in power systems by fusing TSCs and TCRs.

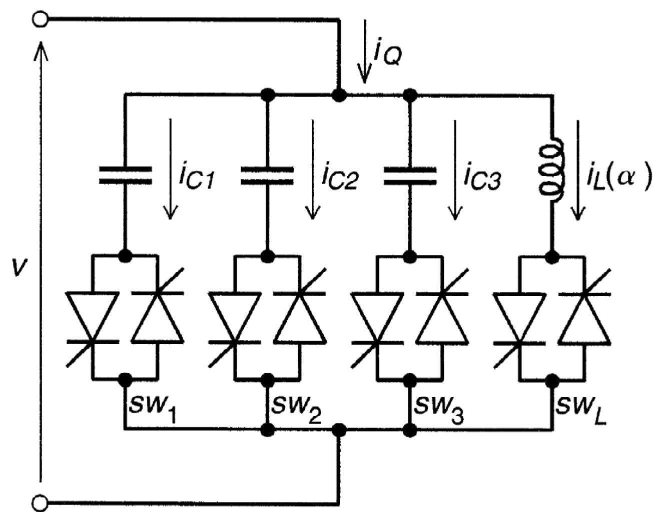


**Figure 2: Thyristor switched capacitor-Thyristor controlled reactor SVC**

Operation of TSC-TCR SVC: The TSC-TCR SVC's operation is based on the regulation of TSCs and TCRs, which regulate the flow of reactive power. Depending on the system needs for compensating capacitive reactive power, the TSCs are either turned on or off. TSCs improve the power factor and voltage levels of the system by adding capacitive reactive power when they are turned on. Depending on the situation, the TCRs can be adjusted to change their impedance and inject or absorb inductive reactive power. The quantity of inductive reactive power introduced into the system may be precisely controlled thanks to the thyristor-controlled switching of the TCRs. With this feature, the TSC-TCR SVC can balance the supply and demand for reactive power, ensuring the best possible power factor and voltage regulation. Voltage, current, and power factor are all constantly monitored by the TSC-TCR SVC's control system. These measurements are used by the control system to decide how to switch the TSCs in the right way and how to change the firing angle of the TCRs to keep the voltage stable and compensate for reactive power to the correct level.

Advantages of TSC-TCR SVC: The TSC-TCR SVC has a number of benefits for managing and operating power systems, including:

a. Compensation for Reactive Power: By integrating TSCs and TCRs, TSC-TCR SVC provides effective reactive power correction. In order to keep the proper power factor and voltage levels, it can inject or absorb reactive power as necessary. This enhances the quality of the electricity, lowers losses, and maximizes the use of system resources.

b. Voltage Stability: By controlling system voltage levels, TSC-TCR SVC improves voltage stability. It corrects voltage fluctuations brought on by changes in load, unbalanced reactive power, or system disturbances. The TSC-TCR SVC provides dynamic voltage regulation, ensuring a stable and dependable power supply.

c. Power Factor Correction: By making up for reactive power imbalances, the TSC-TCR SVC raises power factor. It lessens the strain on generators, transformers, and other system components by assisting in keeping the power factor within specified bounds. As a result, system efficiency is increased, and losses are decreased.

d. Quick Response: The TSC-TCR SVC provides quick reactive power compensation because of the TSCs' quick switching capabilities. It is appropriate for applications that call for quick voltage control and power factor correction since it can react to system changes in just milliseconds. The TSC-TCR SVC's quick response time guarantees the power system's dependable and steady functioning.

e. Versatile Operation: The TSC-TCR SVC offers variable reactive power control. Under various system situations, it can precisely regulate voltage and rectify power factor by adjusting the reactive power output over a wide range. TSC-TCR SVC's adaptability enables it to meet varied load requirements and shifting grid conditions.

Applications of TSC-TCR SVC: TSC-TCR SVC is used in a variety of power system settings, including:

a. System of Transmission: High-voltage transmission systems frequently employ TSC-TCR SVC to improve voltage stability and manage reactive power flow. It can be used to make up for voltage losses, voltage oscillations, and reactive power imbalances at key points along transmission lines. TSC-TCR SVC improves power flow and aids in ensuring dependable power transmission over long distances[7]–[10].

b. Distribution Networks: To maintain voltage stability and manage reactive power flow, TSC-TCR SVC is essential in distribution networks. It ensures a steady supply of electricity to users by adjusting for voltage changes brought on by shifting loads and reactive power imbalances. Distribution network performance is improved, power losses are decreased, and voltage regulation is improved by TSC-TCR SVC.

c. TSC-TCR SVC is used in industrial facilities to control voltage levels, enhance power factor, and control the flow of reactive power. In the presence of dynamic and variable loads, such as motors, drives, and large machinery, it aids in maintaining ideal power factor and voltage stability. Industrial operations are operated effectively and with less power usage thanks to TSC-TCR SVC.

d. Grid Integration of Renewable Energy Sources: TSC-TCR SVC helps the grid integrate renewable energy sources like wind and solar. The varied and intermittent generation that these sources frequently display can affect the stability of the voltage. The TSC-TCR SVC contributes to voltage regulation, reactive power compensation, and easy integration of renewable energy systems into the current grid architecture.

e. Voltage Support: In the event of emergencies or voltage dips in the power supply, TSC-TCR SVC can offer voltage support. The TSC-TCR SVC helps restore and maintain voltage levels by injecting capacitive reactive power, providing continuous power delivery to vital loads.

For reactive power compensation and voltage management in power systems, the Thyristor Switched Capacitor-Thyristor Controlled Reactor (TSC-TCR) SVC is a flexible option. The TSC-TCR SVC provides advantages such reactive power compensation, voltage stability augmentation, power factor correction, quick reaction, and flexible operation by integrating TSCs with TCRs.

## CONCLUSION

By controlling voltage levels and enhancing power quality, static shunt compensators are essential components of power systems. They contribute to the preservation of steady voltage profiles and the reduction of voltage fluctuations by offering reactive power assistance. Voltage control is made possible by their parallel connection to the power supply, which is quick and effective. When SSCs are used, the performance of the power system is increased, transmission losses are decreased, voltage stability is improved, and existing infrastructure is utilized more effectively. The usage of static shunt compensators will be crucial in ensuring a dependable and high-quality power supply as power systems continue to develop.It has uses in scenarios including voltage support, industrial facilities, renewable energy integration, distribution networks, and transmission systems. The use of TSC-TCR SVC contributes to the improvement of power quality, performance optimization of power systems, and dependable and efficient operation of electrical networks.

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**CHAPTER 9**

# APPLICATION OF THE AC TRANSMISSION STATOR

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**ABSTRACT:**

The versatile and effective Static Synchronous Compensator (STATCOM) is utilized in power systems for reactive power compensation and voltage management. It works as a voltage source inverter and is powered by power electronics. An overview of STATCOM's functions, uses, and advantages is given in this chapter. In order to maintain voltage stability, enhance power quality, and improve power system performance generally, the chapter emphasizes the significance of STATCOM.An essential part of alternating current (AC) transmission systems, the transmission stator is essential to the effective and dependable transfer of electrical power over long distances. In this abstract, the main characteristics and purposes of the AC transmission stator are highlighted. An AC generator or motor's stator, which consists of a core and windings, is a stationary component. It is in charge of producing a magnetic field that rotates or transforming mechanical energy into electrical energy. The stator's importance in the conversion and transmission of AC power is highlighted in the abstract.

**KEYWORDS:**

Power Factor, Reactive Power, Reactive Power Compensation, Static Synchronous Compensator, STATCOM, Voltage Stability.

## INTRODUCTION

The Static Synchronous Compensator (STATCOM), a power electronic component, is essential for reactive power compensation and voltage regulation in power systems. It is an adaptable and effective solution that contributes to the upkeep of voltage stability, the improvement of power quality, and the improvement of the electrical grid's general functionality. STATCOM uses cutting-edge power electronics technology and functions as a voltage source inverter. Maintaining stable voltage levels is difficult due to the growing complexity and variability of modern power systems, which are influenced by elements including the incorporation of renewable energy, dynamic loads, and shifting grid circumstances. Voltage sags, voltage swings, and reactive power imbalances are just a few problems that can result from voltage instability. These flaws may have a negative effect on the performance of electrical machinery, result in poor power quality, or even cause system failures. By dynamically adding or removing reactive power from the power supply as required, STATCOM responds to these problems.

By modifying its output voltage in reaction to system variables, it controls voltage levels. STATCOM helps to reduce voltage fluctuations, maintain voltage stability within acceptable bounds, and enhance power quality by offering quick and precise voltage management. Insulated gate bipolar transistors (IGBTs) or other power semiconductor devices are the foundation of STATCOM's operation. The STATCOM can respond to changes in system conditions within milliseconds thanks to these devices' precise and quick converter control. Typically attached in parallel to the grid, STATCOM functions as a shunt device. It has the capacity to produce both capacitive and inductive reactive power. STATCOM injects capacitive reactive power into the grid when the system needs it, making up for any reactive power shortages and boosting power factor. However, if there is too much reactive power, STATCOM can take it in and keep the power factor within specified bounds.

Voltage, current, and power factor are all continuously monitored by STATCOM's control system. The control system modifies the STATCOM's output voltage based on these readings in order to control reactive power flow and preserve voltage stability. Numerous power industry industries have found extensive use for STATCOM. It is frequently employed in transmission and distribution networks to improve voltage control and stabilityparticularly in setups where renewable energy sources are heavily incorporated. STATCOM is used in industrial facilities as well to control voltage levels, boost power quality, and optimize power factor. For voltage regulation and compensating reactive power, STATCOM is a crucial part of power systems. It is a vital component of the contemporary power grid due to its capacity to deliver quick and precise voltage regulation, better power quality, and increase system performance. A stable and effective electrical infrastructure is made possible by STATCOM, which is a vital enabler thanks to the continual improvements in power electronics technology[1]–[3].

The fast-acting Static synchronous Compensator (STATCOM) controls the voltage at the point of connection to the power grid by supplying or absorbing reactive current. It falls under the category of FACTS (Flexible AC Transmission System) devices. The technology is based on modular multi-level VSC configurations with semiconductor valves. However, non-symmetrical designs are conceivable by introducing mechanically or thyristor switched shunt elements with unified control systems to suit the majority of common applications. The dynamic reactive current output range is symmetrical (under typical disturbed network conditions). Because STATCOMs may provide quick fault current injection that is only limited by the rated current, they are highly useful for preserving voltage during network faults and improving short-term voltage stability. Additionally, STATCOMs can adjust power factor, manage reactive power, dampen low-frequency power oscillations (often through reactive power modulation), implement active harmonic filtering, reduce flicker, and enhance power quality. Electric power transmission, distribution, heavy industrial plant electrical networks, arc furnaces, high-speed rail systems, and other electric systems are typical applications where voltage stability and power quality are crucial.

**Technology types:**Multi-level VSCs based on IGBTs, phase reactors, and step-up transformers make up a common STATCOM design. The grid is shunt-connected to it. By creating a regulated internal voltage waveform, the reactive current is either supplied or absorbed. The majority of STATCOMs on the market today function as GFCs and need a grid voltage reference to function (with a specific degree of grid strength). In response, the voltage waveform is modified taking into account the voltage at the grid connection point. In general, the STATCOMs function as AC current-controlled devices, but the output current is controlled by modulating the internal voltage of the STATCOM (behind the phase reactor), whose angle to the grid connection point voltage is almost 90 degrees. Capacitive reactive electricity is supplied to the grid if the STATCOM voltage amplitude is greater than the system voltage amplitude. If current travels in the other direction, from the system to the STATCOM, inductive reactive power is produced. The thermal limits of the IGBTs are reached by the reactive current, which is dependent on the voltage difference and the transformer short circuit reactance. The system voltage is within predetermined bounds, both voltage amplitudes are equal, and no reactive power is exchanged with the grid during normal operation. An established control is for the STATCOM to function as an inductive element and absorb reactive power from the grid by decreasing the amplitude of the STATCOM voltage waveform if the grid voltage is higher than the threshold value. The size of the voltage waveform will increase as the grid voltage rises beyond the threshold level, turning the STATCOM into a capacitive element and supplying reactive current to the grid.

The STATCOM (also known as the SSC) is a shunt-connected reactive-power compensation device that can generate, absorb, or both, and whose output can be adjusted to regulate particular system characteristics.

In principle, it is a solid-state switching converter that, when fed from an energy source or energy storage device at its input terminals, is able to generate or absorb independently regulated real and reactive power at its output terminals.

The STATCOM that is being discussed in this chapter is a voltage-source converter that creates a series of 3-phase ac output voltages from a given input of dc voltage, each of which is coupled to the corresponding ac system voltage through a relatively small reactance (which is either provided by an interface reactor or the leakage inductance of a coupling transformer). An energy-storage capacitor provides the direct current voltage.

According to IEEE, STATCOM is a self-commutated switching power converter that can be connected to an AC power system for the exchange of independently controllable real and reactive power. It is powered by a suitable electric energy source and operates to produce a set of adjustable multiphase voltage.

## DISCUSSION

Statcom is a managed source of reactive power. It completely uses electronic processing of the voltage and current waveforms in a voltage-source converter (VSC) to generate and absorb the appropriate reactive power. Figure1 depicts a single-line STATCOM power circuit in which a VSC is magnetically coupled to a utility bus. A STATCOM is depicted in Figure1 as an adjustable voltage source behind a reactance, which eliminates the need for capacitor banks and shunt reactors for the generation and absorption of reactive power. This results in a STATCOM's compact design, small footprint, low noise, and minimal magnetic impact. By changing the amplitude of the converter's 3-phase output voltage, Es, the exchange of reactive power between the converter and the ac system can be managed.

That is, if the output voltage amplitude rises over the utility bus voltage, /Et/, current flows via the converter's reactance and into the ac system, where it is converted into capacitive-reactive power. Current flows from the ac system to the converter and the converter absorbs inductive-reactive power from the ac system if the amplitude of the output voltage is reduced below the utility bus voltage.

The reactive-power exchange becomes zero when the output voltage reaches the ac system voltage, and the STATCOM is then considered to be in a floating condition. Real-power exchange between the converter and the ac system can be similarly controlled by adjusting the phase shift between the converter-output voltage and the ac system voltage. In other words, if the converter output voltage is set to lag the voltage of the ac system, the converter can give actual power to the ac system from its dc energy storage. On the other hand, if its voltage lags behind the ac-system voltage, it can actually absorb real power from the ac system for the dc system. A STATCOM exchanges the instantaneous reactive power among the ac system's phases to produce the desired reactive power. By taking into account the relationship between the converter's output and input powers, it is possible to comprehend the method by which the converter internally generates and/or absorbs the reactive power. The converter switches link the dc-input circuit and the ac-output circuit together directly. This means that, when losses are taken into account, the net instantaneous power at the ac output terminals must always be equal to the net instantaneous power at the dc input terminals.

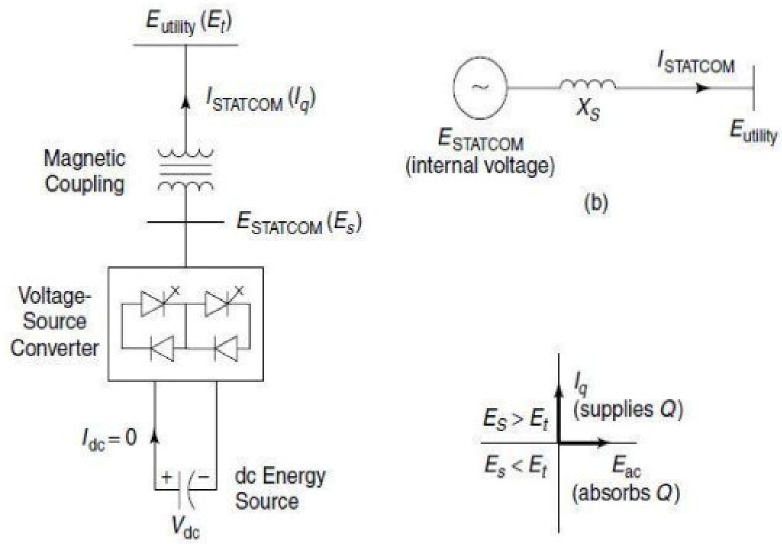


**Figure 1: Block Diagram of STATCOM**

Suppose the converter is being used to deliver reactive output power. In this scenario, the converter's real power intake from the dc source must be zero. Additionally, since the reactive power at zero frequency (dc) is by definition zero, the dc source does not contribute any reactive power to the converter's input, and the converter does not produce any reactive output power as a result.

In other words, the converter merely interconnects the three output terminals to allow free flow of the reactive output currents. When the ac system's terminals are viewed in this light, the converter creates a circulating reactive-power exchange between the phases. However, the dc capacitor must naturally be provided to or absorbed from its dc terminals in order to supply or absorb the actual power that the converter exchanges with the ac system at its ac terminals.Although converter switches internally generate reactive power, a dc capacitor must still be attached across the converter's input terminals. The capacitor is primarily required to act as a voltage source and circulating-current route. To avoid it, the size of the capacitor is designed so that the dc voltage across its terminals stays relatively constant from adding to the dc current's turbulence.

The smooth sinusoidal current from the ac system is pulled into a staircase wave that represents the VSC-output voltage, producing a small variation in the converter's output power. However, the converter must draw a fluctuating current from its dc source in order to comply with the instantaneous power-equality requirement at its input and output terminals. It is possible to determine the minimal capacitance needed to meet system requirements, such as ripple limitations on the dc voltage and the rated-reactive power support required by the ac system, depending on the converter architecture used. When using the capacitive- or inductive- reactive current, the VSC functions at the same rated-current capacity. As a result, a VSC with a particular MVA rating provides the STATCOM with twice the MVAR dynamic range (which also aids in compact design)[4]–[6].

To sustain (stabilize) the controlled dc voltage required for the VSC's operation, a dc capacitor bank is used. Voltage-source converter-type power electronics are used to generate the reactive power of a STATCOM. Depending on the required output power and voltage, the VSC may be a 2-level or 3-level kind. The STATCOM is created by connecting a number of VSCs in a multi-pulse configuration. To reduce converter losses in the steady state, the VSCs use fundamental-frequency switching. However, a pulse width modulated (PWM) mode is employed to stop the fault current from accessing the VSCs during transitory situations brought on by line faults. In this manner, transients on the AC side can be handled by the STATCOM without blocking.

**Operation of STATCOM:**A Static Synchronous Compensator (STATCOM)'s ability to provide voltage control and reactive power compensation in power systems depends on a number of essential parts and control techniques. This response will give a general overview of how STATCOM operates, describing its essential parts, control strategies, and the function it plays in preserving voltage stability and enhancing power quality.

Converter System: One of the most important parts of STATCOM is the converter system, which is made up of power semiconductor components including insulated gate bipolar transistors (IGBTs) and gate turn-off thyristors (GTOs). The exact control of electricity flow to or from the grid is made possible by these devices. The converter system transforms the incoming grid-supplied AC voltage into DC voltage before creating the desired output AC voltage waveform. The converter system serves as an interface between the grid and the DC connection and functions as a voltage source inverter (VSI).

DC Link: The DC link, which serves as an energy storage medium, is a crucial component of the STATCOM. It is made up of a capacitor bank that stores power as DC voltage. The converter system may generate the desired AC voltage waveform at the output thanks to the energy supplied by the capacitor bank. To guarantee the stability and functionality of the STATCOM, a control mechanism maintains the DC link voltage at a consistent level.

Control System: STATCOM's control system is essential for controlling voltage and reactive power flow. It continuously checks system variables like voltage, current, power factor, and reactive power and modifies the converter system's operation as necessary. To maintain the intended system conditions, the control system employs a variety of control techniques, including as voltage control, power factor control, and reactive power management. These control methods entail modifying the switching frequency of the converter system as well as the strength and phase of the output voltage.

Voltage Control: Voltage control is one of STATCOM's main duties. In order to determine the desired reference voltage, the control system measures the grid voltage. The control system modifies the STATCOM's output voltage magnitude and phase angle based on the comparison in order to keep the grid voltage within the specified bounds. The STATCOM helps reduce voltage fluctuations and maintain grid voltage stability by injecting or absorbing reactive power.

Power factor regulation: STATCOM is also essential for power factor regulation. The grid's power factor is measured by the control system, and it is then contrasted with the ideal reference power factor. In order to obtain the appropriate power factor, the control system modifies the reactive power output of the STATCOM based on the comparison. The STATCOM injects capacitive reactive power when the power factor is behind, and it absorbs inductive reactive power when the power factor is leading. The STATCOM aids in enhancing the power factor and lowering system losses by doing this.

Reactive Power Control: Another crucial component of STATCOM operation is reactive power control. To maintain a balance between reactive power supply and demand, the control system continuously analyzes the reactive power flow within the system and modifies the output reactive power of the STATCOM. The STATCOM helps control the flow of reactive power, increase voltage stability, and improve power quality by injecting or absorbing reactive power as necessary.

Protection and communication: STATCOM is often integrated into the power grid's overall control and protection system. It interacts with other control mechanisms and systems to coordinate actions and exchange data. Additionally, STATCOM is outfitted with a number of security measures to guarantee dependable and secure operation. These safeguards include fault detection, overcurrent protection, and overvoltage protection.

**V-I Characteristics of STATCOM:** Figure 2 shows a typical STATCOM V-I characteristic. As can be seen, regardless of the level of ac-system voltage, the STATCOM is able to independently manage its output current over the rated maximum capacitive or inductive range and can provide both capacitive and inductive compensation. In other words, the STATCOM can deliver all capacitive-reactive power, even at the lowest system voltage of 0.15 pu. The STATCOM's ability to deliver the full output of capacitive generation practically regardless of the system voltage (constant-current output at lower voltages) indicates the technology's strength. When the STATCOM is required to maintain the system voltage during and after disturbances, this capability is very helpful because voltage collapse would otherwise be a limiting factor.

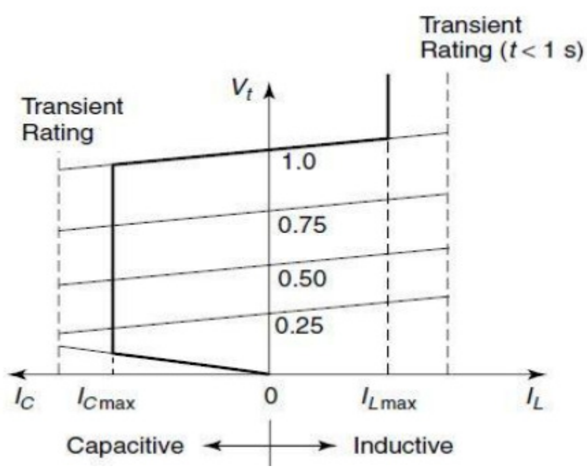


**Figure 2: V-I Characteristics of STATCOM**

The STATCOM has a higher transient rating in both the capacitive and inductive operating zones, as shown in Figure 2. The maximum current turn-off capability of the converter switches determines the maximum transient overcurrent that can be achieved in the capacitive zone. The maximum permissible junction temperature of the converter switches controls the transient current rating of the STATCOM because the converter switches are naturally commutated in the inductive region. Since the converter's semiconductor switches are not lossless in practice, the energy stored in the dc capacitor must eventually be used to offset the converter's internal losses. The voltage of the dc capacitor decreases. However, when the STATCOM is utilized for the creation of reactive power, the converter itself can the capacitor had reached the necessary voltage level of charge. This duty is completed by causing the converter's output voltages to lag behind ac system voltages by a slight angle (often between 0.18 and 0.28). In order to cover its internal losses and maintain the desired capacitor voltage, the converter uses a tiny amount of real power from the ac system. The same process can be used to change the capacitor voltage and, consequently, the converter output voltage's amplitude to adjust the creation or absorption of var.The STATCOM and ac system's interchange of reactive and actual power can be managed separately from one another. If the STATCOM is fitted with an energy-storage device, any combination of actual power generation or absorption with var generation or absorption is feasible.

**Typical application of STATCOM:**In order to address voltage stability difficulties, boost power quality, and improve the overall performance of electrical grids, the Static Synchronous Compensator (STATCOM) is a flexible device used in several applications across power systems. This response will give an overview of common STATCOM applications while highlighting its function and advantages in various situations.

Voltage Stability Enhancement: Voltage stability enhancement is one of the main uses for STATCOM. Voltage instability in power systems can be caused by a number of things, including heavy and variable loads, reactive power imbalances, or the incorporation of renewable energy sources. STATCOM contributes to maintaining steady voltage levels within permissible bounds and mitigating voltage fluctuations. STATCOM changes the voltage in real-time by injecting or absorbing reactive power, providing voltage stability and reducing the chance of voltage collapse.

Transmission systems: STATCOM is frequently used to enhance voltage control and manage power flow in high-voltage transmission systems. To make up for voltage losses and reactive power imbalances, it can be carefully deployed at specified points along transmission lines. When there are varying load conditions, voltage sags, or other contingencies, STATCOM aids in maintaining voltage stability. STATCOM improves the efficiency of power transmission, lowers losses, and raises the general performance of transmission networks by dynamically managing the flow of reactive power.

Distribution Networks: STATCOM is essential for preserving voltage stability and power quality in distribution networks. Voltage levels may change as electricity is delivered to consumers as a result of shifting loads and reactive power imbalances. Distribution substations use STATCOM to control voltage and account for fluctuations in reactive power. It guarantees that voltage stays within appropriate ranges, enhances power factor, and lessens end-user voltage swings. STATCOM aids to the dependable functioning of distribution networks and boosts the functionality of connected electrical equipment by improving power quality.

Renewable Energy Integration: STATCOM plays a crucial role in the grid's ability to incorporate renewable energy sources like wind and solar. The voltage quality and variability of the grid may be impacted by these sources' frequent fluctuating and intermittent generation patterns. By providing voltage support and adjusting for reactive power variations, STATCOM lessens the difficulties posed by the integration of renewable energy sources. It helps to keep the grid's voltage stable, control power flow, and guarantee the seamless integration of renewable energy technologies. Increased use of renewable energy is made possible by STATCOM while preserving the stability and dependability of the grid.

Applications in Industry: STATCOM is widely used in industrial facilities to control voltage levels and improve power quality. Industries frequently feature dynamic and erratic loads, such as motors, drives, and large machinery, which might compromise the stability of the power system. STATCOM enhances power factor, corrects for reactive power imbalances, and offers quick voltage management. It lessens voltage fluctuations, aids in voltage stabilization during load changes, and assures the effective running of industrial processes. Additionally, STATCOM helps reduce power losses and optimize energy use, which saves money for industrial consumers.

Reactive Power Compensation: Reactive power compensation is yet another crucial STATCOM application. It contributes to power factor correction by balancing the supply and demand for reactive power. When necessary, STATCOM injects or absorbs reactive power to keep the power factor within desirable bounds. By doing this, the power system becomes more efficient overall, losses are decreased, and the use of the electrical infrastructure is improved.

The Static Synchronous Compensator (STATCOM), in sum, has a variety of uses in power systems. Voltage stability improvement, transmission and distribution network assistance, renewable energy integration, industrial applications, and reactive power compensation are some of its key responsibilities. STATCOM is a crucial tool for preserving stable and dependable electrical networks because of its capacity to control reactive power flow, regulate voltage, and enhance power quality. The implementation of STATCOM increases power factor adjustment, facilitates the integration of renewable energy sources, improves industrial process efficiency, and improves transmission and distribution system performance.

**Application of STATCOM under dynamic state:**The Static Synchronous Compensator (STATCOM) is an adaptable and dynamic device with a variety of uses in power systems. Power systems go through quick changes in load, voltage, and system conditions in dynamic states. In these situations, STATCOM offers reactive power compensation, quick and precise voltage control, and increased system stability. This response will give an overview of STATCOM's uses in dynamic states, highlighting its functions and advantages in diverse contexts.

Voltage Support during Transient Conditions: Power systems frequently face sudden variations in voltage and current during transient events like system faults or switching activities. These occurrences may result in voltage dips, swells, and fluctuations, which may create instability and perhaps harm equipment. By quickly injecting or absorbing reactive power in response to these transitory situations, STATCOM helps to maintain the system voltage. STATCOM minimizes equipment disturbances, prevents voltage collapse, and keeps the system stable by offering voltage support during these dynamic events.

Fault Ride-Through Capability: STATCOM is essential in assisting the grid's fault ride-through capability in the case of a fault in the electricity system. A defect causes a sudden rise in current in the system, which can cause a substantial reduction in voltage. The voltage dip is efficiently mitigated and the system recovers more rapidly thanks to STATCOM's quick response and injection of reactive power. This functionality guarantees continuous power supply and minimizes downtime, particularly in delicate applications where even a little voltage dip might have serious repercussions.

Integration of Renewable Energy Sources: Renewable energy sources have variable and sporadic generation patterns, including wind and sun. Voltage regulation and the stability of the power system are challenged by the integration of these sources. Through the provision of dynamic voltage support and reactive power correction, STATCOM plays a crucial part in guaranteeing the seamless integration of renewable energy sources. It contributes to system voltage regulation, reduces voltage variations brought on by fluctuating renewable energy, and enhances the grid's overall stability under dynamic circumstances.

Grid Resynchronization: Following a blackout or system restoration, STATCOM aids in the safe and reliable reconnection of the electricity system during grid resynchronization. Voltage and frequency can change considerably as the system is brought back up. By offering reactive power compensation and assuring a controlled and gradual resynchronization process, STATCOM contributes to the maintenance of steady voltage levels. STATCOM helps the grid regain steady operating conditions free of jarring voltage or frequency fluctuations by dynamically changing its output.

Load Shedding Mitigation: STATCOM assists in reducing the necessity for load shedding when the power system is subjected to high and fluctuating loads. The regulated reduction of electricity demand known as load shedding is done to avoid system overload or instability. Reactive power injection via STATCOM helps the system maintain voltage levels and lessens the requirement for load shedding during periods of high demand or unexpected load changes. This guarantees a constant supply of electricity, limits consumer disturbances, and raises the overall dependability of the power system[7]–[10].

Rapid Voltage Regulation: STATCOM provides accurate and swift voltage regulation, enabling it to react swiftly to modifications in system circumstances. To maintain the desired voltage levels, it continuously monitors the system voltage and modifies its output voltage as necessary. In order to provide a consistent and dependable supply of electricity, this dynamic voltage management aids in stabilizing the grid during transient events, load fluctuations, and disturbances.

The Static Synchronous Compensator (STATCOM) is a flexible tool that finds useful applications in power systems under dynamic situations. It is an invaluable instrument for maintaining grid dependability, minimizing voltage disturbances, promoting the integration of renewable energy sources, and guaranteeing uninterrupted power supply due to its capacity to provide quick and accurate voltage management, reactive power compensation, and system stability enhancement. The dynamic capabilities of STATCOM make it a crucial part of contemporary electrical grids since they contribute to the overall efficiency and stability of power systems.

## CONCLUSION

In order to control voltage and compensate for reactive power, STATCOM has become an essential part of power systems. It is a crucial instrument for preserving voltage stability because of its quick and precise voltage regulation capabilities, particularly when using renewable energy sources and dynamic loads. Numerous benefits of STATCOM include its quick response time, high level of adaptability, and effective functioning. It contributes to a higher power factor, lower losses, and better power system performance by injecting or absorbing reactive power as necessary. The deployment of STATCOM is becoming more common in transmission and distribution networks, renewable energy systems, and industrial applications as a result of the rising demand for dependable and high-quality power supply. The capabilities and efficacy of STATCOM are anticipated to be substantially improved by the current developments in power electronics technology, making it a crucial tool for voltage regulation and reactive power compensation in upcoming power systems.

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## CHAPTER 10

# APPLICATION OF THE STATIC SERIES COMPENSATORS

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**ABSTRACT:**

Devices called static series compensators (SSCs) are used in electrical power networks to control the voltage on transmission lines, reduce power oscillations, and improve system stability. They typically provide regulated voltage injection and are connected in series with the transmission line. An overview of SSCs, their operation, and their substantial contributions to power system control and stability are given in this chapter.Power systems use static series compensators (SSCs) as important components to increase transmission effectiveness, voltage management, and system stability. The main characteristics and functions of Static Series Compensators are highlighted in this abstract as an overview. Power electronic-based Static Series Compensators are connected in series with transmission lines to improve the performance of the power system. They manage the transmitted power and reactive power flow by dynamically injecting or absorbing voltage in series with the line. The importance of SSCs in optimizing power transmission and voltage regulation is highlighted in the abstract. The main varieties of static series compensators, such as voltage-sourced series converters (VSCs) and thermistor-controlled series capacitors (TCSCs), are covered in the abstract. In contrast to VSCs, which use voltage source converters based on insulated gate bipolar transistors (IGBTs) to adjust the injected voltage, TCSCs use thermistor-based switching elements to change the line reactance. The series voltage compensation can be precisely controlled for both types.

**KEYWORDS:**

Reactive Power, Series Capacitive Compensation, Thyristor-Switched Series Capacitor, TSSC, Voltage Stability.

## INTRODUCTION

Reactive shunt compensation has been demonstrated to be very successful at upholding the required voltage profile along the transmission line linking two ac system buses and supporting the end voltage of radial lines in the face of rising power demand. Therefore, if a sufficiently large angle between the two end voltages could be formed, reactive shunt compensation, when applied at sufficiently near intervals along the line, may theoretically make it possible to transmit power up to the thermal limit of the line. Shunt compensation is unsuccessful at regulating the actual transmitted power, which is ultimately governed by the series line impedance and the angle between the line's end voltages at a certain transmission voltage.

It has long been understood that the series reactive impedance of the line is what essentially restricts the transmission of ac power over long distances. Years ago, series capacitive compensation was developed to reduce some of the reactive line resistance and boost transmittable power. The FACTS program has since shown that variable series compensation is extremely successful in regulating power flow in the line and enhancing stability. A key component of FACTS technology is controllable series line compensation. By regulating power flow in the lines, eliminating loop flows, and using quick controls to lessen the impact of system disturbances, it can be used to achieve maximum utilization of transmission assets and reduce traditional stability margin needs[1]–[3].This section will go through the fundamentals of reactive series compensation in order to lay the groundwork for the discussion of compensators based on power electronics. We'll look at how series compensation affects the fundamental variables that determine the maximum power that can be transmitted while maintaining steady-state power transmission limits, transient stability, voltage stability, and power oscillation damping.

**Series capacitive compensation:**A method used in power systems to increase voltage stability and transmission capacity is series capacitive compensation. To account for the transmission line's inductive reactance, capacitors are installed in series with the lines. An overview of the idea of series capacitive compensation, its advantages, and its use in power systems will be given in this response. Transmission lines in power systems show both resistance and inductive reactance due to the inductance of the line. Along the line, this reactance may result in voltage drops that cause voltage instability and power losses. By adding series capacitors, the line's overall reactance is decreased, which enhances voltage regulation and boosts transmission capacity. The reactance inversion property of capacitors is the core idea behind series capacitive compensation. In contrast to inductive reactance (jXL), capacitors exhibit a negative reactance (-jXc). Transmission lines see a net drop in reactance when capacitors are connected in series with them because the negative reactance of the capacitors cancels out the positive reactance of the line. This decrease in reactance enhances the voltage profile down the line and boosts the capacity for power transfer.

**Series capacitive compensation has several advantages, including:**

Voltage Profile Improvement: Series capacitors make up for the transmission lines' inductive reactance, reducing voltage dips and enhancing voltage regulation. This promotes constant voltage levels and enhances the grid's power quality for grid-connected consumers.

Enhanced Power Transfer Capability: Series capacitive compensation improves the transmission line's power transfer efficiency by lowering reactance. Higher power transfer is possible thanks to the enhanced voltage profile without going against the voltage limitations.

Power Loss Reduction: Series capacitors aid in the reduction of power losses in transmission lines. Reduced reactance lowers the voltage drop across the line, reducing I2R losses and raising total system efficiency.

Enhanced System Stability: Series capacitive compensation increases the overall stability of the power system by enhancing voltage stability and lowering voltage fluctuations. It lessens the chance of voltage breakdown and aids in maintaining acceptable voltage levels during emergencies.

The installation of capacitors at predefined points along the transmission line is required to conduct series capacitive compensation. To enable control of the compensation level, the capacitors are normally connected to the line through an appropriate switching configuration. Depending on the needs and conditions of the system, the compensation level can be changed. When adopting series capacitive compensation, it is crucial to take into account a number of aspects, such as:

Voltage Control: Appropriate control mechanisms must be in place to regulate the reactive power output of the series capacitors and keep voltage within acceptable bounds. Monitoring the system voltage and modifying the correction level as necessary are required.

Transient Response: It is important to take into account how the series capacitors will behave under transient circumstances, such as switching operations or malfunctions. To ensure the safe and dependable operation of the compensation system, appropriate protection and control mechanisms should be put in place.

Harmonics and Resonance: Series capacitive compensation may introduce harmonic currents and perhaps lead to resonance problems. To reduce harmonic distortion and prevent resonance issues, appropriate filtering and harmonic mitigation techniques should be used.

Communication and Control System: To coordinate the compensation level and guarantee its interoperability with other control devices and protection systems within the power network, series capacitive compensation requires a strong communication and control system.

Series capacitive compensation is a useful method for increasing the transmission speed and voltage stability in power systems. Capacitors are added in series with transmission lines to compensate for the inductive reactance, which enhances voltage profiles, boosts power transfer efficiency, and lowers power losses. In order to successfully use series capacitive compensation and provide improved power system performance and reliability, proper design, control, and coordination are crucial.

**Series compensation:**Modern power electronics-based shunt compensators can be made in one of two ways: one uses switching power converters to create a controllable synchronous voltage source, while the other uses switching capacitors and reactors controlled by thyristors to realize available reactive admittance. A reversal of the shunt compensator is the series compensator. The shunt compensator, which is connected in parallel with the transmission line to adjust its voltage, functions as a controlled reactive current source. When linked in series with the transmission line to control its current, the series compensator functions as a controlled voltage source. This equivalence implies that a series compensator exists for both the admittance and voltage source type shunt compensators. In fact, as previously mentioned, the series compensator can be implemented as either a controlled voltage source in series with the line or as a changeable reactive impedance. Due to the contrast between the shunt and series compensators, many of the principles, circuit designs, and control strategies mentioned earlier can be applied to the current subject in a complementary manner. That is to say, in shunt compensation, the transmission voltage serves as the primary reference parameter, whereas in series compensation, the line current does. As a result, the functioning of the series compensator is seen from the perspective of the line current, whereas that of the shunt compensator is seen from the perspective of the transmission voltage. In order to develop a general understanding and unified perspective for the role and application of controllable reactive compensation for electric power transmission, this chapter will take advantage of this complementary relationship to build upon the principles established for shunt compensation and extend them to series compensation.

**Summary of functional requirement:**Power flow issues are primarily addressed by the series compensator. These issues could be caused by the structure of the transmission network or the length of the line. Fixed (percent) compensation of the line allows the electric length to be reduced to accommodate the needs of power transmission. Controlled series compensation may be necessary for network structure-related issues, which frequently lead to power flow unbalance, parallel power flows, and loop power flows, especially if contingency or planned network modifications are anticipated. The end-voltage variation of radial lines can also be reduced and voltage collapse can be avoided by using fixed or controlled series capacitive compensation. Series compensation, when properly controlled to counteract current machine swings, can significantly improve post-fault systems' transient stability and be a highly effective power oscillation dampener. To maximize transmission efficiency, appropriately organized and controlled series compensation can be used without running the risk of sub synchronous resonance lines.

Flexible AC Transmission Systems of the future will use a variety of controlled series compensators will be crucial in sustaining power flow along predetermined lines, creating backup flow routes in case of emergency, managing line loading, and generally guaranteeing the most effective use of the transmission network. As with shunt compensation, it will be demonstrated that voltage-source type converter-based compensators and thyristor-controlled impedance type compensators may both achieve controlled series compensation to satisfy the aforementioned functional requirements. However, the two types of series compensators have quite different performance and operational characteristics.

## DISCUSSION

**GTO Thermistor-controlled series capacitor:** A specialized component used in power systems to offer series capacitive compensation is the GTO (Gate Turn-Off) Thyristor-Controlled Series Capacitor (TCSC). To dynamically adjust the reactance of transmission lines, it combines a series capacitor and the switching ability of GTO thermistors. This answer will go into great detail on the GTO Thermistor-Controlled Series Capacitor's operation, advantages, and uses in power systems. A power electronic component called the GTO Thyristor-Controlled Series Capacitor (TCSC) is intended to give transmission lines dynamic series capacitive compensation. GTO thyristors are used as the switching components in this more sophisticated type of series capacitive compensation. The GTO thyristors provide for exact control of the compensation level, enabling dynamic modification of the reactive power output of the series capacitor.

The GTO Thyristor-Controlled Series Capacitor's Operation: A series capacitor, a switching module using thyristors, and a management system make up the TCSC. The thyristor switches govern the connection and disconnection of the series capacitor from the transmission line, which is connected in series with it. The series capacitor is cut off from the line while the TCSC is in the bypass mode during typical operation. In this situation, the transmission line's inductive reactance is the only factor affecting the line's reactance. The thyristor switches are triggered to turn on, connecting the series capacitor to the line, when reactive power compensation is necessary. The capacitor reduces the line's overall reactance by injecting reactive power into it. This correction aids in enhancing the power system's overall stability, power transmission capacity, and voltage regulation. The voltage, current, and line impedance of the system are all constantly monitored by the TCSC's control system. The control system determines the necessary compensation level based on these readings and activates the thyristor switches in accordance. The reactive power output of the series capacitor is precisely and promptly adjusted by the control system to satisfy shifting system needs[4]–[6].

GTO Thyristor-Controlled Series Capacitor Advantages: Several advantages of the GTO Thyristor-Controlled Series Capacitor (TCSC) in power systems include:

a. Improved Voltage Stability: The series capacitor is precisely and dynamically controlled by the TCSC, enabling efficient voltage management. The TCSC aids in system voltage stabilization by injecting or absorbing reactive power as necessary, particularly during transient events and voltage swings.

b. Increased Power Transfer Capability: The TCSC improves the power transfer capability of the transmission line by dynamically changing the reactive power output of the series capacitor. By lowering the line's reactance, it increases power transfer while staying within voltage restrictions and maintaining system stability.

c. Improved Power System Stability: By adjusting voltage and managing reactive power flow, the TCSC increases the power system's overall stability. During emergencies or system problems, it aids in reducing voltage fluctuations, dampening oscillations, and preventing voltage collapse.

d. Better Power Quality: The TCSC's accurate regulation of reactive power contributes to stable voltage levels and reduces voltage fluctuations for customers. This raises the reliability of the power supply, lowers the chance of equipment damage, and increases power quality.

e. Flexible and Quick Response: The TCSC's GTO thyristors have fast switching capabilities that allow for quick reaction to shifting system conditions. In order to address voltage differences, load variations, or transient events and ensure optimal system performance, the TCSC can swiftly modify the compensation level.

f. Reactive Power Exchange Control: The TCSC permits the flow of reactive power in both directions. It allows for efficient regulation and balancing of the system's reactive power exchange by injecting or absorbing reactive power from the transmission line.

GTO Thyristor-Controlled Series Capacitor Applications: The GTO Thyristor-Controlled Series Capacitor is used in several power system contexts, including:

a. lengthy Transmission Lines: Where the inductive reactance is strong, lengthy transmission lines are especially advantageous for TCSC. The TCSC enhances voltage stability and power transfer capabilities by adjusting for the line's reactance, enabling effective long-distance transmission.

b. Voltage Control in Weak Grids: The TCSC offers voltage support and stability augmentation in weak grids with low short-circuit levels or limited voltage control capability. It aids in keeping voltage levels within acceptable ranges, particularly during system emergencies or times of heavy demand.

c. Renewable Energy Integration: The TCSC is crucial to the grid's integration of renewable energy sources. Because intermittent and fluctuating renewable generating sources are common, the TCSC offers dynamic reactive power compensation to guarantee grid stability and dependable operation.

d. Power System Damping: The TCSC can be used for oscillation control and power system damping. The TCSC aids in dampening unfavorable oscillatory modes, increasing the system's dynamic reactivity and stability by supplying or absorbing reactive power in response to system oscillations.

e. Grid Resynchronization: The TCSC aids in the quick and stable resynchronization of the grid following a system blackout or restoration. In order to avoid voltage and frequency instability, it aids in controlling the interchange of reactive power and voltage during the resynchronization process.

An innovative power circuit component that offers dynamic series capacitive compensation in power systems is the GTO Thyristor-Controlled Series Capacitor (TCSC). The TCSC provides precise control over reactive power output, enhancing voltage stability, increasing power transfer capability, and enhancing overall power system performance. GTO thyristors are used as switching elements. The TCSC finds use in lengthy transmission lines, weak grids, the integration of renewable energy, power system dampening, and grid resynchronization, all of which help modern power systems run more effectively and dependably.

**Thyristor Switched Series Capacitor (TSSC):** A power system component known as a thyristor-switched series capacitor (TSSC) uses thyristor switches to provide series capacitive compensation. It is an affordable way to increase power transfer capacity and voltage stability in transmission lines. The Thyristor-Switched Series Capacitor, its advantages, and its applications in power systems will all be thoroughly explained in this response. A power electronic component used in power systems for series capacitive compensation is the thyristor-switched series capacitor (TSSC). To connect and unplug a series capacitor from the transmission line, it uses thyristor switches. The TSSC can dynamically modify the compensation level by managing the thyristors' switching, supporting reactive power and improving voltage stability.

Thyristor-Switched Series Capacitor Operating Principle: A series capacitor, thyristor switches, a control system, and safety equipment make up the TSSC. The thyristor switches govern the connection and disconnection of the series capacitor from the transmission line, which is connected in series with it. The series capacitor is detached from the line and the thyristor switches stay in an off-state throughout normal operation. In this case, the transmission line's inductive reactance is the only factor affecting the line's reactance. The control system activates the thyristor switches, connecting the series capacitor to the line, when reactive power compensation is required. The capacitor lowers the total reactance by injecting reactive power into the line. This adjustment boosts the power system's reliability, power transmission capacity, and voltage regulation. Voltage, current, and line impedance are just a few of the parameters that the control system is constantly keeping an eye on. The control system determines the necessary compensation level based on these readings and activates the thyristor switches in accordance. To achieve correct compensation and prevent voltage and current transients, the switching order and time are carefully regulated. During abnormal conditions or fault situations, protective mechanisms like overcurrent and overvoltage protection are included in to protect the TSSC and the transmission line.

Thyristor-Switched Series Capacitor Benefits: The Thyristor-Switched Series Capacitor benefits power systems in a number of ways.

a. Improved Voltage Stability: A better level of voltage stability is achieved thanks to the TSSC's dynamic series capacitive compensation, which enables accurate voltage control. The TSSC aids in system voltage stabilization by injecting or absorbing reactive power as necessary, particularly during transient events or voltage variations.

b. Increased Power Transfer Capability: The TSSC improves the power transfer capability of the transmission line by dynamically regulating the reactive power output of the series capacitor. By lowering the line's reactance, it increases power transfer while staying within voltage restrictions and maintaining system stability.

c. Cost-Effective Approach: When compared to conventional fixed or mechanically switched capacitors, the TSSC offers a cost-effective method for series capacitive compensation. Thyristor switches can be used in place of bulky, expensive mechanical switching equipment to provide quick and precise control.

d. Adaptability and Flexibility: The TSSC is adaptable and can be simply integrated into existing transmission lines, allowing for system expansions and upgrades. Due to its dynamic compensating capabilities, adjustments can be made according to the needs and conditions of the system.

e. Quick Response: The fast-switching characteristics of the thyristor switches employed in the TSSC enable quick reaction to altering system conditions. To address voltage differences, load variations, or transient occurrences, the TSSC may quickly change the compensation level.

f. Improved Power System Stability: By regulating voltage and managing reactive power flow, the TSSC helps to maintain the overall stability of the power system. During emergencies or system problems, it aids in reducing voltage fluctuations, dampening oscillations, and preventing voltage collapse.

Thyristor-Switched Series Capacitor Applications: The Thyristor-Switched Series Capacitor is used in a number of power system components, including:

a. Long Transmission Lines: Where the inductive reactance is high, long transmission lines are especially advantageous for TSSC. The TSSC enhances voltage stability and power transfer capabilities by adjusting for the line's reactance, allowing for effective long-distance transmission.

b. Voltage Control in Weak Grids: The TSSC offers voltage support and stability augmentation in weak grids with low short-circuit levels or limited voltage control capability. It aids in keeping voltage levels within acceptable ranges, particularly during system emergencies or times of heavy demand[7]–[10].

c. Renewable Energy Integration: The TSSC is essential to the grid's integration of renewable energy sources. Because intermittent and fluctuating renewable generating sources are common, the TSSC offers dynamic reactive power compensation to guarantee grid stability and dependable operation.

d. Power System Damping: The TSSC can be utilized for oscillation control and power system damping. The TSSC aids in dampening unfavorable oscillatory modes, enhancing the system's dynamic reactivity and stability by injecting or absorbing reactive power in response to system oscillations.

e. Grid Resynchronization: The TSSC aids in the quick and stable resynchronization of the grid following a system blackout or restoration. In order to avoid voltage and frequency instability, it aids in controlling the interchange of reactive power and voltage during the resynchronization process. A power electronic component known as a thermistor-switched series capacitor (TSSC) is used in power systems to dynamically compensate for series capacitance. The TSSC gives precise control over reactive power output through the use of thermistor switches, improved voltage stability, expanding power transfer capability, and enhancing overall power system performance. The TSSC finds use in lengthy transmission lines, weak grids, the integration of renewable energy, power system dampening, and grid resynchronization, all of which help modern power systems run more effectively and dependably.

## CONCLUSION

Static series compensators (SSCs) are essential for the stability and regulation of the power system. SSCs can adjust transmission line voltage, reduce power oscillations, and enhance system stability by adding controllable voltage in series with the transmission line. Because of their capacity to dynamically alter voltage levels, transmission networks can ensure continuous power flow and avoid voltage collapse. Additionally, SSCs give power system operators improved control capabilities that let them improve power flow, lower system losses, and make better use of already-existing transmission infrastructure. The usage of static series compensators is becoming more and more important in guaranteeing the stable and efficient operation of the electrical grid as power systems confront rising demands and complicated difficulties.

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**CHAPTER 11**

# SERIES COMPENSATOR: TCSC, TCSR, TSSR, SSSC

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**ABSTRACT:**

Series compensators are devices used in power systems to improve transmission line stability, control power flow, and improve system performance. These devices include Thyristor-Controlled Series Capacitors (TCSCs), Thyristor-Controlled Series Reactors (TCSRs), Thyristor-Switched Series Reactors (TSSRs), and Static Synchronous Series Compensators (SSSCs). An overview of these series compensators' functionality and major contributions to the stability and control of the power system are given in this chapter.In order to increase transmission effectiveness, voltage control, and system stability, compensators like the Thyristor-Controlled Series Compensator (TCSC), Thyristor-Controlled Series Reactor (TCSR), Thyristor-Switched Series Reactor (TSSR), and Static Synchronous Series Compensator (SSSC) are essential components used in power systems. This abstract gives a summary of various compensators while emphasizing their characteristics and capabilities.A power electronic device called a thyristor-controlled series compensator (TCSC) uses thyristor switches to dynamically alter the line impedance. The transmission line reactance is continuously and quickly controlled, resulting in improved power flow management, dampening of power oscillations, and system stability.

**KEYWORDS:**

Reactive Power Compensation, Synchronous-Static Series Compensator, Thyristor-Controlled Series Capacitor, Thyristor-Control Series Reactor, Thyristor-Switched Series Reactor.

## INTRODUCTION

The capacity of a power system to maintain constant voltage levels within acceptable bounds during routine operations and in the presence of disturbances is referred to as voltage stability. Voltage variations can cause equipment damage, system instability, and even blackouts, making it a crucial component of power system performance. This article offers a thorough analysis of voltage stability, including its sources, effects, methods for measurement, and control strategies. It emphasizes the importance of voltage stability in maintaining a dependable and secure electrical grid. Voltage stability, which ensures the consistent delivery of electricity to consumers, is a crucial component of power system operation. It is described as a power system's capacity to maintain acceptable voltage levels within predetermined bounds. When these restrictions are exceeded, it can have negative effects on the system, such as system instability, equipment overheating, and poor power quality. In big, interconnected power systems, where disturbances can spread and damage the entire grid, voltage stability is very important. For the grid to remain reliable and to avoid catastrophic catastrophes, it is crucial to comprehend voltage stability and put efficient control measures in place[1], [2].

Causes of Voltage Instability: Voltage instability can be brought on by a number of things, including changes in load, modifications to the system's configuration, reactive power imbalances, and insufficient voltage management. Voltage dips and increased reactive power usage are also possible effects of high load demand. Additionally, the incorporation of intermittent renewable energy sources might generate voltage fluctuations and affect the stability of the system. Voltage instability can also result from errors and disturbances like short circuits or abrupt changes in load. For the purpose of creating effective control measures, it is essential to comprehend the underlying reasons of voltage instability.

Impacts of Voltage Instability: Voltage instability can have detrimental effects on the performance of the power system. Excessive voltage dips can cause voltage collapse, in which voltage levels rapidly decline, potentially causing blackouts and a cascading failure. Voltage instability can also result in equipment failure, injury to electrical equipment, and decreased power quality, which has an effect on commercial operations and consumer services. Voltage instability also has an impact on the financial performance of the power system since utilities must reduce generation or import power to keep the system stable. To avoid these effects, voltage instability must be promptly detected and mitigated. Assessment Techniques: Voltage stability is evaluated using a variety of techniques and indices. The voltage stability margin, which gauges how close a system's operational point is to a voltage collapse, is one often employed indication. Through the use of voltage stability analysis and load flow analysis, this margin can be assessed. The steady-state operating conditions are determined using load flow analysis, which also evaluates the voltage profiles under various load scenarios. Techniques for voltage stability analysis, such as the continuous power flow approach and time-domain simulations, make it possible to examine how a system behaves in a dynamic environment and pinpoint vulnerable areas.

Voltage Stability Control Techniques: Both preventive and corrective actions are used to control voltage stability. The overall resilience and stability of the electricity system are to be enhanced by preventive measures. These consist of effective reactive power management, appropriate generator and load allocation, and proper network planning. Voltage control devices, improved transmission infrastructure, and system-wide monitoring and control are additional preventive voltage stability measures. When voltage instability is noticed or expected, corrective action is taken. Shunt capacitors, static var compensators, and static synchronous compensators (STATCOMs), among other voltage control devices, are used in these procedures. To provide quick and precise voltage regulation, advanced control techniques like model predictive control and adaptive control are also used.

Voltage stability ensures the dependable and secure transmission of electricity and is a crucial component of power system performance. Creating efficient control techniques requires a thorough understanding of the sources and effects of voltage instability. The stability of the system is assessed, and key spots are identified, using assessment techniques including load flow analysis and voltage stability analysis. Under typical operating circumstances, preventive techniques like reactive power management and network planning help to ensure voltage stability. Corrective actions are taken to address voltage instability and stop blackouts, including the use of advanced control techniques and the deployment of voltage control equipment. Voltage stability should be prioritized, and the right controls should be put in place to ensure reliable operation, reduce hazards, and provide consumers with high-quality electricity.

**Improvement of Transient stability:**The ability of the system to endure and recover from serious disturbances like faults or abrupt changes in operating conditions depends on the transient stability being improved. The ability of the system to keep synchronism and stable voltage levels after a disturbance is referred to as transient stability. In order to increase system resilience and reliability, this article presents a thorough overview of transient stability, including its significance, elements that affect it, assessment tools, and control strategies. In order to keep power systems stable and reliable, transient stability is essential. It is concerned with how the system reacts after a disruption, like a malfunction or a sudden shift in load. Enhancing transient stability aims to prevent voltage breakdown and cascading failures while allowing the system to swiftly recover and sustain stable operation. Enhancing transient stability is crucial for avoiding blackouts, reducing equipment damage, and ensuring that customers have constant access to power.

Influences on Transient Stability: The transient stability of a power system is influenced by a number of factors. The system's inherent dynamic properties, such as the behavior of the excitation system, the governor reaction, and the generator rotor inertia, are important. Transient stability is also impacted by the performance and accessibility of automatic control systems and protective relays. Additionally, the resilience of the system can be impacted by the strength of the transmission network, particularly the presence of transmission lines that are underpowered or severely laden. Understanding these elements is essential for putting meaningful improvements in transient stability into action.

Assessment Methods: Analysis of the system's reaction to disturbances and evaluation of the stability margin are two steps in the assessment process for transient stability. Time-domain simulations, eigenvalue analysis, and transient energy function techniques are all used in stability assessment. Modeling the dynamics of the system and simulating the reaction to perturbations are both part of time-domain simulations. To determine stability, eigenvalue analysis assesses the eigenvalues of the linearized dynamic model of the system. Lyapunov theory is used by transient energy function methods to evaluate the stability of the system based on energy functions. These evaluation techniques assist in locating crucial regions where temporary stability might be jeopardized.

Control Methods for Increasing Transient Stability: A number of control methods are used to increase transient stability and lessen the effects of disruptions. These methods can be roughly divided into remedial and preventive actions. Preventive methods aim to increase the system's overall stability by concentrating on system planning, design, and operation. They consist of reliable control system design, effective transmission network architecture, and proper generator and load allocation. The goal of preventive measures is to make the system more resilient to disruptions and naturally stable.

When a disturbance arises or when proactive measures fall short of preserving stability, corrective action is taken. Power system stabilizers (PSS) or supplemental damping controllers are two common corrective measures. PSS devices keep track of the system dynamics and send additional control signals to the generator excitation system to increase damping and boost transient stability. Other corrective solutions include using flexible AC transmission system (FACTS) components to control reactive power and enhance system damping, such as static var compensators (SVC) and thyristor-controlled series compensators (TCSC). To further improve transient stability, advanced control strategies such model predictive control, adaptive control, and robust control are used. These methods enhance the system's ability to respond to disturbances and optimize control actions depending on current system conditions. In order to improve system stability and response, wide-area monitoring and control systems (WAMS) were developed. These systems allow for the deployment of coordinated control techniques. Improving transient stability is essential to keeping power systems secure and reliable. Blackouts and equipment damage are less likely to occur if the system's capacity to tolerate and recover from disturbances is improved. Transient stability is greatly influenced by variables such system dynamics, transmission network strength, and control strategies. While control methods, such as preventative and corrective measures, help increase stability and system resilience, assessment methods help identify crucial areas for development. The development of transient stability is crucial to ensuring the stable and effective operation of the electrical grid as power systems encounter additional difficulties, such as the integration of renewable energy sources and the expansion of complex networks[3], [4].

## DISCUSSION

**Thyristor Controlled Series Capacitor:** The Thyristor-Controlled Series Capacitor (TCSC) is a power system component that uses thyristor-controlled reactors and capacitors to produce series capacitive compensation. It is an adaptable and effective way to increase power transfer capacity, voltage control, and power system stability. The Thyristor-Controlled Series Capacitor (TCSC), its benefits, and its applications in power systems will all be thoroughly explained in this response. A power electronic component known as the Thyristor-Controlled Series Capacitor (TCSC) combines capacitors with thyristor-controlled reactors (TCR) to offer series capacitive compensation in power systems. By regulating the amount of reactive power fed into the line, it enables precise control of the transmission line's reactance[5].

**Thyristor-controlled series capacitor (TCSC) operating principle:**

A capacitor bank, a TCR bank, a control system, and safety measures make up the TCSC. The TCR bank is linked in parallel with the capacitor bank, while the capacitor bank is connected in series with the transmission line. The TCR bank is made up of thyristor-controlled reactors that can change their inductive reactance by adjusting the thyristors' firing angles. The TCSC continues to operate normally in a bypass mode, with the capacitors detached from the line and the TCRs completely conducting. The transmission line's inductive reactance governs the line's reactance in this state since the TCSC is not providing any series capacitive compensation. The control system initiates the firing of the thyristors, modifying the inductive reactance of the TCRs, when reactive power compensation is required. The amount of inductive reactance that the TCRs introduce depends on their firing angle, and the capacitors provide the necessary series capacitive correction. The TCSC is able to dynamically alter the amount of reactive power injected into the line by changing the firing angle of the thyristors. This enhances voltage management, power transfer efficiency, and system stability by allowing exact control of the transmission line's reactance. The voltage, current, and line impedance of the system are all constantly monitored by the TCSC's control system. Protective mechanisms are built into the TCSC to ensure the security and dependability of the system. Based on these measurements, the control system determines the necessary compensation level and modifies the firing angle of the thyristors to produce the desired reactive power injection. To safeguard the TCSC and the power system from harm, these devices have overcurrent protection, overvoltage protection, and fault detection methods.

Thyristor-Controlled Series Capacitor (TCSC) Benefits: In power systems, the Thyristor-Controlled Series Capacitor (TCSC) has a number of benefits.

a. Improved Voltage Stability: A better voltage stability is achieved thanks to the TCSC's precise control of reactive power injection, which enables efficient voltage management. The overall stability of the power system is improved by its assistance in maintaining stable voltage levels, particularly during transient events and voltage fluctuations.

b. Enhanced Power Transfer Capability: The TCSC minimizes the transmission line's reactance, enhancing the power transfer capability, by dynamically modifying the series capacitive compensation. Higher power transfer is made possible without going above voltage restrictions or jeopardizing system stability.

c. Flexible and Quick Response: To adapt to shifting system conditions, the TCSC provides a flexible and quick response. To respond promptly to changes in voltage, load, or transient events, the control system can change the firing angle of the thyristors, assuring optimum system performance.

d. Power System Oscillations Can Be Effectively Damped the TCSC can effectively damper oscillations in the power system, enhancing system stability. It assists in dampening undesirable oscillations and improves the dynamic response of the system by injecting or absorbing reactive power in response to oscillatory modes.

e. Power System Fault and Contingency Mitigation: The TCSC assists in reducing the effects of power system faults and contingencies. In order to maintain voltage stability and prevent voltage collapse under fault conditions, it can swiftly change the reactive power compensation, resulting in dependable operation.

f. Grid Resynchronization: The TCSC aids in the quick and stable resynchronization of the grid following a system blackout or restoration. In order to avoid voltage and frequency instability, it aids in controlling the interchange of reactive power and voltage during the resynchronization process.

**Thyristor-Controlled Series Capacitor (Tcsc) Applications:** The Thyristor-Controlled Series Capacitor (TCSC) is used in a number of power system components, including:

a. Long Transmission Lines: Long transmission lines with high inductive reactance benefit most from the TCSC. The TCSC enhances voltage stability and power transfer capabilities by adjusting for the line's reactance, allowing for effective long-distance transmission.

b. Voltage Control in Weak Grids: The TCSC offers voltage support and stability augmentation in weak grids with low short-circuit levels or limited voltage control capability. It aids in keeping voltage levels within acceptable ranges, particularly during system emergencies or times of heavy demand.

c. Renewable Energy Integration: The TCSC is essential to the grid's integration of renewable energy sources. Because intermittent and fluctuating renewable generating sources are common, the TCSC offers dynamic reactive power compensation to guarantee grid stability and dependable operation.

d. Power System Damping and Oscillation Control: The TCSC can be used to dampen and control oscillation in the power system. The TCSC aids in dampening unfavorable oscillatory modes, increasing the system's dynamic reactivity and stability by supplying or absorbing reactive power in response to system oscillations.

e. Grid Resynchronization: The TCSC aids in the quick and stable resynchronization of the grid following a system blackout or restoration. In order to avoid voltage and frequency instability, it aids in controlling the interchange of reactive power and voltage during the resynchronization process.

a power electronic component that offers series capacitive compensation in power systems is the thyristor-controlled series capacitor (TCSC). The TCSC enables precise control over reactive power injection, strengthening voltage stability, increasing power transfer capability, and enhancing overall power system performance. It does this by utilizing thyristor-controlled reactors (TCR) and capacitors. The TCSC finds use in lengthy transmission lines, weak grids, the integration of renewable energy, power system dampening, and grid resynchronization, all of which help modern power systems run more effectively and dependably.

**Thyristor Controlled Series Reactor:**A power system component known as the Thyristor-Controlled Series Reactor (TCSR) uses thyristor switches to offer series inductive compensation. It is used to control the flow of reactive power in transmission lines as well as line impedance regulation. In-depth information about the Thyristor-Controlled Series Reactor, including its advantages and uses in power systems, will be provided in this response. Power electronic equipment called the Thyristor-Controlled Series Reactor (TCSR) is utilized in power systems for series inductive compensation. To connect and disconnect a series reactor from the transmission line, it uses thyristor switches. The TCSR can dynamically modify the compensation level by managing the thyristors' switching, supporting reactive power and improving voltage stability [6]–[8].

Thyristor-Controlled Series Reactor Operating Principle: A series reactor, thyristor switches, a control system, and safety equipment make up the TCSR. The thyristor switches govern the connection and disconnection of the series reactor from the transmission line, which is connected in series with it. The series reactor is unconnected from the line and the thyristor switches stay in an off-state throughout normal operation. In this case, the transmission line's inductive reactance is the only factor affecting the line's impedance. The control system activates the thyristor switches, connecting the series reactor to the line, when reactive power compensation is required. The reactor increases the impedance overall by injecting inductive reactance into the line. This adjustment aids in controlling power flow, regulating voltage, and improving the stability of the power system. Voltage, current, and line impedance are just a few of the parameters that the control system is constantly keeping an eye on. The control system determines the necessary compensation level based on these readings and activates the thyristor switches in accordance. To achieve correct compensation and prevent voltage and current transients, the switching order and time are carefully regulated. The TCSR and the transmission line are protected by protective devices, such as overcurrent and overvoltage protection, when abnormal conditions or fault occurrences occur.

**Thyristor-Controlled Series Reactor Benefits:** There are various benefits to using the Thyristor-Controlled Series Reactor in power systems:

a. Stable voltage To enable accurate voltage control, the TCSR offers dynamic series inductive compensation. The TCSR aids in system voltage stabilization by injecting or absorbing reactive power as necessary, particularly during transient events or voltage variations.

b. Power Flow Control: By adjusting the line impedance, the TCSR may manage power flow in the transmission line. The TCSR can alter the compensation level to raise or decrease the line impedance, allowing for the best possible power flow and avoiding voltage violations.

c. Enhanced Stability: By regulating voltage and managing reactive power flow, the TCSR improves the stability of the entire power system. During emergencies or system problems, it aids in reducing voltage fluctuations, dampening oscillations, and preventing voltage collapse.

d. Adaptability and Flexibility: The TCSR is adaptable and can be simply integrated into existing transmission lines, allowing for system expansions and upgrades. Due to its dynamic compensating capabilities, adjustments can be made according to the needs and conditions of the system.

e. Quick Response: The fast switching characteristics of the thyristor switches employed in the TCSR enable quick reaction to altering system conditions. Voltage changes, load changes, or transient events can all be quickly addressed by the TCSR by quickly adjusting the compensation level.

f. Improved Power Quality: By limiting reactive power flow and regulating voltage, the TCSR helps to maintain stable voltage levels and reduces voltage changes that consumers experience. This raises the reliability of the power supply, lowers the chance of equipment damage, and increases power quality.

**Thyristor-Controlled Series Reactor Applications Include:** The Thyristor-Controlled Series Reactor is used in several power system contexts, including:

a. Long Transmission Lines: In long transmission lines, when resistive losses are high, TCSR is especially helpful. The TCSR increases power transfer efficiency, lowers power losses, and improves voltage stability by correcting for the line impedance.

b. Voltage Control in Weak Grids: The TCSR offers voltage support and stability improvement in weak grids with low short-circuit levels or limited voltage control capability. It aids in keeping voltage levels within acceptable ranges, particularly during system emergencies or times of heavy demand.

c. Renewable Energy Integration: The TCSR is essential for incorporating renewable energy sources into the grid. Because intermittent and fluctuating output are common in renewable generation sources, the TCSR offers dynamic reactive power compensation to guarantee grid stability and dependable operation.

d. Power System Damping: The TCSR can be utilized for oscillation control and power system damping. The TCSR aids in dampening unfavorable oscillatory modes, increasing the system's dynamic reactivity and stability by supplying or absorbing reactive power in response to oscillations.

e. Grid Resynchronization: The TCSR aids in the quick and stable resynchronization of the grid following a system blackout or restoration. In order to avoid voltage and frequency instability, it aids in controlling the interchange of reactive power and voltage during the resynchronization process.

To sum up, a power electronic component known as the Thyristor-Controlled Series Reactor (TCSR) offers dynamic series inductive compensation in power systems. The TCSR gives precise control over reactive power output through the use of thyristor switches, improved voltage stability, expanding power transfer capability, and enhancing overall power system performance. The TCSR finds use in lengthy transmission lines, weak grids, the integration of renewable energy, power system dampening, and grid resynchronization, all of which help modern power systems run more effectively and dependably.

**Thyristor Switched Series Reactor:**The Thyristor Switched Series Reactor (TSSR) is a power system component that uses thyristor switches to produce series inductive compensation. It is applied to control reactive power flow, increase voltage stability, and manage line impedance in transmission systems. We will go into great detail on the Thyristor

Switched Series Reactor in this response, along with its benefits and uses in power systems. A power electrical device called the Thyristor Switched Series Reactor (TSSR) uses thyristor switches to connect and disconnect a series reactor from the transmission line. The TSSR can dynamically modify the compensation level by managing the thyristors' switching, supporting reactive power and improving voltage stability.

Thyristor Switched Series Reactor Operating Principle: A series reactor, thyristor switches, a control system, and safety equipment make up the TSSR. The thyristor switches govern the connection and disconnection of the series reactor from the transmission line, which is connected in series with it. The series reactor is unconnected from the line and the thyristor switches stay in an off-state throughout normal operation. In this case, the transmission line's inductive reactance is the only factor affecting the line's impedance. The control system activates the thyristor switches, connecting the series reactor to the line, when reactive power compensation is required. The reactor increases the line's overall impedance by introducing inductive reactance. This adjustment aids in controlling power flow, regulating voltage, and improving the stability of the power system. Voltage, current, and line impedance are just a few of the parameters that the control system is constantly keeping an eye on. The control system determines the necessary compensation level based on these readings and activates the thyristor switches in accordance. To achieve correct compensation and prevent voltage and current transients, the switching order and time are carefully regulated. The TSSR and the transmission line are protected by protective devices, such as overcurrent and overvoltage protection, when abnormal conditions or fault occurrences occur.

**Thyristor Switched Series Reactor Benefits:** The Thyristor Switched Series Reactor benefits power systems in a number of ways:

a. Stable voltage: to enable accurate voltage control, the TSSR offers dynamic series inductive compensation. The TSSR aids in maintaining system voltage, especially during transient events or voltage variations, by injecting or absorbing reactive power as necessary.

b. Power Flow Control: By adjusting the line impedance, the TSSR may regulate power flow in the transmission line. The TSSR can alter the compensation level to raise or decrease the line impedance, allowing for the best possible power flow and avoiding voltage violations.

c. Enhanced Stability: By regulating voltage and managing reactive power flow, the TSSR improves the stability of the entire power system. During emergencies or system problems, it aids in reducing voltage fluctuations, dampening oscillations, and preventing voltage collapse.

d. Adaptability and Flexibility: The TSSR is adaptable and can be simply integrated into existing transmission lines, allowing for system expansions and upgrades. Due to its dynamic compensating capabilities, adjustments can be made according to the needs and conditions of the system.

e. Quick Reaction: The thyristor switches utilized in the TSSR have fast switching capabilities that enable quick reaction to altering system conditions. To address voltage differences, load variations, or transient occurrences, the TSSR can quickly change the compensation level.

f. Improved Power Quality: By limiting reactive power flow and regulating voltage, the TSSR helps to maintain stable voltage levels and reduces voltage changes that consumers experience. This raises the reliability of the power supply, lowers the chance of equipment damage, and increases power quality.

**Thyristor Switched Series Reactor Applications:** The Thyristor Switched Series Reactor is used in several power system contexts, including:

a. Voltage stability and control: When there are voltage fluctuations or stability problems, the TSSR is utilized to control the voltage levels in transmission networks. The TSSR improves system stability by injecting or absorbing reactive power, which helps keep voltage within reasonable bounds.

b. Power System Damping: The TSSR can be used for oscillation control and power system damping. The TSSR enhances the system's dynamic response and stability by supplying reactive power support and modifying the line impedance. This helps reduce undesired oscillatory modes.

c. The TSSR makes it possible to control the flow of power through transmission lines. The TSSR can promote efficient power transfer, avoid line overloading, and preserve transmission system dependability by modifying line impedance.

d. Voltage Support in Weak Grids: The TSSR offers voltage support and aids in grid stabilization in weak grids or regions with little ability to regulate voltage. It makes up for voltage drops and reactive power shortages, ensuring that users receive dependable and high-quality power supply.

e. Grid Resynchronization: The TSSR aids in the grid's smooth and steady resynchronization following a system blackout or restoration. In order to avoid voltage and frequency instability, it aids in controlling the interchange of reactive power and voltage during the resynchronization process.

f. Grid Integration of Renewable Energy Sources: The TSSR is essential to the grid's integration of renewable energy sources. Because intermittent and fluctuating output are frequent characteristics of renewable generation sources, the TSSR offers dynamic reactive power compensation to guarantee grid stability and dependable operation.

The Thyristor Switched Series Reactor (TSSR) is a power electronic component that offers power systems' series inductive compensation. The TSSR allows precise control over reactive power output through the use of thyristor switches, improved voltage stability, increasing power transfer capabilities, and enhancing overall power system performance. The TSSR has uses in grid resynchronization, renewable energy integration, power system dampening, voltage support in weak grids, and power flow regulation. The TSSR helps modern power systems run effectively and dependably by being flexible, quick to react, and able to improve power quality.Static Synchronous Series Compensator: A power electronic component used in power systems for dynamic series compensation is the Static Synchronous Series Compensator (SSSC). By injecting controlled voltage in series with the transmission line using voltage-source converter (VSC) technology, it is able to precisely control the reactive power flow and line impedance. We will discuss the benefits, uses, and workings of the Static Synchronous Series Compensator in this retort.

Static Synchronous Series Compensator (SSSC) Operating Principle: A VSC, a coupling transformer, and control and protection systems make up the SSSC. Insulated gate bipolar transistor (IGBT) technology, which offers quick and precise switching capabilities, is often the foundation of the VSC. The VSC is coupled to the transmission line via the coupling transformer. The SSSC runs in voltage control mode under normal conditions. The voltage waveform produced by the VSC is in phase with the line current. The SSSC can modify the injected voltage's magnitude and phase angle to alter the line impedance and reactive power flow. The control system senses system parameters like voltage, current, and power factor when reactive power correction is necessary. The control system determines the desired compensation level using these readings and modifies the output of the VSC accordingly. The VSC alters the transmission line's impedance by injecting a programmable voltage in series with it. This allows for fine control of reactive power flow. The control system also keeps an eye on the state of the system and reacts immediately to any modifications. In order to maintain system stability, control voltage, and enhance power quality, it modifies the compensation level.

**Static Synchronous Series Compensator (Sssc) Benefits Include:** The SSSC benefits electricity systems in a number of ways:

a. Dynamic adjustment: The SSSC offers precise and dynamic reactive power adjustment. It can swiftly adapt to changes in system conditions by injecting or absorbing controlled voltage and adjusting the line impedance to maintain voltage stability and manage power flow.

b. Increased Power Transfer Capability: By successfully controlling the line impedance, the SSSC improves the power transfer capability of transmission lines. It maximizes the use of the current transmission infrastructure by dynamically managing the reactive power flow.

c. Voltage Control and Stability: As needed, the SSSC injects or absorbs reactive power to improve voltage control and stability. In particular during voltage variations or emergencies, it aids in maintaining desirable limits on system voltage.

d. Power System Damping: The SSSC helps regulate oscillation and dampen the power system. It can assist in dampening unfavorable oscillatory modes, enhancing system dynamic response and stability, by altering the line impedance.

e. Grid Congestion Management: By regulating the power flow through transmission lines, the SSSC can reduce grid congestion. It can improve grid reliability by rerouting power flows and relieving overloads in transmission corridors that are frequently overloaded.

f. Versatile Operation: The SSSC can function in a number of modes, including impedance control, power factor control, and voltage control. It is a flexible solution for power system management and control because of its ability to adjust to various system conditions and requirements.

**Static Synchronous Series Compensator (SSSC) Applications Include:** The SSSC has applications across a range of power system domains:

a. Transmission System Voltage Control: Transmission system voltage control is handled by the SSSC, which is particularly useful when there are voltage fluctuations or stability problems. It supports reactive power and aids in keeping voltage within reasonable bounds.

b. Power Flow Control: Power flow control is made possible by the SSSC in transmission lines. It is possible to enable efficient power transfer, avoid line overloading, and keep the dependability of the transmission system by regulating the line impedance.

c. The SSSC can assist in dampening power system oscillations, which enhances system stability and responsiveness. In order to suppress undesired oscillatory patterns and preserve system stability, it injects or absorbs reactive power.

d. Grid Congestion Management: By regulating power flow in transmission lines, the SSSC is used to manage grid congestion. By reducing traffic in congested areas, it enhances the stability and dependability of the grid.

e. Renewable Energy Integration: The SSSC is essential to the grid's integration of renewable energy sources. In order to ensure seamless integration and dependable operation of renewable generation, it provides reactive power adjustment and voltage assistance.

The Static Synchronous Series Compensator (SSSC) is a power electronic component used in power systems for dynamic series compensation. The SSSC offers fine control over line impedance and reactive power flow by leveraging voltage-source converter technology. Dynamic compensation, improved power transmission, voltage control, power system dampening, grid congestion management, and flexible operation are just a few of its benefits. The SSSC is used for grid congestion management, renewable energy integration, oscillation damping, power flow control, and voltage control. The SSSC helps to increase the stability, efficiency, and reliability of the power system with its enhanced control capabilities[9]–[10].

**Control Range and VA Rating:** A Static Series Compensator (SSC)'s control range and VA rating depend on a number of variables, including the particular design, application requirements, and the desired amount of compensation. We will go over an SSC's control range, VA rating, and the variables that affect them in this response.

Static Series Compensator Control Range: The range across which an SSC can adjust the line impedance and offer reactive power compensation is referred to as its control range. The minimum and maximum reactive power values that the SSC can inject or absorb serve as its typical definition. The SSC's power electronic components and control system's design and capabilities influence the control range.

The unique application and system requirements might have a big impact on the control range of an SSC. It may be a few MVAR (mega-volt-ampere reactive) or as much as several hundred MVAR. The control range should be built with enough flexibility to accommodate anticipated system reactive power variations as well as the intended compensation requirements. The size and capacity of the series reactor, the control method used, the system voltage and current levels, and the power electronic devices used all have an impact on the control range of an SSC. The control range can be expanded, allowing for accurate and effective reactive power adjustment, thanks to sophisticated control algorithms and intelligent control systems.

Static Series Compensator VA Rating: An SSC's VA (volt-ampere) rating describes how much reactive power and voltage it can tolerate. The SSC can tolerate this amount of perceived power up to a certain point without going over its heat and voltage limits. The rating of an SSC's power electronic parts, such as the voltage-source converter (VSC) and the series reactor, determines its VA rating. The maximum voltage and current allowed in the system, the intended level of compensation, and the anticipated operating circumstances all affect an SSC's VA rating. To ensure that the SSC can manage the reactive power flows and voltage fluctuations in the system without going over its thermal limits and degrading its performance, it is crucial to choose a suitable VA rating. Depending on the particular application and system needs, an SSC's VA rating might range from a few MVA (mega-volt-amperes) to several hundred MVA or more. To calculate the proper VA rating for the SSC, it is critical to precisely examine the state of the power system, load requirements, and reactive power changes. It is important to remember that an SSC's control range and VA rating are related. A wider control range is often possible with a higher VA rating since it has the potential to tolerate higher reactive power flows. However, based on the system requirements, cost-effectiveness, and overall system performance, the precise control range and VA rating should be optimized. The design, application requirements, and desired amount of compensation are some of the variables that affect the control range and VA rating of a static series compensator (SSC). While the VA rating shows the SSC's capability to manage both reactive power and voltage levels, the control range specifies the range over which the SSC can offer reactive power compensation and control the line impedance. To satisfy the unique requirements of the system, the control range and VA rating should be carefully chosen, taking into account things like power electronic device capability, control strategy, and system voltage and current levels.

## CONCLUSION

Series compensators, such as TCSCs, TCSRs, TSSRs, and SSSCs, provide efficient ways to increase the control and stability of power systems. Controlled series capacitors are used by TCSCs to control power flow and transmission line voltage, improving system stability and lowering power oscillations. The reactive power compensation and voltage support provided by TCSRs and TSSRs, which use thyristor-controlled or thyristor-switched series reactors, reduce voltage dips and improve system performance. Because they are static synchronous devices, SSSCs have sophisticated control capabilities to actively control voltage and power flow, ensuring the transmission system operates steadily and effectively. Numerous advantages result from the use of series compensators, including higher grid dependability, decreased line losses, reduced system damping, and improved power transfer capabilities. The usage of series compensators becomes essential in sustaining a dependable and robust electrical grid as power systems continue to encounter problems related to growing demand and integrating renewable energy sources.

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## CHAPTER 12

# STATIC VOLTAGE AND PHASE ANGLE REGULATORS

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**ABSTRACT:**

Power systems employ static voltage and phase angle regulators (SVARs) to regulate and control voltage levels and phase angles, ensuring optimum power flow and boosting system stability. The real-time reactive power and voltage regulation capabilities of SVARs enable the efficient and dependable operation of the electrical grid. An overview of SVARs, their function, advantages, and uses in power system control are given in this chapter.Static Voltage and Phase Angle Regulators (VAPARs), which regulate voltage levels and phase angles in power systems, are crucial components. The main characteristics and functionalities of Static VAPARs are highlighted in this abstract. Static VAPARs are power electronic-based devices used in power transmission and distribution networks to control voltage and phase angle. For the purpose of maintaining the desired operating conditions and ensuring effective power transfer, they can dynamically change the voltage magnitude and phase angle. The abstract emphasizes the role of static VAPARs in voltage regulation and the stability of power systems.

**KEYWORDS:**

Power Flow Control, Power Flow Regulation, Phase Angle Regulators, Phase Angle Regulation, Voltage Phase Angle.

## INTRODUCTION

According to the simple equations that were developed to calculate the transmitted real power, P, and reactive line power, Q, both of these quantities depend on the transmission line impedance, the magnitude of the voltages at the sending and receiving ends, and the phase angle between these voltages. The discussion demonstrates that increased real power transmission will invariably lead to increased reactive power demand on the end-voltage bus systems (generators) and increased voltage variation along the transmission line. The discussion focuses on the control of transmission voltage by attacking the changing reactive line power, which is the primary cause of its variation. It was found that, despite fluctuating real power demand, regulated reactive shunt compensation is extremely effective at preserving the correct voltage profile along the transmission line[1]–[3].

To maintain the required voltage levels for loads, sometimes at the end of a sub transmission or distribution system, regulated reactive shunt compensation of bulk transmission networks is not typically a problem. For instance, a mechanical on load tap changer is typically used to connect a high voltage line to a lower voltage line for increased power transmission in order to shield the lower voltage system from the high voltage line's significant voltage variations brought on by seasonal or daily load changes. Similar to this, from the beginning of ac transmission, voltage regulators using on-load tap changers have been used to maintain the required user voltage despite fluctuating transmission voltage and loads. Tap changers can often be used to regulate reactive power flow in the line in addition to voltage adjustment. Since transmission line impedances tend to be reactive, adding an in-phase voltage component to the transmission circuit will result in a substantially quadrature (reactive) current flow. By controlling the magnitude and polarity of this current flow, it is possible to use this reactive current flow to enhance existing reactive power flows.

While reactive compensation and voltage regulation via on-load tap changers seem to serve the same purpose in terms of transmission control, there is a significant operational distinction to be made between the two. While a reactive compensator modifies the existing reactive power by supplying it to the ac system or by absorbing it from it the tap changer-based voltage regulator cannot supply or absorb reactive power, and as a result, it cannot directly control the transmission line voltage. It controls immediately the transmission voltage on one side and relies on the electrical grid to supply the required reactive power to keep that voltage constant. The system's overall voltage may collapse if the power system is unable to meet the demand for reactive power. It is generally known that under certain circumstances, on-load tap changers can contribute to voltage collapse.

For instance, the transmission line must provide growing load current at lowering load power factor when the tap changers increase the transformation ratio to reduce the voltage drop for mostly motor loads when the transmission system is overloaded. Naturally, this further lowers the transmission voltage and, as a result, raises the current, which continues until the voltage collapses and the protection relays cut off the load. Reactive power management focuses on the control of transmitted power by series reactive compensation, which can be a highly effective way to control power flow in the line as well as improving the dynamic behavior of the transmission system. However, the on-load tap changer and its electronic counterparts, which will be discussed in this and the following chapter, play a significant role in transmission power flow control by providing the important functions of voltage regulation and reactive power management. Although series reactive compensation is typically quite successful for controlling power flow, applying it to some transmission issues may be impracticable, labor-intensive, or not financially feasible. The transmission angle has something to do with these issues. For instance, the prevailing transmission angle might not be suitable for a particular line's transmission needs or it might change with daily or seasonal system loads over a wide enough range to keep some affected lines' acceptable power flow. Controlling actual and reactive loop flows in a mesh network is another issue. The effective angle [the third variable of the fundamental transmission relationships presented in to which the relevant transmission line or network is exposed must typically be controlled in order to find a solution to difficulties of this nature.

In order to improve power flow and make better use of transmission lines, mechanical phase angle regulators (PARs) or phase shifting transformers (PSTs) with on-load tap changers and quadrature voltage injection were first used in the 1930s. On-load tap changers with quadrature voltage injection regulate real power via phase adjustment, whereas those with in-phase voltage injection control reactive power via voltage magnitude adjustment. Both the reactive and actual power flow regulation are made possible by their combined use. Therefore, in the past, PARs have been utilized to improve and balance the burden of interconnected transmission lines by rerouting current flows and reducing inherent loop flows in interconnected systems[4]–[6].

The function of contemporary voltage phase angle regulators with quick electronic control can be expanded to handle dynamic system events in addition to steady-state voltage and power flow regulation. Improvement of transient stability, power oscillation damping, and the reduction of post-disturbance overloads and the related voltage dips are examples of potential application areas. Voltage and phase angle regulators add a new component to the control of dynamic events—the ability to interchange real powerin comparison to reactive compensators. The voltage and angle regulators, which are based on the traditional configuration of tap-changing transformers, lack reactive compensators that can provide or absorb reactive power; thus the power system is left to bear this burden.

The fundamental methods of voltage and angle regulation are examined in the section that follows in order to provide the essential framework for the discussion of power electronics-based approaches. It is also looked at how phase angle management affects the fundamental elements determining the maximum power that can be transmitted (steady-state power transmission limit, transient stability, and power oscillation damping).

## DISCUSSION

**Voltage and Phase Angle Regulation:** Regulating voltage and phase angle are essential components of power system functioning because they maintain a stable and dependable electricity supply. Voltage levels and phase angles must be properly regulated for effective power transfer, optimum system performance, and the avoidance of voltage collapse. The relevance, methods, and effects of voltage and phase angle regulation on the stability and dependability of the power system are all thoroughly covered in this article. The major goals of voltage and phase angle regulation in power systems are to keep voltage levels within reasonable ranges and to regulate the relative phase angles of voltages at various places. To ensure adequate power flow, reduce voltage fluctuations, and preserve system stability, these regulations are required. While phase angle regulation assures synchronized operation and reduces power transmission losses, voltage regulation concentrates on preserving voltage magnitudes. For the electrical grid to operate reliably and efficiently, effective voltage and phase angle management is essential[7]–[9].

Importance of Voltage and Phase Angle Regulation: Regulation of voltage and phase angles is crucial for supplying consumers with a steady and dependable supply of power. Equipment faults, poorer power quality, and even damage to electrical devices can result from voltage levels that are not maintained as planned. Voltage regulation is essential for making up for voltage decreases brought on by reactive power mismatches, load changes, and transmission line resistance and reactance. Voltage regulation ensures the smooth operation of electrical equipment and reduces power quality issues, such as flickering lights or voltage-sensitive device faults, by maintaining voltage levels within acceptable limits. On the other side, phase angle adjustment is essential for ensuring synchronous functioning in power systems. To maintain adequate power flow and system stability, it is crucial to properly adjust the relative phase angles of voltages at various sites. Significant phase angle deviations can cause system instability, imbalanced loading, and power oscillations. Power system operators can reduce these problems and preserve a balanced and stable operation across the entire grid by controlling phase angles.

**Voltage and Phase Angle Regulation Techniques:** A variety of techniques and equipment are used in power systems to regulate voltage and phase angle. Among the often-employed methods are: On-Load Tap Changers (OLTCs): On-Load Tap Changers (OLTCs) are tools used in transformers to modify the turns ratio and thus regulate the output voltage. OLTCs can account for voltage variations and maintain a target voltage level by adjusting the tap location. Shunt Reactive Power Compensation:  Shunt capacitors and static var compensators (SVCs), which inject reactive power, are two examples of devices used in shunt reactive power compensation. By injecting or absorbing reactive power and controlling the magnitude of the voltage, these devices aid in maintaining voltage levels.

Series Reactive Power Compensation: Techniques like series capacitors and thyristor-controlled series compensators (TCSCs) are used to compensate for series reactive power. These units provide reactive power support, which helps to control voltage levels and improve power transfer efficiency. They are connected in series with transmission lines.

Synchronous Condensers: Synchronous condensers are revolving devices that have the ability to generate or absorb reactive power. Synchronous condensers can adjust voltage levels and increase system stability by managing the field excitation.

Flexible AC Transmission System (FACTS) Devices: Advanced power electronic devices called FACTS devices, such static synchronous compensators (STATCOMs) and static synchronous series compensators (SSSCs), may control both voltage and phase angle. These tools can improve system stability and power flow control while providing quick and precise reactive power control.

**Impact on the stability and reliability of the power system:**

Power system stability and dependability are significantly impacted by effective voltage and phase angle regulation. Here are several major advantages:

Enhanced Stability: The stability of the power system is enhanced by proper management of voltage levels and phase angles. Voltage and phase angle regulators help prevent voltage collapse, reduce power oscillations, and provide steady-state and dynamic stability by maintaining voltages within acceptable ranges and managing phase angles.

Improved Power Transfer Capability: Transmission lines' power transfer efficiency is improved by voltage and phase angle management techniques. Power system operators can optimize the use of transmission infrastructure, minimize transmission losses, and support larger power flows by managing voltage levels and phase angles.

Power Quality Improvement: Voltage regulation is essential for maintaining high power quality and improving it. Voltage fluctuations, flicker, and malfunctions of voltage-sensitive equipment can be reduced by keeping voltage levels within reasonable bounds. Customer happiness and power quality both improve as a result.

Grid Integration of Renewable Energy Sources: Renewable energy sources are increasingly being incorporated into the grid, which makes voltage and phase angle adjustment even more crucial. Because renewable energy production is intermittent, competent regulation is necessary to provide grid stability and a dependable integration of renewable energy into the current power system.

Voltage Profile Improvement: Voltage and phase angle regulation strategies aid in preserving a desirable voltage profile throughout the power system. By ensuring that voltage magnitudes are within the allowed ranges, overvoltage or under voltage situations are avoided, and a balanced and stable system operation is maintained.

Voltage and phase angle regulation are essential components of a functioning power system. For a consistent, dependable, and high-quality electrical supply, proper voltage regulation and phase angle control are essential. To accomplish efficient voltage and phase angle regulation, a variety of methods are used, such as on-load tap changers, shunt and series reactive power compensation, synchronous condensers, FACTS devices, and advanced control strategies. Power system stability, power transfer efficiency, power quality, and grid integration of renewable energy sources can all be considerably enhanced by maintaining voltage magnitudes within reasonable bounds and managing relative phase angles. Voltage and phase angle regulation will be increasingly important as power systems develop and work toward a more resilient and sustainable future.

**Power flow control by phase angle regulators:**A crucial component of power system operation is the management of power flow via phase angle regulators, which enables efficient and dependable electricity transfer. The devices known as phase angle regulators (PARs) regulate the relative phase angles between the voltages in various areas of the power system. Power flow can be rerouted, congestion can be reduced, and system stability can be improved by altering the phase angles. In-depth information about the operation, advantages, and effects of phase angle regulators on power system performance is provided in this article. In order to ensure the effective and dependable movement of electrical energy, power flow regulation is a crucial component of power systems. In the past, switching devices and generation resources were mostly used to regulate active power injections in order to control power flow. However, by adjusting the relative phase angles between voltages, the usage of phase angle regulators has shown to be a useful technique for controlling power flow.

Operation of Phase Angle Regulators: Phase angle regulators (PARs) are often positioned at critical places in the power system, such as transmission substations or interconnection points, and they control the phase of an electrical current. To change the phase angles of voltages, PARs are made up of controlled reactors or capacitors that may be turned in and out of the system. The needed phase shift can be achieved by altering the reactive power output of PARs, enabling efficient power flow control. When a PAR is added to the system, it changes the transmission line's effective impedance, which changes the phase angle between voltages at various points. PARs can change the phase angle difference, redirect power flow, and reduce congestion on heavily congested lines by increasing or decreasing the reactive power output.

**Benefits of Using Phase Angle Regulators to Control Power Flow:**

Congestion Management: Congestion management is one of the main advantages of employing PARs to control power flow. In order to redistribute power flows, relieve clogged transmission lines, and ensure the best possible use of the current transmission infrastructure, PARs can strategically modify the phase angles. This lessens the need for costly transmission line modifications and helps prevent overloading.

Enhanced Power transport Capability: The transmission system's capacity to transport power is improved by power flow regulation employing PARs. PARs enable more effective use of the available transmission capacity by rerouting power flows. When integrating renewable energy sources or during times of high demand, this is especially helpful because it increases the operating flexibility of the power system.

Voltage Stability Enhancement: PARs can also help to improve voltage stability. In order to minimize voltage collapse or excessive voltage fluctuations, PARs can help maintain an adequate reactive power balance across the system by managing the phase angles. This maintains consistent and dependable voltage levels across the whole power system.

Flexible Grid Operation: More adaptable grid operation is made possible by power flow regulation employing PARs. By altering the phase angles in real-time, operators can react to dynamic changes in load patterns, generation availability, and network circumstances. This adaptability improves system stability, lowers transmission losses, and efficient power flow management.

Renewable Energy Integration: The power system's ability to incorporate renewable energy sources is greatly aided by PARs. PARs can manage power imbalances, optimize power flows, and guarantee the stable integration of renewable resources as intermittent renewable generation becomes more prevalent. This encourages the creation of a power system that is more resilient and sustainable.

Challenges and Considerations: While employing PARs to manage power flow has many advantages, there are some difficulties and things to take into account.

Coordination and communication: To provide coordinated power flow regulation and system stability, effective coordination and communication between PARs and other control devices are crucial. Real-time monitoring and control of PARs require sophisticated control and communication systems.

System modeling and control techniques: For the best power flow regulation with PARs, the power system must be well modeled, and efficient control techniques must be used. The correct PAR settings and control actions are chosen using sophisticated algorithms and optimization approaches in order to meet the intended power flow goals.

Protection and security: To ensure safe and dependable operation, protective relays and security systems should be properly coordinated with the functioning of PARs. To avoid potential weaknesses and guarantee the integrity of the electrical system, appropriate protection strategies and cybersecurity measures are crucial.

Phase angle regulators' capacity to control power flow provides considerable advantages for power system performance, including improved power transfer efficiency, improved voltage stability, flexible grid operation, and effective integration of renewable energy sources. PARs offer a flexible and efficient way to manage power flows and maximize the use of the transmission infrastructure by altering the phase angles between voltages. However, to ensure the successful application of power flow control utilizing PARs, proper coordination, sophisticated control mechanisms, and careful consideration of protection and security considerations are needed. The use of phase angle regulators will be more crucial as power systems develop in the future for creating an electricity grid that is more dependable, dependable, and sustainable.

**Real and Reactive power loop power flow control:**Real and reactive power flow control, which aims to maintain the balance between power generation and consumption, regulate voltage levels, and assure system stability, is a crucial component of power system functioning. Reactive power refers to the energy required to keep voltage levels constant, whereas real power represents the actual energy transmission in the system. The regulation of actual and reactive power flow, as well as the methods employed to govern each, are discussed in this article.

Real power flow control: The regulation of active power in the power system is the main goal of real power flow control. The actual energy that is delivered from power generators to consumers is known as active power, sometimes referred to as real power or watts. Real power flow must be managed in order to balance production and consumption, avoid overloading transmission lines, and ensure effective use of the available resources.

**Real Power Flow Control Techniques:**

Generator Control: Using generator control, real power flow can be managed. The mechanical power input or output of generators can be changed to alter the active power produced. To meet the required power demand, respond to system emergencies, and preserve system stability, generators can be run at various load points.

Transformer Tap Changers: On-load tap changers (OLTCs) on transformers offer a way to modify voltage levels and control actual power flow. By adjusting the tap location, the turns ratio of the transformer is altered, which changes the output voltage's magnitude and affects the active power flow.

Switching Devices: By allowing the reconfiguration of the power system topology, switching devices, such as circuit breakers and power electronic devices, contribute to the regulation of actual power flow. In order to improve power transfer and reduce system congestion, particular transmission lines or tie lines might be opened or closed.

Reactive Power Flow Control: Controlling the flow of reactive power in the power system is the main goal of reactive power flow control. Reactive power is required to support the operation of inductive loads and maintain voltage levels. For voltage stability, voltage regulation, and minimizing losses in the power system, reactive power flow must be properly controlled.

**Reactive power flow control techniques:**

Shunt Capacitors and Reactors: For the purpose of compensating reactive power, shunt capacitors and reactors are frequently employed. Shunt reactors take in reactive power while shunt capacitors add it to the system. Voltage levels can be controlled and reactive power imbalances can be reduced by strategically placing capacitors or reactors.

SVCs (Static Var Compensators) are power electrical devices that offer quick and accurate management of reactive power. They are made up of thyristor-controlled reactors (TCRs), capacitors, and reactors. To maintain system stability and control voltage levels, SVCs can either inject or absorb reactive power. They are suitable for dynamic reactive power regulation due to their capacity to react quickly to changes in system conditions.

Synchronous Condensers: Synchronous condensers are rotating devices that, depending on the situation, either produce or consume reactive power. Synchronous condensers can manage reactive power flow and maintain system voltage levels by managing field excitation.

Significance of Real and Reactive Power Flow Control: Real and reactive power flow control is significant because it keeps systems stable and ensures that voltage is regulated and that power is transferred effectively. Real power flow can be properly managed to balance production and consumption, avoid overloads, and guarantee the best possible use of the resources available for production. Voltage stability, reduced voltage fluctuations, and increased system reliability are all benefits of reactive power flow regulation.

Real and reactive power flow regulation are essential components of power system operation, in our opinion. Active power is regulated by real power flow regulation to keep production and consumption in balance. Reactive power is regulated via reactive power flow control to maintain voltage levels and guarantee system stability. For efficient real and reactive power flow control, a variety of techniques are used, including generator control, tap changers, switching devices, shunt capacitors, reactors, SVCs, and synchronous condensers. Power systems can function effectively, dependably, and securely by maintaining an appropriate balance between actual and reactive power.

**Improvement of transient stability with phase angle regulators:**An important part of power system operation that aims to improve the system's capacity to tolerate and recover from transient disturbances is the improvement of transient stability with phase angle regulators. The ability of a power system to sustain synchronism and steady operation after a disruption, such as a malfunction or abrupt shift in load, is referred to as transient stability. In order to improve transient stability, phase angle regulators (PARs) are essential for managing power flow and altering phase angles. The function of phase angle regulators, how they work, and how they affect the efficiency of the power system are all covered in this article.

The Importance of Transient Stability in Power Systems: Transient stability is crucial in power systems because it assures a consistent and uninterrupted flow of electricity to users. Power system stability may be jeopardized by transient events like faults or abrupt changes in load. The ability of the system to sustain synchronism and voltage stability after disturbances is evaluated using transient stability analysis, which helps to avoid system failure and ensure a smooth restoration of power flow. To preserve grid dependability, avoid extensive blackouts, and reduce power supply interruptions, transient stability must be improved.

Operation of Phase Angle Regulators for Transient Stability Improvement: Phase angle regulators (PARs) are devices located in important areas of the electrical system, such as transmission substations or interconnection points, to manage the phase angles between voltages. They are used to improve transient stability. In order to change the effective impedance of transmission lines and affect the phase angle difference, PARs typically adjust the reactive power output.

**Pars can be used in transient events in the following ways to increase transient stability:**

Power Flow Diversion: Power flow can be diverted away from overloaded or problematic sections of the system by altering the phase angles with the help of PARs. This change in power flow improves the system's capacity to withstand transient shocks and reduces stress on crucial components like transmission lines or transformers.

Voltage Support: In order to keep voltage levels stable during transient events, PARs can supply reactive power support. PARs aid in controlling voltage amplitudes and preventing voltage collapse by injecting or absorbing reactive power. For the ongoing operation of loads and the stability of the power system, stable voltage levels are essential.

Damping of Oscillations: Transient occurrences can cause power oscillations, which, if unchecked, might cause a system's instability. By altering the phase angles and managing the power flow, PARs can be used to suppress these oscillations. This dampening effect enhances the system's transient stability and speeds up the process of returning it to a stable condition.

Phase angle regulators' effects on transient stability: Enhancing transient stability is significantly impacted by the use of phase angle regulators:

Better problem Ride-Through Capability: When there is a problem, PARs can help reroute electricity and stop failures from cascading. By regulating the phase angles, PARs help the system retain stability and ride through fault circumstances, lowering the possibility of widespread disturbances or blackouts.

Faster System Recovery: In the wake of transitory events, PARs speed up system recovery. PARs assist in restoring stable operation and synchronism by modifying power flow and phase angles, cutting down on the time needed for system restoration and minimizing the impact on customers.

Enhanced Voltage Stability: Transient stability and voltage stability are closely related. PARs help to maintain stable voltages throughout and after transient occurrences by controlling voltage levels using reactive power regulation. This increases the system's resilience to disruptions and raises the overall system reliability.

Optimal Use of System Assets: By rerouting power flow and reducing congestion, PARs maximize the use of transmission assets. This effective use reduces the need for expensive infrastructure improvements and contributes to system stability.

Phase angle regulators are essential for improving power system transient stability. PARs help to divert power flow, support voltage levels, dampen oscillations, and enhance the system's capacity to endure and recover from transitory disturbances by regulating power flow and altering phase angles. The installation of PARs improves the capacity to ride through faults, hastens system recovery, assures voltage stability, and maximizes the use of system resources. In order to increase transient stability and guarantee the dependable and robust functioning of power systems, the employment of phase angle regulators will continue to be a crucial technique.

**Power Oscillation Damping with Phase Angle Regulators:**Electrical power systems employ the Power Oscillation Damping (POD) with Phase Angle Regulators (PARs) approach to reduce and manage power oscillations. Numerous reasons, including variations in power demand, generator output, or system disturbances, can cause power oscillations. These oscillations have the potential to cause the electricity system to become unstable, experience voltage swings, and experience cascading failures. Phase angle regulators are fixtures put in place in transmission lines or at the locations where two power systems link. By altering the transmission line impedance, they can change the phase angle of the voltage. PARs can affect the power flow and assist in reducing power oscillations in the system by adjusting the phase angle. The fundamental idea underlying POD with PARs is to identify power oscillations and then utilize the PARs to send the system a corrective signal. The goal of this compensating signal is to stop the oscillatory behaviour and bring stability again. The oscillations can be successfully dampened by the PARs by quickly adjusting the phase angle to absorb or release power from the system.

Monitoring system characteristics including generator speeds, voltages, and line currents is often part of the control approach for POD with PARs. Power oscillations are found using specialized algorithms, which also determine the correct compensation signal needed to suppress them. The PARs then receive this compensation signal and modify the phase angle as required. POD with PARs has been successfully used to improve the stability and dependability of power systems. It aids in maintaining system voltages within acceptable bounds and avoids system-wide disturbances by actively controlling power oscillations. Large, linked power grids, where power oscillations can spread over great distances and have an impact on numerous places, frequently employ this technology. It is important to note that POD with PARs is simply one of several techniques used to maintain the stability and control of the power system. To offer complete stability solutions, other methods, such power system stabilizers, are frequently used in conjunction with PARs. POD with PARs can be implemented and configured in a variety of ways, depending on the power system's characteristics and the desired control goals.

**Summary of functional requirements:** Phase angle regulators are mainly used for power flow management, which includes line loading control and loop flow mitigation. Reactive power flow and terminal voltage management are handled by voltage regulators. In order to control the actual and reactive loop power flows, they must be functional. In order to maintain functioning voltage levels in sub transmission and distribution networks, voltage regulators are crucial. Phase angle regulators can increase transient stability and offer power oscillation dampening when they have the necessary control capabilities to offset prevalent machine swings. The functional capabilities of traditional voltage and phase angle regulators, with contemporary solid-state implementations, will play a significant role in the optimal utilization of the transmission network by real and reactive power flow management and voltage control in flexible ac transmission systems of the future. As with controlled shunt and series compensation, it will be clear that the aforementioned functional requirements can be met by either adapting the traditional on load tap changer concept for quick and unrestricted thyristor control or by using a novel method in which switching converters are used as voltage sources and are set up to provide the desired voltage injection for voltage and phase angle regulation[10]–[12].

## CONCLUSION

Static Voltage and Phase Angle Regulators (SVARs) are essential for the control and stability of power systems. SVARs provide adequate power flow and maintain stable voltage profiles by adjusting voltage levels and phase angles. They offer real-time reactive power modifications, enabling effective use of the transmission infrastructure and boosting system stability. Applications for SVARs include grid integration of renewable energy sources, networked systems, and long-distance transmission lines. The installation of SVARs leads to improved grid reliability, decreased transmission losses, higher power transfer capabilities, and better voltage regulation. The utilization of SVARs will be crucial in ensuring a reliable and resilient electrical grid as power systems continue to develop.

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CHAPTER 13

# THYRISTOR CONTROLLED VOLTAGE AND PHASE ANGLE REGULATORS

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**ABSTRACT:**

Important components used in power systems for controlling voltage and reactive power are thyristor controlled voltage and phase angle regulators (TC-VARs). To control voltage levels and adjust phase angles, TC-VARs use thyristor-based technology. This enables effective power flow management and voltage stability improvement. An overview of TC-VARs, their function, advantages, and effects on power system performance are given in this chapter.Power systems use Thyristor-Controlled Voltage and Phase Angle Regulators (TC-VAPARs) as essential components to control phase angles and voltage levels. In this abstract, the main characteristics and practicalities of TC-VAPARs are summarized. Thyristor switches are used by power electronic-based TC-VAPARs to regulate the magnitude and phase angle of the voltage in power transmission and distribution networks. For optimum power flow and system stability, they provide precise and dynamic control over the system voltage and phase angle. The significance of TC-VAPARs in voltage regulation and power system operation is emphasized in the abstract. The main TC-VAPAR benefits and characteristics are covered in the abstract. For effective power transfer and voltage stability, they provide continuous and quick regulation of the voltage magnitude and phase angle. The thyristor switches' firing angles can be changed using TC-VAPARs, which also improve system stability and control power factor.

**KEYWORDS:**

Discrete Level Control, Phase Angle Regulators, Reactive Power Flow, Voltage Phase Angle, Thyristor Tap Changer.

## INTRODUCTION

It is demonstrated that there are two fundamental methods for creating contemporary, power electronics-based reactive compensators: one uses conventional thyristors to regulate current in reactive impedances (which commutate "naturally" at current zeros), and the other uses turn-off (GTO) thyristors (or similar devices) in switching power converters to create controllable synchronous voltage sources. Voltage and phase angle regulators also use a variant of this dual strategy. As stated at the beginning of this chapter, in-phase and, respectively, quadrature voltage injection are typically used to regulate voltage and angle. therefore, between the specified bus and the controlled terminal or line, a controlled voltage is inserted using both the standard thyristor- and GTO-controlled converter-based techniques. The main distinction between the two is that the GTO-based approach generates the insertion voltage from a dc power source, whilst the thyristor-based approach derives it from the appropriate taps of the regulating ("excitation") transformer. Therefore, in the first method, the thyristor-based controller serves as an on-load tap-changer by choosing the appropriate regulating transformer tap and injecting the resulting voltage, often by way of an insertion transformer, in series with the line[1]–[3].

The purpose of the GTO-based voltage source is to produce the necessary voltage and inject it in series with the line using an insertion transformer as well. The differences between the two strategies initially seem negligible, sighi. But as will be seen, the two methods produce significant operational and performance disparities, with the most The voltage-source-based approach's capacity to be self-sufficient in supplying or absorbing the reactive power necessary for voltage regulation or angle control is noteworthy demands. The actual and reactive power necessary for the thyristor-based technique to function must be supplied outside, often by the system, in order to achieve the desired regulation. The unlimited controllability of the injected voltage, which opens up a wide range of novel functional possibilities in Flexible AC Transmission Systems, is another significant distinction. This is discussed in more detail in the following chapter. As a prelude to the more comprehensive discussion, the thyristor-controlled voltage and phase angle regulators (TCVRs and TCPARs) are reviewed in this part, and converter-based voltage and phase angle regulators are introduced in the section that follows. Thyristor-Controlled Voltage and Phase Angle Regulators are used in place of mechanical on-load tap changers for two main reasons: The first is the removal of the costly routine maintenance, and the second is the provision of the rapid response time required for dynamic system control. Both voltage regulators and angle regulators provide a voltage with a variable magnitude from a fixed voltage source from the perspective of the thyristor controller. Naturally, this serves the same purpose as creating a fixed-magnitude voltage from a variable-magnitude source.

To put it another way, the voltage that the thyristor-controller regulates does not purposefully vary its angular orientation; in most cases, the voltage at the output is in phase with the voltage provided at the input. The angular shift caused by voltage regulation based on delay angle control will be evident, though. Thus, whether the transformer winding configuration offers an in-phase or a quadrature voltage input for the thyristor controller determines whether the regulator arrangement is a voltage or angle regulator. Due to this, voltage and angle regulators will not be separated in the explanations that follow, and "regulators" will be used exclusively in the collective sense. Similar to its mechanical cousin, the on-load tap changer, the thyristor controller utilized in (voltage and angle) regulators will be referred to as the thyristor tap changer. The configuration of thyristor tap changers can offer continuous or discontinuous level control. Similar to what was previously introduced, continuous control is based on delay angle control. As can be observed, delay angle control always produces harmonics. The configurations of thyristor tap changers must offer discrete level control to produce little to no harmonic production.

Transformers and thyristor valves, along with their heat sinks, snubbers, and gate-drive controls, are the major component elements of a thyristor tap changer enabling discrete level control. Numerous designs are conceivable that enable discrete level control with tap step sizes generated by traditional electromechanical equipment. Some of these layouts may result in fewer transformer taps being needed, which is often favorable. Figure.1 displays a single line diagram representing two fundamental ideas. One idea, illustrated in Figure 1(a), relies on n identical transformer windings and bi-directional thyristor bridge circuits to deliver zero to n voltage steps in either direction. Each bridge circuit has the ability to link the relevant transformer winding with either polarity or to bypass it. The second idea is based on ternary progression and is depicted in Figure 1(b): the transformer windings and the thyristor bridge voltage ratings are proportioned in the ratio of 1:3:9: and the number of steps, n, in one direction is given with the number of windings, /, by the expression n: (3t*I)12. The three-winding configuration shown in Figure.1(b) contains 13 steps in each direction as a result.

The thyristor tap changer can be structurally further simplified if phase-delay angle control is used to accomplish continuous voltage control. The two thyristor valves used only need to be qualified for the requisite maximum % of voltage regulation. As previously mentioned, these continuous control methods have two drawbacks: the implementation of their control for all load power factors is somewhat

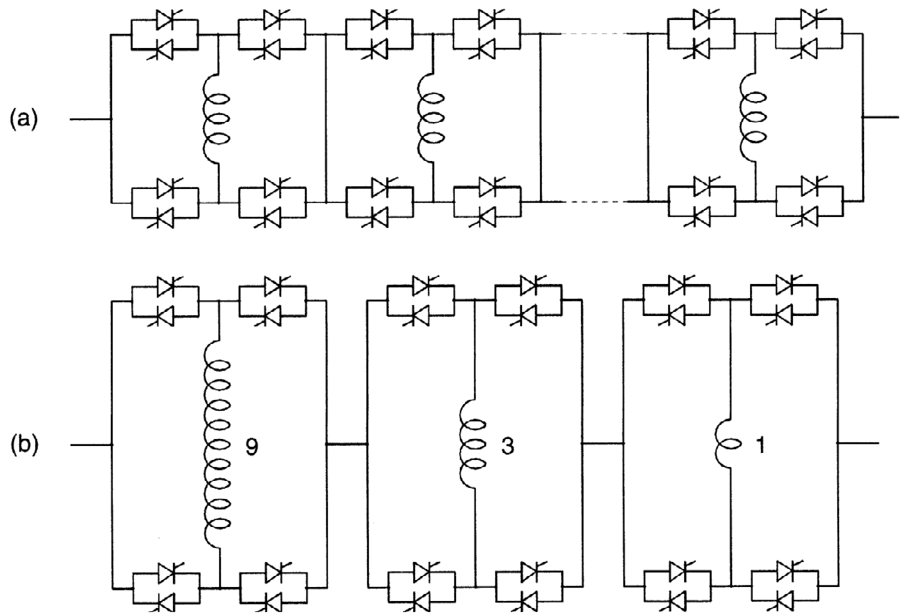


**Figure 1: Basic thyristor tap-changer configurations: (a) identical windings and thyristor valve ratings, (b) windings and thyristor valve voltage ratings in ternary progression.**

Difficult, and they introduce harmonics of the supply frequency into their terminal voltage. In a single-phase example, the output of a continuously regulated regulator comprises all of the system frequency's odd order harmonics. It contains the typical six-pulse type harmonics of the order of (6rn + 1) in the three-phase case with equal loads and control settings on all three phases, where m is any integer from L to oo. The harmonic content for the three-phase case becomes equal, in terms of the frequency components present, to that for the single-phase case if the loads or control settings are not the same on all three phases. Thyristors utilized in utility applications must be able to withstand the fault currents and transient voltages common to utility systems in all of the aforementioned ways. Thus, the actual transient voltages and currents generated during surges and faults have a significant impact on the number of thyristors needed for a voltage regulator application. As a result, specifications needs and protection plans might have a big impact on equipment costs[4]–[6].

## DISCUSSION

**Approaches To Thyristor-Controlled Voltage and Phase Angle Regulators (TCVRS And TCPARs):** TCVRs and TCPARs are thyristor-controlled voltage and phase angle regulators. Power electronic devices used in power systems to manage voltage and phase angles include thyristor-controlled voltage regulators (TCVRs) and thyristor-controlled phase angle regulators (TCPARs). These regulators are essential for preserving system stability, maximizing power flow, and raising system efficiency. In this talk, we will examine several methods and strategies applied in TCVRs and TCPARs.

Fixed-Tap TCVRs: One of the most straightforward and often used methods for controlling voltage is the fixed-tap TCVR approach. The TCVR transformer in this method has a fixed number of taps, and each tap stands for a distinct voltage level. It is possible to change the output voltage by choosing the right tap position. This method offers stepped voltage control but forbids continuous output voltage fluctuation.

Phase-Controlled TCVRs: By altering the thyristors' triggering angles, phase-controlled TCVRs continuously control the output voltage. The conduction period and subsequently the average output voltage are controlled by the thyristors, which are triggered at specific angles throughout each half-cycle of the AC waveform. The voltage at certain locations in the power system can be regulated using this method, which enables fine-grained voltage management.

**TCVRs Based on Voltage Sourced Converters** (VSC):

Voltage-Sourced Converter (VSC)-Based TCVRs: Voltage-Sourced Converters, power electronic devices that convert AC power to DC and then back to AC with variable voltage and frequency, are used by VSC-based TCVRs. Voltage and phase angles can be controlled precisely and flexibly with VSC-based TCVRs. To switch the voltage and control the output, they employ high-power semiconductor components like Insulated Gate Bipolar Transistors (IGBTs) or Gate Turn-Off Thyristors (GTOs). Fast response, greater dynamic performance, and improved controllability are all made possible by this method.

TCVRs Based on Modular Multilevel Converters (MMC): Modular Multilevel Converters, a modern power electronic converter capable of high-voltage, high-power applications, are used in MMC-based TCVRs. MMCs are made up of a number of coupled in series sub-modules to achieve the necessary voltage level. A number of switching components, usually IGBTs or Integrated Gate-Commutated Thyristors (IGCTs), are included in each sub-module and are controlled to provide the correct output voltage and phase angle. Excellent voltage control, little harmonic distortion, and higher power capabilities are all features of MMC-based TCVRs[7]–[9].

Advanced Control Techniques: Different advanced control approaches are used to improve the performance of TCVRs and TCPARs. These consist of:

Proportional-Integral-Derivative (PID) control: PID control algorithms are frequently used in TCVRs and TCPARs to alter the output voltage or phase angle depending on the difference between the desired and actual values. To maintain precise regulation, PID control modifies the thyristors' triggering angle.

Model Predictive Control (MPC): Model Predictive Control (MPC) is a sophisticated control technique that use a dynamic model of the system to forecast future behavior and optimize control actions in accordance with that prediction. To decrease overshoot, increase stability, and speed up response time, MPC algorithms can be used in TCVRs and TCPARs.

Adaptive Control: Using system identification and estimation algorithms, adaptive control approaches continuously modify the control parameters in accordance with the operating circumstances and system properties. The performance of TCVRs and TCPARs is improved through adaptive control across a range of load and system situations.

Communication and Coordination: Communication and coordination may be necessary between TCVRs and TCPARs and other control devices and system components in big, interconnected power systems. Information can be exchanged and coordinated control actions made possible by communication protocols like IEC 61850 or DNP3. In order to maintain system stability and voltage management, TCVRs and TCPARs must cooperate with other components like Automatic Voltage Regulators (AVRs) and Power System Stabilizers (PSSs).

TCVRs and TCPARs are essential components in power systems for controlling voltage and phase angle. Variable methods provide varied degrees of control flexibility and performance, including fixed-tap, phase-controlled, VSC-based, and MMC-based methods. The efficiency of TCVRs and TCPARs in preserving system stability, optimizing power flow, and assuring reliable power transmission is further increased by modern control approaches and coordination mechanisms.

**Continuously Controllable Thyristor Tap changers:**Constantly Adjustable Thyristor Modern devices called tap changers (CCTT) are used in electrical power systems to regulate the voltage levels of transformers. Within the confines of a 1000-word constraint, I will describe the guiding principles, benefits, and applications of CCTT. In high-voltage and extra-high-voltage power transmission systems, where CCTTs are used, they are essential to preserving a steady and dependable power supply. In transformers, these tap changers are used to modify the turns ratio and therefore control the output voltage. The CCTT can correct for voltage differences brought on by changes in load, voltage drops, and other factors by altering the turns ratio, ensuring that the desired voltage is provided to the consumers. Thyristor-controlled reactors (TCRs) and thyristor switches are crucial to the operation of CCTTs. TCRs are inductive devices that can be used to change the turns ratio of a transformer by connecting them in series or parallel with the transformer winding. Solid-state electronic thyristors function as switches by allowing or preventing the flow of current. The conduction duration can be precisely adjusted, allowing for fine control of the reactive power flow and tap changing action, by modifying the firing angle of the thyristors. The CCTT system measures the output voltage and compares it to the target value when a voltage correction is required. The control system determines the necessary correction if a deviation exists in order to reach the specified voltage level. The CCTT system adjusts the turns ratio by activating the relevant thyristors and TCRs in accordance with this computation.

The reactive power flow and tap position are determined by the thyristors' firing angles, resulting in precise voltage regulation. The continuous controllability of CCTTs is one of their key benefits. CCTTs offer a virtually limitless number of tap positions, in contrast to traditional tap changers that only give discrete tap positions. This continuous regulation enables precise voltage level adjustments, improving system stability and voltage quality as a result. Additionally, CCTTs have quicker response times than mechanical tap changers, allowing for quick load and voltage adjustment. Power factor correction benefits from the continuous controllability of CCTTs. CCTTs may actively regulate the power factor of the system, maximizing its efficiency and lowering line losses, by regulating the reactive power flow. The performance of the power system as a whole is enhanced, and fewer additional compensating devices are required. Additionally, CCTTs support the overall durability and dependability of power transformers.

Continuous voltage regulation lowers the strain on the transformer windings, lowering the possibility of insulation damage and overheating. With this improved protection, the transformer will last longer and require less maintenance. CCTTs are used in a number of power industry industries. They are frequently employed in power distribution and transmission systems, where voltage regulation is essential for preserving grid stability and voltage quality. In order to modify the voltage levels in accordance with grid needs, CCTTs are also used in renewable energy producing systems, such as wind farms and solar power plants. Furthermore, CCTTs are essential in industrial applications requiring accurate voltage regulation. Data centers, manufacturing, chemical processing, and other sectors with sensitive gear depend on CCTTs to maintain a steady power supply and guard against equipment damage. CCTTs, or continuously controllable thyristor tap changers, are sophisticated devices that allow exact and continuous control of transformer voltage levels. CCTTs provide unlimited tap positions and quick response times by utilizing thyristor-controlled reactors (TCRs) and thyristor switches, which enhance voltage regulation, power factor correction, and overall system reliability. These gadgets are used in power transmission, distribution, renewable energy production, and industrial sectors, enhancing efficiency and ensuring a steady supply of power.

**Thyristor Tap Changer with Discrete Level Control:**A typical type of tap changer used in electrical power systems to vary the voltage levels of transformers is the thyristor tap changer with discrete level control. Within the allotted 1000 words, I will describe the operation, benefits, and applications of thyristor tap changers with discrete level control. Power transformers use thyristor tap changers with discrete level controls to alter the turns ratio and subsequently control the output voltage. The number of tap locations offered by these tap changers is set and often predetermined based on the specifications and design of the transformer. To obtain the appropriate voltage adjustment, switching between these tap positions is possible using the discrete level control. Thyristor switches, also known as silicon-controlled rectifiers (SCRs), are used to connect various transformer winding taps to the electrical circuit in thyristor tap changers with discrete level control. SCRs are solid-state electronic switches that can let current flow or block it in response to a control signal. The tap changer's control system checks the output voltage against the target value to determine whether a voltage correction is necessary.

The control system switches the tap connection if there is a deviation by activating the necessary SCRs. This increases the transformer winding's number of turns, which changes the turns ratio and causes the necessary voltage adjustment. In power systems, thyristor tap changers with discrete level control offer a number of benefits. In comparison to mechanical tap changers, they first offer faster tap changing. Thyristor switches' electronic nature enables quick switching between tap positions, ensuring a speedier response to voltage changes and load changes. The power system's stability and dependability are enhanced by this capability. Thyristor tap changers have the additional benefit of not having any moving parts. Mechanical tap changers are subject to wear and tear over time since they rely on physical mechanisms such mechanical gears, springs, and contacts. Thyristor tap changers, on the other hand, are solid-state electronics, resulting in lower maintenance needs and greater durability. Furthermore, better voltage regulation is made possible by thyristor tap changers with discrete level control. The precise voltage adjustment choices provided by the fixed tap placements ensure that the intended voltage level is kept within allowable bounds. Both the utility and the final consumers profit from this precise regulation's contribution to the reliability and quality of the electricity supply. In power distribution networks, where maintaining proper voltage levels is critical, these tap changers also play a significant role.

Thyristor tap changers with discrete level control assist in making up for voltage reductions that may happen as a result of transmission line losses or heavy demand by modifying the turns ratio of the transformer. The voltage sent to consumers is regulated to ensure that it stays within allowable bounds, protecting electrical equipment and maintaining dependable functioning. Applications for thyristor tap changers with discrete level control can be found in the power industry. They are frequently employed in distribution substations where they provide voltage control and regulation for numerous feeders. These tap changers are also used in industrial situations, including as large commercial buildings and manufacturing factories, where delicate machinery and equipment needs accurate voltage adjusting. Additionally, discrete level control thyristor tap changers are used in renewable energy systems like wind farms and solar power plants. By regulating voltage levels in accordance with grid needs and preserving the stability of the entire power system, these tap changers aid in optimizing power output. Thyristor tap changers with discrete level control are electronic devices that are used to modify transformer voltage levels. When compared to mechanical tap changers, they offer faster tap shifting, better voltage regulation, and increased reliability. Thyristor tap changers with discrete level control are used in distribution systems, industrial settings, and renewable energy systems to support steady power supply, voltage management, and optimum system performance.

**Thyristor Tap Changer Valve Rating Considerations:** Several valve rating considerations must be made while building a thyristor tap changer for a power transformer. These factors make sure that the tap changer performs reliably and safely under the required operating circumstances. The following are some vital valve rating factors for thyristor tap changers:

Voltage Rating: The maximum voltage that the tap changer will experience when it is in use should match the voltage rating of the thyristor valves. To ensure secure and dependable functioning, it is essential to choose valves that can resist the greatest voltage levels.

Current Rating: The greatest current that will pass through thyristor valves during tap changing procedures determines their current rating. The transformer's rated current and the anticipated overload situations should be taken into consideration while choosing this current rating.

Surge Current Rating: Thyristor valves should be equipped with a surge current rating that can withstand the significant current surges that happen during switching operations. The current through the valves can briefly increase dramatically when a tap change takes place. The valves can withstand these transitory currents without being harmed thanks to the surge current rating.

Voltage Recovery Rating: The thyristor valves must first go through a voltage recovery period after being shut off during a tap change before they can be turned back on. The maximum voltage that the valves can withstand during this recovery period is specified by the voltage recovery rating. In order to prevent voltage breakdown and guarantee safe operation, it is crucial to use valves with the proper voltage recovery rating.

Frequency Rating: Thyristor valves should be made to function at the power system's frequency in order to meet the need for frequency rating. In order to handle the frequency harmonics and ensure correct operation, the valves should be rated appropriately because the majority of tap changers are made for power systems that run at 50 Hz or 60 Hz.

Energy Handling Capacity: Thyristor valves need to have enough energy handling capability to handle the energy loss during switching operations. This covers both the energy lost when the thyristor valves are turned on and off. Overheating is avoided and dependable operation is ensured by enough energy handling capacity.

Cooling and Heat Dissipation: Thyristor valves produce heat while they are operating, thus it is important to have the right cooling mechanisms in place to effectively dissipate this heat. In order to prevent overheating and keep the valves within their designated temperature ranges, the cooling system should be created.

Surge Protection: Thyristor valves should have the proper surge protection in place to guard against voltage surges brought on by switching transients and lightning strikes. Surge arresters and other surge protection devices are fitted to redirect excessive surge currents and safeguard the valves from harm.When choosing thyristor valves for tap changers, it is crucial to refer to the manufacturer's requirements and recommendations. The valves will be properly rated for the particular application and operating circumstances if you follow the manufacturer's guidelines. To guarantee that the valves continue to operate within their rating limitations and deliver dependable performance over time, proper maintenance and routine inspections should also be carried out.

**Switching Converter Based Voltage and Phase Angle Regulators:**Voltage and phase angle regulators based on switching converters are electronic components used to regulate the voltage and phase angle of an AC power supply. These regulators modify the output waveform's voltage and phase angle using switching converter technology, such as pulse width modulation (PWM). In order to maintain stable and dependable performance, AC power systems must regulate the voltage and phase angle. By adjusting for variations in the input voltage or changes in the load, voltage regulation makes sure that the output voltage stays within predetermined limits. The phase connection between the voltage and current waveforms is controlled by phase angle regulation, which is crucial for power factor correction and for maximizing power transfer.

**The Following Components Are Frequently Found in Voltage and Phase Angle Regulators Based On Switching Converters**:

Power Semiconductor Devices: In the converter circuits, switches such as insulated gate bipolar transistors (IGBTs) or power MOSFETs are used. They can quickly turn on and off, regulating the voltage and current flow.

Control Circuitry: The control circuitry consists of a microcontroller or digital signal processor (DSP) that keeps track of the waveforms of the input and output current and voltage. The control circuitry generates the appropriate control signals to modulate the switching of the power semiconductor devices based on the specified voltage and phase angle settings.Pulse Width Modulation (PWM) Controller: To regulate the power semiconductor devices, the PWM controller creates high-frequency switching signals. The PWM controller can alter the phase angle and average output voltage by varying the switching pulse width.

Regulation of Voltage: The control circuitry gauges the output voltage and compares it to the intended voltage reference. The control circuitry modifies the duty cycle of the switching pulses produced by the PWM controller if there is a divergence. Average output voltage rises with increasing duty cycle whereas average output voltage falls with decreasing duty cycle. The regulator maintains the output voltage within the appropriate range by continuously altering the duty cycle. Phase Angle Regulation: Adjusting the phase relationship between the voltage and current waveforms is known as phase angle regulation. Usually, timing the switching pulses is how this is accomplished. The phase angle between the voltage and current waveforms can be changed by varying the timing. This facilitates power factor correction and enhances the system's power transfer.

**Voltage And Phase Angle Regulators Based on Switching Converters Have the Following Benefits In Power Systems**:

Fast Response: Rapid Voltage and Phase Angle Adjustments: These regulators have a short response time and can quickly adapt to changes in the input voltage or load circumstances. This aids in preserving system stability and adapting to changes in the dynamic load.

Great Efficiency: When compared to conventional linear regulators, switching converters are noted for their great efficiency. Power semiconductor devices with PWM control provide effective energy conversion, which lowers power losses and improves system effectiveness overall.

Flexibility: These regulators are simple to modify to meet various voltage and phase angle control specifications. The control circuitry is adaptable for a variety of applications because it may be designed to meet unique system requirements.

In power distribution systems, renewable energy systems, and industrial applications where precise control of voltage and phase angle is necessary, switching converter-based voltage and phase angle regulators are frequently utilized. They are essential for preserving system stability, improving power factor, and facilitating effective power transfer.

**Hybrid Phase Angle Regulators:**Modern electronic devices called hybrid phase angle regulators (HPARs) are used to regulate the phase angle of AC power systems. To improve performance and versatility, these regulators combine the benefits of switching converter-based voltage regulators and thyristor-based phase angle regulators. In order to improve power transfer and rectify power factor, hybrid phase angle regulators' main job is to change the phase relationship between the voltage and current waveforms. HPARs can enhance the power quality and efficiency of AC power systems by regulating the phase angle. By combining switching converter technology with thyristor-based control elements, these regulators attain their hybrid nature. The following are the main elements and operating ideas of hybrid phase angle regulators:

**Control components based on thyristors:** Thyristors are the main control components used by HPARs to manage the phase angle. Solid-state electronic thyristors can switch very high currents and voltages. They have the ability to modify the AC waveform's conduction angle, which enables accurate phase angle correction.

**Switching Converter Circuitry:** To enable fine control and adjustment of the phase angle, HPARs also employ switching converter circuitry, such as pulse width modulation (PWM) methods. Power semiconductor components, such as insulated gate bipolar transistors (IGBTs) or power MOSFETs, are used in the switching converter circuitry to quickly switch on and off **to control the flow of current and voltage.**

**Control Circuitry:** Digital signal processors (DSPs) or microcontrollers that keep an eye on the input and output waveforms make up the control circuitry of HPARs. These tools track the phase angle in real time and compare it to the intended reference value. The control circuitry creates the proper control signals to regulate the thyristors and switching converter circuitry based on this comparison.

**The following succinct statement describes how hybrid phase angle regulators function:**

Phase Angle Regulation: A continuous measurement of the phase angle between the voltage and current waveforms is made by the control circuitry. The control circuitry modifies the firing angle of the thyristors to control the phase angle if there is a divergence from the required reference value. To facilitate the appropriate phase angle modification, the switching converter circuitry additionally modifies its switching patterns. The phase angle is precisely controlled by this combination procedure.

Voltage Regulation: Voltage regulation is another feature that hybrid phase angle regulators may offer. HPARs regulate the average output voltage by varying the duty cycle of the switching pulses, much as switching converter-based voltage regulators. By doing this, they are able to manage the phase angle and regulate the output voltage within the appropriate range.

**In AC power systems, hybrid phase angle regulators provide the following benefits**:

Enhanced Performance: Thermistor-based control and switching converter technologies are combined to create HPARs, which offer precise control over voltage and phase angle. As a result, power transfer is optimized, power factor correction is improved, and system performance is increased.

Flexibility: Hybrid phase angle regulators are very adaptable to different voltage and phase angle control needs. The control circuitry is adaptable for various applications since it may be programmed to meet unique system requirements.

Rapid Adjustment: These regulators can make quick adjustments to preserve system stability and adapt to dynamic load variations in response to changes in the phase angle or voltage needs.

In power distribution networks, renewable energy systems, and industrial settings where precise control of phase angle and voltage is essential, hybrid phase angle regulators are used. They help AC power systems work more optimally and with higher energy efficiency and better power quality[10]–[12].

## CONCLUSION

Thyristor Controlled Voltage and Phase Angle Regulators (TC-VARs) are useful components that are crucial to the operation and management of power systems. TC-VARs allow precise control over voltage levels and reactive power flow through the use of thyristor-based technology, which has many advantages for the performance of power systems. By altering the phase angles and controlling the reactive power flow, TC-VARs provide effective power flow management. This makes it possible to use transmission infrastructure to its fullest potential, reduces traffic, and improves the overall stability and reliability of the system. In order to preserve voltage stability, prevent voltage collapse, and guarantee dependable and consistent operation of loads, TC-VARs enable precise control over voltage levels. The use of TC-VARs has a number of benefits, including enhanced voltage regulation, improved power transfer, and increased system adaptability. By controlling power imbalances and maintaining stable grid operation, TC-VARs aid in the integration of renewable energy sources. TC-VARs enable effective voltage and reactive power regulation, making them essential instruments in contemporary power systems. Their implementation promotes the integration of renewable energy sources, facilitates the smooth and efficient flow of electricity, and helps power systems operate more reliably and securely. TC-VARs will become more crucial as electricity systems develop in order to maintain the grid's stability and sustainability.

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