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Enhancing Power Transmission Efficiency Using Static Synchronous Series Compensators: A Comprehensive Review

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Abstract: In recent decades, the demand for electricity has continuously increased. Power generation facilities are predominantly situated at substantial distances from consumption centers, necessitating transmission over extensive, high-voltage lines. Such configurations lead to significant energy losses and diminished capacity and capability of transmission systems. Consequently, enhancements in transmission line performance have become a focal point for power system operators. The integration of the flexible alternating current transmission system (FACTS) technology has emerged as a pivotal solution, facilitating dynamic control over power flow and amplifying the existing capacity of power lines without the need for constructing new infrastructure. Among various FACTS devices, the static synchronous series compensator (SSSC) plays a crucial role by injecting variable capacitive or inductive reactance as required, thereby optimizing power flow and enhancing voltage stability. This review paper meticulously examines the functionality of different FACTS technologies, with a specific focus on the SSSC. Comparative analyses of transmission line performance, uncompensated, compensated through traditional series capacitors, and enhanced via SSSC, were conducted. The findings underscore the versatility of SSSC in reducing transmission losses and stabilizing network operations. This investigation not only details the operational benefits of SSSC but also explores its potential in addressing contemporary challenges in power transmission systems.

Keywords: Flexible alternating current transmission system; Static synchronous series compensator; Power flow control; Power compensation; Voltage stability; Loss reduction

1 Introduction

Due to the increasing demand for electrical power, it is crucial to raise the capability of transmission lines to efficiently convey the electricity generated and demanded by end users. The main goal of the electrical system is to provide reliable power to end users, particularly industrial customers. It is obvious that the demand for electricity has been increasing. However, upgrading the transmission lines and increasing the generation units require a high capital cost and have an adverse impact on the environment [1]. The FACTSA provides a great opportunity to regulate the transmission of alternating current (AC), which makes immediate responses to the issues of stability and increases or decreases the power flow in specific transmission lines, thereby increasing the capacity of the transmission lines for power transmission. The FACTS is generally based on power electronics. Several electrical system operators have seen the considerable effect of the FACTS in controlling power transmission and raising the ability of transmission lines to transmit more power to the load centers [2]. In this study, the SSSC was reviewed comprehensively to investigate its properties. This device is used to sustain the voltage stability of the system and compensate for both active and reactive power [3]. The mentioned types of power flow in the transmission lines can be accomplished by the SSSC. Unlike the traditional compensation by series capacitors which depend on current, voltage compensation is achieved regardless of the line current voltage. It is possible to change and control the amplitude and phase angle of the three-phase voltage systems using the SSSC, similar to synchronous voltage sources. It should be mentioned that the SSSC does not create resonance with the inductive line resistance and avoids synchronous resonance oscillations [4]. The synchronous compensator can produce or absorb the system's reaction energy. It is possible to use direct current (DC) batteries instead of DC capacitors to provide real power compensation in transmission lines. The stability of the traditional power system can be improved by controlling the current flow under stable conditions. Furthermore, the application of the SSSC significantly mitigates voltage drops through its reactive power compensation, facilitating improved voltage regulation within power systems. The device is also capable of simulating either an inductive or capacitive reaction through power injection [5].

2 Literature Review

Several studies have investigated the effects of connecting the SSSC with the transmission lines. The purpose, conclusion, and drawbacks of each study were summarized. The optimal SSSC control to minimize transmission losses while preserving the ratios of the reactance to the resistance (X/R ratios) and voltages within acceptable limits was proposed in this study. The impact of X/R ratios on power transmission in a connected system was discussed. It was found that the planned SSSC reference voltage generation technique effectively regulated the transmission power and minimized the loss of transmission in the chain lines while preserving the voltage and X/R within acceptable limits. The key findings include the enhancement of both power transmission through SSSC links at the lowest power loss level and system stability. Nema and George [6] found that the existence of an active source on the DC side of the inverter and the complexity of the system were the main limitations requiring further investigation. Aleem et al. [7] presented the effects of static synchronized series compensation. In addition, the behaviour of the power system in two kinds of compensation was compared using the SSSC and the improvements in both the active and reactive energy flow and the stability of the power system were evaluated.

One of the previous studies demonstrated that the FACTS based on computational intelligence enhanced the steady-state and dynamic performance of power grids [8]. In the study of Hoseynpoor et al. [9], the FACTS device was used to increase the capability of power transmission, better use the existing transmission system assets and their controllability, and raise both the availability and reliability of transmission systems, thereby enhancing the power systems. Fadhil and Vural [10] addressed the deployment and evaluation of three FACTS devices, namely, the thyristor controlled series compensator (TCSC), the SSSC and the static synchronous compensator (STATCOM).

Table 1 shows the contribution fields of several current studies on FACTS devices, specifically the SSSC.

Table 1. Contribution fields, limitations and future work for the SSSC

References	Contribution Fields	Limitations	Future Work
[9–14]	• The improvement of the power system stability of transmission lines. • Both capacitive and inductive injection have been provided, irrespective of the value of the line current. • The improvement of the overall reactive power and the voltage drop of the transmission lines. • The electric power flow control.	• The implementation requires a high cost. • The capacitor charge decreases over time. • The amount of capacitor storage needs to be reduced. • The lack of considering other factors influencing the function of the power system.	• Suitable locations of the SSSC.
[12, 13, 15–19]	• The control of the active power of the transmission lines. • The improvement of voltage stability in power systems.	• Specific concentration in a single district. • Limitations to accurately forecast the heat demand. • The need for future expansion to more complicated systems.	• Expanding the use of the SSSC to more complicated power. • Examining the effect of the SSSC on different types of power systems.
[17–25]	• Reactive power compensation. • Voltage stability improvement. • Active power flow control in the transmission lines.	• Focus on a specific substation. • The potential need for further research on stability improvement. • For actively controlled equipment, there is a potential for instability or oscillation of the AC system. • A high cost.	• Exploring the concept of distributed FACTS for cost-effective and reliable power flow control.

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References	Contribution Fields	Limitations	Future Work
[25–32]	• The control of active and reactive powers. • The control of the damping oscillations in a transient mode. • 10% of the nominal voltage system can be injected by the SSSC. • The enhancement of power transmission capability and controllability. • Utilization of existing transmission lines in a good way. • An increase in reliability and availability. • The enhancement of power transmission capacity. • The improvement in voltage stability. • The regulation of the amount of injected voltage into the transmission lines.	• Lack of control in the power system. • Negative effect on stability. • Absence of addressing the limitations of new installations. • Stability challenges and thermal limits. • The infeasibility of the former research method and the extension of applying the SSSC to more complex systems.	• The need for further improvement in the damping capability of the system. • Potential areas for future research to develop more efficient and flexible power flow control methods and optimize the FACTS technologies for enhanced power system operation and control.
[33–38]	• Implementation and testing of the SSSC in a transmission line, designed as a voltage source inverter (VSI) with PWM pulses generated by a dsPIC microcontroller. • Use of MATLAB/Simulink for simulation, confirming the experimental operation of the SSSC. • The improvement of the system's dynamic behaviour. • Loss reduction • The enhancement of the performance of power transmission.	• Lack of discussions on long-term performance or maintenance considerations. • The need for a suitable solution in the near future to meet the increasing power demand. • Potential economic constraints.	• The impact of unbalanced faults. • The effectiveness of the FACTS devices in mitigating losses. • Research on the specific mechanisms to improve the system's stability, security, availability, and reliability using the FACTS devices.
[39–47]	• Minimization of transmission line loss. • The enhancement of transmittable power. • The regulation of the system voltage. • The control of active and reactive power flow. • The enhancement of the system's ability for power transmission.	• Focus on specific aspects of the SSSC implementation without addressing other potential challenges. • The need for future work to address the X/R ratio.	• Addressing the X/R ratio to reduce transmission loss and improve power system stability and power oscillation damping. • Modifying the algorithm for active power control of the SSSC.

3 FACTS Controllers

FACTS controllers play a pivotal role by modifying the flow of power along transmission lines. This modification is primarily achieved through the manipulation of three key characteristics as elucidated in Eqs. (1) and (2) [48–51]:

(a) The voltages at both-sending and-receiving ends.

(b) Line reactance or impedance.

(c) The value of the phase-angle difference between the voltages at both sending and receiving ends.

$$P = \frac{V_S * V_R \sin\delta}{X_L} \tag{1}$$

The amount of the power flow can be controlled by changing any of the above-mentioned three characteristics.

$$Q = \frac{V_S * V_R(1 - \cos\delta)}{X_L} \tag{2}$$

where, V_S is the voltage at the sending end, V_R is the voltage at the receiving end, δ is the phase angle between the voltages at both sending and receiving ends, X_L is the series reactance of the transmission lines, V_S is the power transferred per phase, P is the real power, and Q is the reactive power.

The reactance and voltage changes can be used to increase the capability of the transmission lines, and the changes in the phase angle can be used to regulate the power flow.

4 Types of the FACTS

The main types of the FACTS are illustrated in Figure 1 [52, 53].

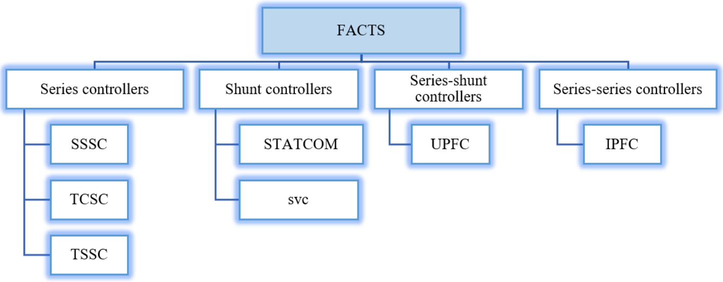

Figure 1. Types of the FACTS

4.1 Series Controllers

The voltage in series with the line voltage is introduced by the series controller, as illustrated in Figure 2. It consists of a capacitor or reactor. The variable reactive power is supplied and consumed by this type of controller.

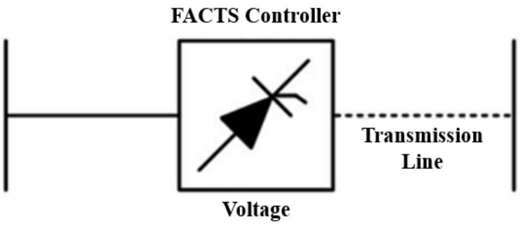

Figure 2. A series controller [11, 54]

4.2 Shunt Controllers

For the purpose of injecting currents into the system at the connection point, a shunt controller is connected in parallel with the line, as shown in Figure 3. It is a combination of an exchangeable inductor or capacitor.

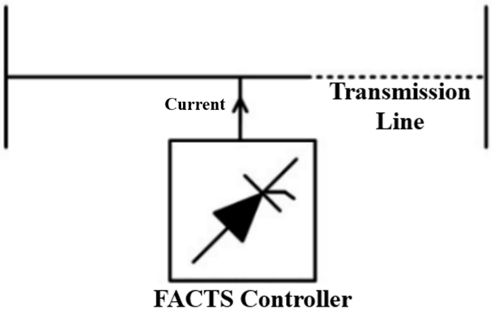

Figure 3. A shunt controller [11, 54]

4.3 Series-Series Controllers

This type of controller includes series controllers connected with each other to provide series compensation in addition to the real power transferring through the line.

4.4 Series-Shunt Controllers

The series-shunt controller is combined with the transmission line.

This type of controller provides voltage in parallel and current in series. Each individual FACTS device provides control separately or collectively by combining with other FACTS devices [54].

Static var compensator (SVC) and STATCOM are used to improve electric power flow in the transmission line by increasing the voltage profile at the connection point.

TCSC-and-SSSC are used to improve the flow of true power, and SSSC is used to regulate the phase angle of the transmission system.

The voltage, impedance and phase angle of the transmission line are controlled by one of the FACTS devices called the unified power flow controller (UPFC) [2, 55].

5 Benefits of the FACTS Devices

The elementary system security rules allow these controllers to qualify transmission owners to attain, on an individual basis, one or more of the following advantages [2, 56]:

(a) The power flow is controlled as per the demand. The power flow control is employed to gather the utility's demands, guarantee optimal power flow, navigate emergency situations, or a combination of all of these.

(b) The loading capacity of the line can be expanded to its thermal limits, encompassing both short-term and long-term considerations. The electric power distribution between lines corresponding to their power transmission ability can be accomplished by overcoming other limitations. It is noted that a line's thermal capability varies greatly depending on the environmental conditions and load history.

(c) The necessity for the overall generation reserve can be reduced, provided that safe connections with tie lines to neighboring utilities and regions are established.

(d) The safety of the system is enhanced by adjusting the transient stability threshold, limiting short-circuit currents and overloads, handling escalating blackouts, and reducing the mechanical reverberations of power systems and devices.

(e) Enhanced flexibility is provided for the positioning of new-generation facilities.

(f) Lines are upgraded.

(g) The capability of the line to carry more dynamic power is increased by decreasing the flow of reactive power.

(h) The loop flows are reduced.

(i) The implementation of the lowest-cost generation options should be increased. Transmission interconnections are designed to employ the lowest-cost generation sources. There is not adequate profitable transmission capacity when this is not possible. The enhancement in economical capacity will increasingly allow for the use of the lowest-cost generation.

6 Comparison Between Different FACTS Controllers

Various types of-FACTS controllers have different contributions to make in developing the power system network. Table 2 shows a comparison of their contributions.

It is obvious from the table that the SSSC is one of the-FACTS devices that has made a significant contribution to the improvement and stability of the electrical power-system.

Table 2. Comparison of different FACTS controllers

#	**Functions/Contributions**	**FACTS Controllers**				
		SSSC	**SATACOM**	**TCSC**	**UPFC**	**IPFC**
1	Power flow control	✓		✓	✓	✓
2	Voltage control	✓	✓	✓	✓	✓
3	VSC	✓	✓		✓	✓
4	System impedance control	✓	✓	✓	✓	✓
5	Reactive power compensation	✓	✓		✓	✓
6	Transient stability	✓	✓	✓	✓	✓

7 SSSC

A SSSC is a series controller, which is used to regulate the power flow and reduce power fluctuations in the power grid.

The SSSC works as a synchronous voltage source instead of inserting a capacitor in series. It affords reactive power compensation to the power system by inserting a three-phase AC compensation voltage at an angle of 90° to the line current. The SSSC injects a compensation voltage in series with the system. The actual power transfer over a transmission line is expressed by the following Eq. (3):

$$P = \frac{V_S * V_R}{X_L} \sin\delta + \frac{V}{X_L} V_q \cos\frac{\delta}{2} \tag{3}$$

where, V_q is the injected voltage of the SSSC.

The above equation shows that the SSSC can either boost or regulate real power transfer by altering the injected voltage (V_q) between positive and negative values.

Power flow reverses its direction if V_q exceeds voltage drop across uncompensated transmission line reactance (X_L), leading to a power flow from the receiving end to the sending end [2, 22, 57].

A functional model of the SSSC is illustrated in Figure 4, where an energy storage device has replaced the DC capacitor, which is similar to the installation of a high energy battery to permit the exchange of both active and reactive power with the AC system. Both the output angle and the magnitude of the SSSC are changeable in order to control the power flow in the transmission line. The active and reactive power can be exchanged with the system by changing the phase angle of the injected voltage (V_{pq}), with respect to the transmission line current (I_{line}).

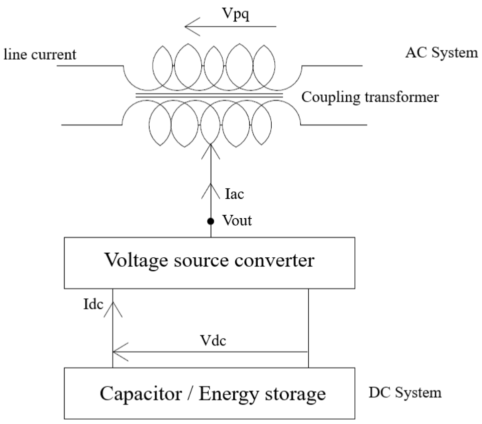

Figure 4. A functional model of the SSSC [7, 58]

8 SSSC and Power Flow Control

The FACTS controllers are combined into an electrical infrastructure. The SSSC is an important device in the family. A series compensator is used to operate a static synchronous generator without an external power supply. The variation in the total reactive voltage decrease is not affected by the line current. The system has energy absorbers that enhance its dynamic behaviour by adding real power to the temporary fluctuations in the real voltage drop on the transmission line. The SSSC can apply a voltage that delays or carries the current. This is applicable to resolving numerous issues with electrical systems. The SSSC provides a uniform series reactance for variable capacitance. The SSSC controllers are proficient at governing the flow of current in a transmission line, raising the transmission threshold, providing continuous variables and impedance, and significantly enhancing the line's stability. The SSSC concept revolves around two fundamental tenets. First, the SSSC provides electromechanical protection against massive power networks by altering the reactivity of the current interconnected power grid. Second, the SSSC alters the apparent resistance at synchronized frequencies to prevent future asynchronous resonances from occurring. Figure 1 and Figure 2 show the basic configuration of the SSSC and the equivalent circuit. Moreover, compensators equipped with power sources are capable of transferring or absorbing active power from transmission lines, as well as controlling the flow of reactive power. As implied by its name, the SSSC is connected to the main power grid through a series of cables, functioning as a series compensator.

The series compensator is connected to the power system with a three-phase series transformer. Figure 4 illustrates a functional model of an SSSC where DC capacitors are substituted by energy storage devices such as high-energy battery devices to provide active and reactive power exchange with the AC system. It is possible to control the output voltage and phase angle of the SSSC by affecting the flow of the current in the transmission line. Active and reactive power are exchanged in the AC system because of the phase shift of the input voltage (V_{pq}) on the transmission line [4].

8.1 Operating Principle

A conventional series capacitance and the associated voltage phasor diagram can be used to illustrate the elementary operating principle of the SSSC. The. phasor. diagram. clearly illustrates that, for a given line current, the voltage across the series capacitor causes the reverse polarity voltage across the series line reactance to increase with the magnitude of the capacitor's voltage. As a result, series capacitive compensation works by boosting the voltage at a given physical line resistance, which in turn boosts the line current and the corresponding transmitted power.

In theory, series capacitance compensation is used to reduce line impedance, but, in practice, it is used to boost the voltage. across a given. impedance. in the physical. network, as previously explained. Therefore, consistent steady-state power transfer can be accomplished if series compensation is afforded by a synchronous AC voltage source whose output exactly matches the series capacitor voltage, as shown in Figure 5 [59].

$$V_q = V_c = -jX_cI = -jkXI \tag{4}$$

where, V_c is. the.voltage.phasor.compensated by injection, I represents the.line.current, X_c is the reactance.of the series capacitor, X represents the line reactance, and $k = \frac{X_c}{X}$ represents the.degree of series compensation.

As with series capacitors, compensation is achieved by determining the synchronous voltage source output as a function of the line current. Figure 6 depicts the elements of an uncompensated power transmission line.

On the other hand, instead of being only a series capacitor injector, the SSSC works as a synchronous voltage source to supply reactive power compensation to the power system by injecting the three-phase AC voltage, which is at 90° with the line current, as illustrated in Figure 7.

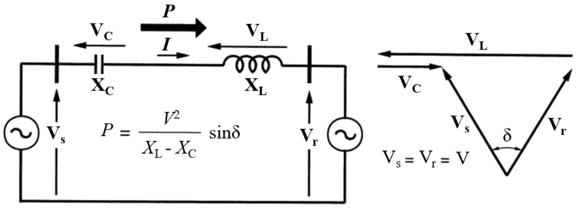

Figure 5. A transmission line with series capacitor compensation [51]

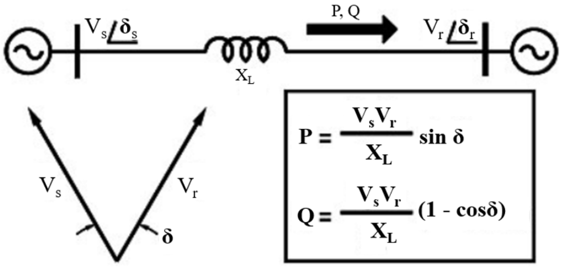

Figure 6. Elements of a power transmission line (uncompensated) [46]

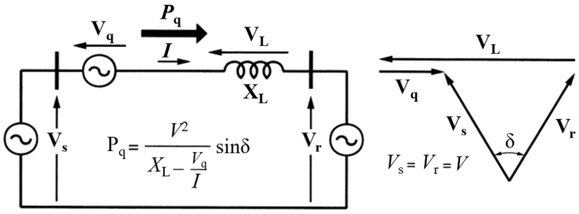

Figure 7. A transmission line compensated by the SSSC [3, 60]

The SSSC can operate either in the inductive region, which means the voltage lags the line current, or in the capacitive region, where the voltage leads the line current. The product of the line current and V_q determine the rating of the SSSC [57].

It is obvious from Figure 7 that the power transmittable and the voltage stability can be controlled using the SSSC. The major difference between the series capacitive injection and the SSSC is that the former only increases the transmittable power while the latter has the ability to control the power flow, either by increasing or decreasing it. Table 3 shows the impact of adding a series capacitive and a SSSC to the transmission line [58–64].

Table 3. Different compensation scenarios for a transmission line

An Uncompensated Transmission Line	A Transmission Line with Series Capacitive Compensation	A Transmission Line Compensated by the SSSC
$P = \frac{V^2}{x_L} \sin\delta$ (assume $V_s = V_r$)	$P = \frac{V^2}{X_L - X_C} \sin\delta$	$P = \frac{V^2}{X_L - \frac{V_q}{I}} \sin\delta$
$Q = \frac{V^2}{X_L}(1 - \cos\delta)$	$Q = \frac{V^2}{X_L - X_C}(1 - \cos\delta)$	$Q = \frac{V^2}{X_L - \frac{V_Q}{I}}(1 - \cos\delta)$
	Capacitive injection.	Capacitive or inductive injection.
	Overall voltage across the transmission line increases.	Overall voltage across the transmission line is controllable.
	Only work in the capacitive region.	Work in both the capacitive and inductive regions.
	Overall line reactance increases.	Overall line reactance can be increased or decreased.
	The injected voltage is a function of the line current.	The injected voltage is independent of the line current.
	Power flow increases.	Power flow is controllable.

8.2 Components of the SSSC

The SSSC comprises several components as follows:

(a) A voltage source converter (VSC) that transforms DC power into AC supply,
(b) A DC energy source which provides the necessary power for conversion,
(c) A control unit,
(d) A series transformer that facilitates coupling with the transmission line.

8.3 Operation Modes of the SSSC

The almost typical voltage source of the VSC allows the SSSC to provide the capacitive and inductive voltage compensator, irrespective of the line current. When the line current changes between zero and Imax, the SSSC can sustain the rated maximum capacitive or inductive compensating voltage. The practical minimum line current is defined as the level at which the SSSC can still absorb enough power to offset its operational losses [4]. Figure 8 shows the operating characteristics of the SSSC for both the inductive and capacitive regions.

The SSSC has the following two operation modes:

(a) The control of the reactance compensation. The capacitive or inductive compensation reactance is maintained at the greatest value when the line current differs between 0 and Imax by the SSSC.

(b) The control of the compensated voltage. The SSSC keeps the capacitive or inductive compensation voltage at the maximum value, irrespective of the current fluctuations in the transmission line between 0 and Imax.

A SSSC can supply power to the transmission line. If only reactive power compensation is required, a smaller power source may suffice. The magnitude of the voltage phasor, which is parallel to the line current phasor, can be controlled in this case. The absolute value of the compensating voltage is continuously controllable within the operating limits of the VSC.

The voltage's magnitude and phase could be altered if the power source has real power management capabilities. A series capacitor and a reactor are two types of behavior. The main difference is that the voltage generated by the SSSC can be controlled independently of the line current. Therefore, an SSSC is capable of functioning both under elevated and reduced line loads.

The compensation of the line of the series capacitor is emulated by injecting the necessitated compensated voltage directly at the original system frequency, without reproducing the characteristics of impedance versus frequency for a physical capacitor.

Regardless of the domain of the operating SSSC, which can be either capacitive or inductive compensation, the system perceives it as a zero-impedance voltage source. The SSSC's swift response could theoretically be used to dampen synchronized oscillations with appropriate control, provided that the prerequisite for synchronized oscillations is established by existing series capacitors.

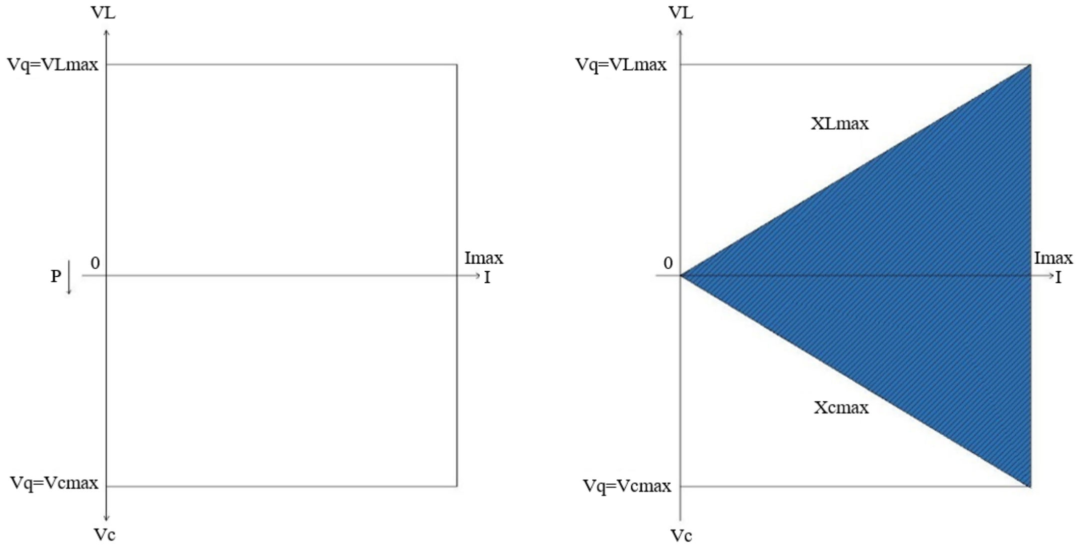

Figure 8. Operating range characteristics of the SSSC [2]

8.4 Advantages of the SSSC

The main purpose of the SSSC is to reduce the voltage during a power system fault. However, the SSSC also has numerous benefits while working under normal conditions as follows [3, 65]:

(a) The correction of the power factor by injecting the voltage continuously together with a structured controller.
(b) The load balancing in the interconnected distribution system.
(c) Covering the demand for capacitive and reactive power.
(d) Control of the power flow.
(e) Using active filtering to decrease the harmonic distortion.

8.5 Location of the SSSC

The placement of the SSSC on the site improves its capacity to offset a certain bus or line. Hence, it is preferable for the SSSC to be positioned in series with the weakest point in the bus (in the case of series connected FACTS controllers) or the line with the lowest ratio of unused capacity (in the case of series connected FACTS controllers). To determine the less efficient bus and the underutilized line in the test system, a continuous power flow analysis was utilized. It is necessary to obtain the initial performance of the test system because of the absence of the SSSC. Voltage profiles were generated for all buses in the test network, and the bus with the most severe collapse compared to other buses was identified as the weakest. The continuous power flow analysis identified the most underutilized line. The line with the lowest power flow relative to its total rating was chosen as the line requiring series compensation [18, 66–68].

8.6 Rating of the SSSC

Capacitive or inductive compensating voltage can be provided by the SSSC, independent of the line current. The maximum value of the line current (at which the compensation is still favorite) and the voltage-ampere (VA) rating of the SSSC are determined by the maximum series compensation voltage (the solid-state inverter and coupling transformer). The VA rating of the SSSC is standardized at 1 per unit (p.u.), corresponding to a control range for compensating reactive VAs (VARs) from -1 p.u. to +1 p.u. [18, 57, 69–72].

8.7 Applications of the SSSC

The SSSC is employed in a variety of applications as follows [73]:

(a) Control of power flow,
(b) Increase in the limits of power transfer,
(c) Improvement of transient stability,
(d) Dampening of power system oscillations,

(e) Mitigation of sub-synchronous resonance (SSR),
(f) Damping of power swings.

9 Conclusion

The use of the SSSC as a FACTS device was extensively investigated in this study. This study illustrated the main types of FACTS devices used in transmission lines along with their potential benefits. Then this study concentrated more on the SSSC, its components, operation modes and basic characteristics. It was found that SSSC was active in enhancing power system stability and damping power system oscillations. The significant contributions of the SSSC, based on previous studies, were identified in this study, along with existing limitations and directions for future research. This study also demonstrated the effectiveness of the SSSC compared to other FACTS devices. It can be clearly observed that the SSSC has many advantages over conventional compensation by connecting series capacitors. The main function of SSSC, which is unavailable in traditional series capacitive, is that it has the ability to control the power flow from both directions. The SSSC can inject either the capacitive or inductive voltage based on the requirements of the transmission line while a conventional series capacitor can only inject the capacitive voltage. The study emphasizes the importance of the SSSC in reconfiguring the FACTS devices for improved power control. The significance of the SSSC as a key component in the FACTS devices for ensuring power system stability and control is thereby highlighted.

Data Availability

Not Applicable.

Conflicts of Interest

The authors declare no conflict of interest.

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