

in system stability and security. The proposed concept is known as Flexible AC Transmission Systems (FACTS) [2], [10]-[12]. The main objectives of FACTS devices are to increase the transmission capacity, minimize the power loss, maintaining stability, reduce the power system cost and control power flow over designated transmission routes [13]. The following are the benefits applications and advantages of FACTS devices are [14]. That is principally derived by using the FACTS controllers:

- Power flow control.
- Increase of transmission capability.
- Voltage control.
- Reactive power compensation.
- Stability improvement.
- Power quality improvement.
- Flicker mitigation.
- Interconnection of renewable and distributed generation and storages [14].
- Rapid, continuous control of the transmission line reactance [15].

4. Basic FACTS Controller and SSSC

Now for maximum utilization of any FACTS device in power system planning, operation and control power flow solution of the network that contains any of these devices is a fundamental requirement, As a result many excellent research works have been carried out in the literature for developing efficient load flow algorithm for FACTS devices [14], [16]-[19]. In general FACTS controller can be dividing into main four categories [2]:

- Series controller: TCSC, SSSC, TSSC, TCSR, TSSR, IPFC.
- Shunt controller: STATCOM, STATCOM-BESS, SVC, SVG or SVA, SVS, TCR, TSC, TSR, TCBR, SMES, BESS, SSG.
- Series-Series controller.
- Series-Shunt controller: UPFC, TCPST, IPC.
- Other controller: TCVL, TCVR.

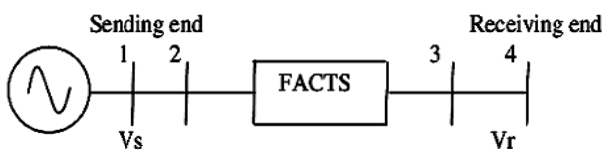


Figure 6. SMIB with FACTS device [20]

The static synchronous series compensator (SSSC) can be operated without an external energy source as reactive power source with and fully controllable independent of transmission line current for the purpose of increasing or decreasing the overall reactive voltage drop across the transmission line and there by controlling the electric power flow shown in figure 7 [21].

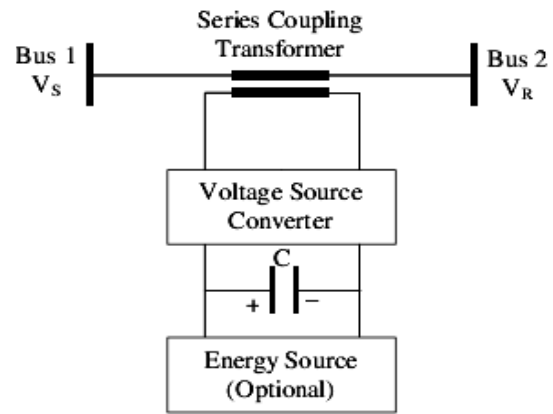


Figure 7. SSSC Configuration [21]

The static synchronous series compensation (SSSC) is a series connected FACTS controller based on VSC [22]. The equivalent circuit diagram of SSSC is shown in figure 8 [22].

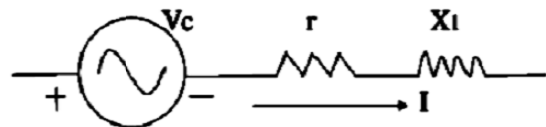


Figure 8. An Equivalent circuit of SSSC [20]

The magnitude of V_c can be controller to regulate power. The winding resistance and leakages reactance of the connecting transformer appears is series with the voltage source V_c . If there is no energy source on the DC side, neglecting losses in the converter and DC capacitor, the power balance in steady state condition [22].

$$\text{Re} [V_c I^*] = 0 \tag{11}$$

The most critical disturbances for the SSSC are faults on the load side that cause high current flows through the series transformer and the conducting VSC valves. Even if the turn off devices is blocked, the fault current may circulate through the anti parallel diodes. In order to prevent these devices from being thermally destroyed a bypass equipment is used. This equipment consists of a bypass electronic switch, made up of two anti parallel thyristor and a mechanical bypass switch that allows the entire SSSC to be bypassed. When the feeder current becomes greater than a threshold level, the thyristor are triggered and start to conduct [23].

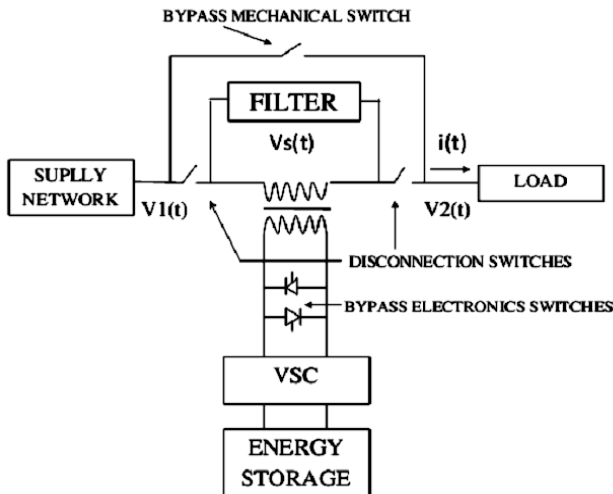


Figure 9. SSSC or SSC general structure [23]

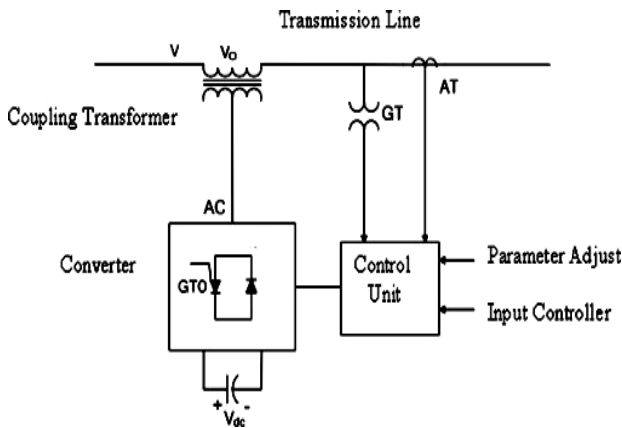


Figure 10. SSSC simplified diagram [24]

Synchronous Series Compensator (SSSC) is a modern power quality FACTS device that employs a voltage source converter connected in series to a transmission line through a transformer. The SSSC operates like a controllable series capacitor and series inductor. The primary difference is that its injected voltage is not related to the line intensity and can be managed independently. This feature allows the SSSC to work satisfactorily with high loads as well as with lower loads [25]. The Static Synchronous Series Compensator has three basic component is shown in figure 11 [25].

- Voltage Source Converter (VSC) – main component.
- Transformer – coupled the SSSC to the transmission line.
- The flow Energy Source – provides voltage across the DC.
- The flow capacitor and compensate for device losses.

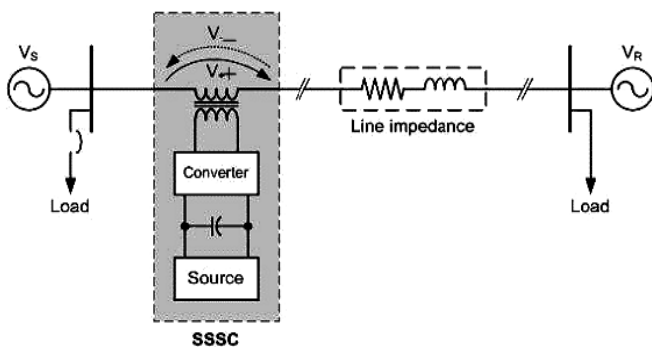


Figure 11. SSSC connected to two machine power system [25]

The SSSC is typically applied to correct the voltage during a fault in the power system. However it also has several advantages during normal conditions [25]:

- Load balancing in interconnected distribution networks.
- It can also help to cover the capacitive and reactive power demand.
- Power flow control.
- Reduces harmonic distortion by active filtering [25].

Table 1 Constraint equation and control variables for FACTS controllers [26]

Controller	Constraint Equation	Control Variable
SVC	$V_p = 0, V_r = 0, I_p = 0, I_r = -B_{SVC} V_1$	B_{SVC}
TCSC	$V_p = 0, I_p = 0, I_r = 0, V_r = X_{TCSC} I_2$	X_{TCSC}
STATCOM	$V_p = 0, V_r = 0, I_p = 0,$	I_r
STATCOM (With Energy Source)	$V_p = 0, V_r = 0$	I_p, I_r
TCPAR (SPAT)	$E = V_1(e^{j\Phi} - 1) - jV_1\Phi, V_1I_p = V_pI_2, V_1I_r = I_2V_r$	Φ
SSSC (S^2C) (SSC)	$V_p = 0, I_p = 0, I_r = 0,$	V_r
SSSC (With Energy Source)	$I_p = 0, I_r = 0,$	V_p, V_r

5. Operating Principle of SSSC

The SSSC sometimes called the S^2C is a series connected synchronous voltage source that can vary the effective impedance of a transmission line by injecting a voltage containing an appropriate phase angle in relation to the line current. It has the capability of exchanging both active and reactive power with the transmission system [27]-[41]. The SSSC comprises a multi phase VSC with a dc energy storage controller and functional representation of active reactive power flow as shown in Figure 12 [7], [26]. Here the controller is connected in series with the transmission line. The operating modes of the SSSC are illustrated in Figure 12.

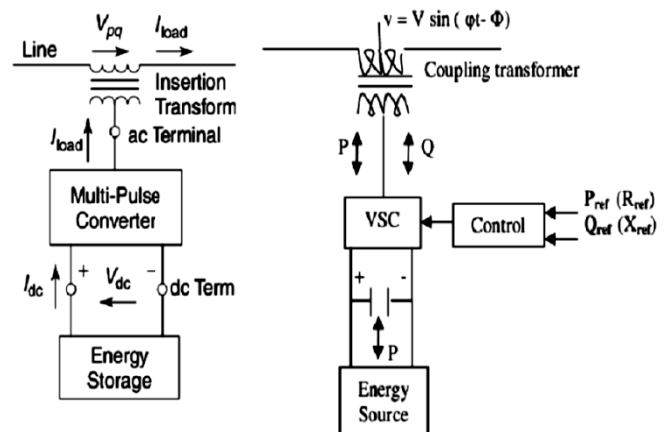


Figure 12. Generalized series connected synchronous voltage source employing multi pulse converter with an energy storage device [26] and Functional representation of active reactive power flow [7]

The sinusoidal voltage at the desired fundamental frequency which controllable amplitude and phase angle generate and absorb reactive power and exchange real power with the ac system and its dc terminal is connected to a suitable dc energy source for storage. To exchange reactive power with the ac system or with an external dc power supply like energy storage device to also exchange independently controllable real power. The references P_{ref} , Q_{ref} or other related parameters such as desired compensating reactive impedances X_{ref} and R_{ref} define the amplitude V and phase angle ϕ of the generated output voltage necessary to exchange desired active and reactive power at the ac output. If the VSC is operated strictly for reactive power exchange P_{ref} or R_{ref} is set to zero [7]. The basic dc voltage for conversion to ac is provided by the capacitor and the dc/ac conversion is achieved by pulse width modulation (PWM) techniques [42], [43].

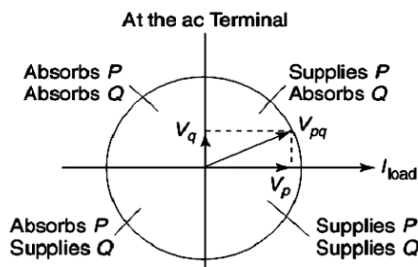


Figure 13. The different operating modes of SSSC for real and reactive power exchange [26]

Table 2. SSSC Phasor diagram description [44]

Quadrant	P and Q
I	$P = V_{pq} I_{Line} \cos \phi > 0$ $Q = V_{pq} I_{Line} \sin \phi > 0$
II	$P = V_{pq} I_{Line} \cos \phi < 0$ $Q = V_{pq} I_{Line} \sin \phi < 0$
III	$P = V_{pq} I_{Line} \cos \phi < 0$ $Q = V_{pq} I_{Line} \sin \phi > 0$
IV	$P = V_{pq} I_{Line} \cos \phi > 0$ $Q = V_{pq} I_{Line} \sin \phi < 0$

Theoretically, SSSC operation in each of the four quadrants is possible but there are some limitations to the injected SSSC voltage due to operating constraints of practical power system. In capacitive mode, the injected SSSC voltage is made to lag the transmission line current by 90° [45]-[47].

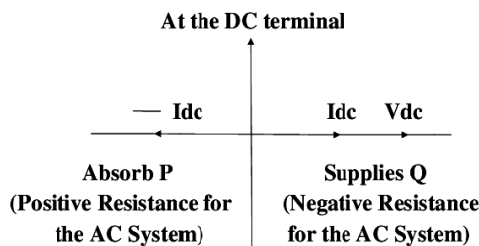


Figure 14. The different operating modes for real and reactive power exchange [26]

A series capacitor compensates the transmission line inductance by presenting a lagging quadrature voltage with respect to the transmission line current. This voltage acts in opposition to the leading quadrature voltage appearing across the transmission line inductance, which has a net effect of reducing the line inductance. Similar is the operation of an SSSC that also injects a quadrature voltage V_C in proportion to the line current but is lagging in phase:

$$V_C = jkXI_L \quad (12)$$

Where, V_C = the injected compensating voltage, I_L = the line current, X = the series reactance of the transmission line, k = the degree of series compensation. The current in a line compensated at its midpoint by the SSSC is expressed as [48], [49]:

$$I_L = 2V \sin \delta / X + V_C / X \quad (13)$$

The corresponding line-power flow is then expressed as

$$P = VI_L \cos(\delta/2) \quad (14)$$

$$P = V^2 \sin \delta / X + VV_C \cos(\delta/2) / X \quad (15)$$

Where, V = the magnitude of voltage (assumed to be the same) at the two ends of the transmission line, δ = angular difference across the line.

6. Power Flow Control and Series Reactive Compensation Using SSSC

The exchange of reactive power between the converter and the ac system can be controlled by varying the amplitude of the 3-phase output voltage E_s of the converter. That is, if the amplitude of the output voltage is increased above that of the utility bus voltage, then a current flow through the reactance from the converter to the ac system and the converter generates capacitive reactive power for the ac system. If the amplitude of the output voltage is decreased below the utility bus voltage, then the current flows from the ac system to the converter and the converter absorbs inductive reactive power from the ac system. In other words, the converter can supply real power to the ac system from its dc energy storage if the converter output voltage is made to lead the ac system voltage [13].

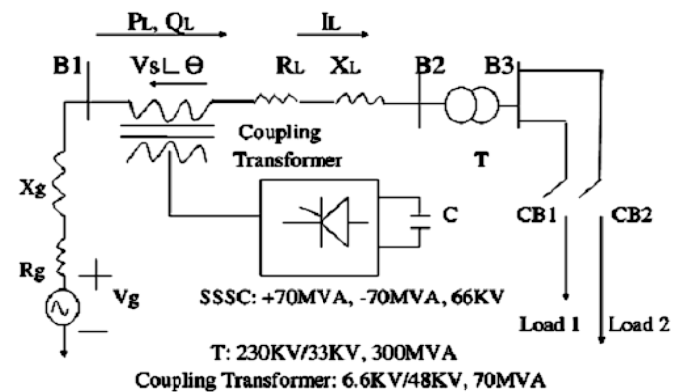


Figure 15. Schematic diagram of SSSC [50]

The system shown in Figure 15 describes the basic configuration of static synchronous series compensator using 48 pulse static synchronous series compensator. The capacity of SSSC is ± 70 MVAR whereas the main transformer has the capacity of 300 MVA (approximately 4 to 5 times). They have represented the model of SSSC by an equivalent Thevenin circuit at bus B1. The other major challenge in the implementation of VSC based SSSC is sufficiently high value of storage capacitor and therefore not cost effective [50].

$$P = V_s V_r \sin(\delta_s - \delta_r) / X_L = V^2 \sin\delta / X_L \quad (16)$$

$$Q = V_s V_r [1 - \cos(\delta_s - \delta_r)] / X_L = V^2 (1 - \cos\delta) / X_L \quad (17)$$

7. The Control System of SSSC and Swing Curve

A typical SSSC control system is shown in Figure 16 [48]. It accomplishes the following functions:

- The introduction of desired series reactive compensation (Capacitive or Inductive).
- The damping of power swing oscillations and enhancement of transient stability.
- The control of current in the SSSC compensated line.

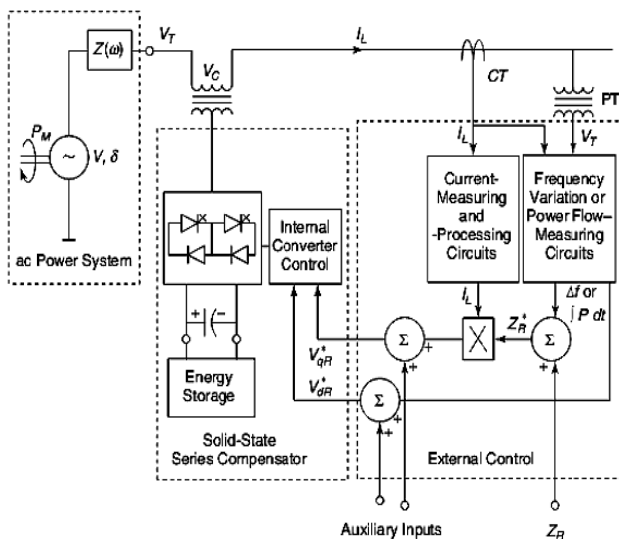


Figure 16. A basic control scheme for the solid state series compensator to control (P and Q), line impedance and improve system stability [48].

The line current I_L and the SSSC terminal voltage V_T are measured together with the bus frequency or the line power flow, which can either be measured directly or calculated from I_L and V_T measurements. The desired SSSC reactance is set by a reactance reference, Z_R . The SSSC acts as a voltage source in synchronism with the ac system voltage, the magnitude and phase of which can be controlled by voltage reference inputs of V^*dr and V^*qr [48]. The signal V^*qr regulates the SSSC output voltage component in quadrature with the line current. It thus determines the amount of reactive compensation (capacitive or inductive) introduced in the transmission line. The reactance reference Z_R is modulated with bus frequency or line power signals to generate Z^*R , which when multiplied with the rms line

current I_L results in the signal V^*qr . The signal V^*dr determines the magnitude of the SSSC output voltage component that is in phase (or out of phase) with the line current [48]. The variation of SSSC injected voltage and STATCOM injected current shown in figure 17 [32].

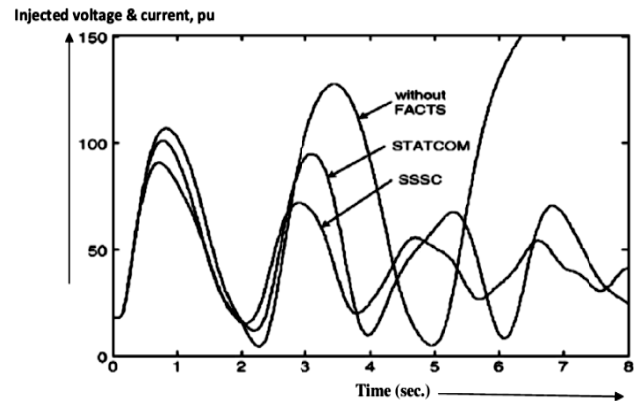


Figure 17. Swing curve of machine with and without a FACTS devices [32].

8. Conclusion

In this paper, the study of power transmission system it is desirable to maintain the voltage magnitude, phase angle and line impedance. Therefore, to control the power flow from one end to another end these concepts of power flow control and voltage injection is applied by Series compensation. The possible control scheme of SSSC and operating modes is described. This paper can be extended in future work for SSSC modeling with number of bus system and determine the method for controlling the active and reactive power flow in power system network.

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