Review of Active Reactive Power Flow Control using Static Synchronous Series Compensator (SSSC)

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Abstract: ***The control of power and the usable capacity enhancement of present as well as new and upgraded line can be effectively done by FACTS technology. In this paper describe the active and reactive power flow into the line for the purposed of compensation as well as enhancement of power transmission capability of transmission line. The active and reactive power flow controls through a transmission line by placing SSSC at the middle of power system. The SSSC is a voltage source convertor based series FACT device that's providing inductive, capacitive compensation independent of line current magnitudes. In this paper the series compensation for the management of power flow control used to improve the performance of the power system. This paper proposed the superior ability can only be achieved by appropriate control scheme and controller setting.***

Keywords: Active and Reactive Power flow control, Flexible AC transmission system (FACTS), Static synchronous series compensator (SSSC), Series Power line compensation

1. Introduction

Now a day's power system are undergoing numerous changes and becoming more complex from operation, control and stability maintenance stand points when they meet ever increasing load demand [1]. The power flow in ac power system give the significant electrical storage, the electrical generation and load must balance at all times [2]. One of the most important problems in the control of energy transmission systems is the reactive power compensation. Reactive power causes the increase in the transmission systems losses, decrease in power capacity carried in the transmission lines and the changes in the voltage amplitude at the end of the lines. Hence it is necessary to provide reactive power compensation in order to increase transmittable power, decrease losses and provide voltage amplitude stability [3].

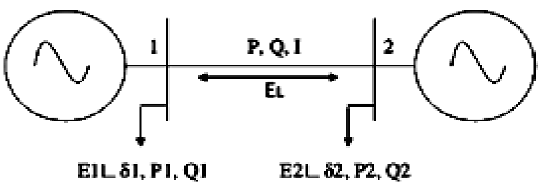

Figure 1. AC power flow control of transmission line between two machine systems [2].

Figure 2 shows that current flow phasor is perpendicular driving voltage (90^0 phase lag). If the angle between the two bus voltages is small, the current flow largely represents the active power. Increase or decreasing the inductive impedance of a line will greatly affect the active power flow. Thus, impedance control which in reality provides current control, can be most cost effective means of controlling the power flow, it can be used for power flow control and or control for stability [2].

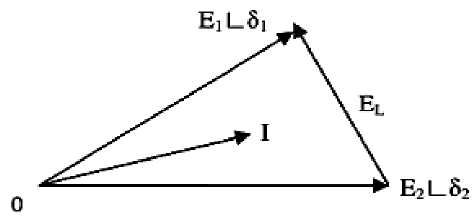

Figure 2. Current flow perpendicular to the driving voltage phasor diagram [2].

Figure 3 corresponding to Figure 2 shows a phasor diagram of the relation between active and reactive current with reference to the voltages at the two ends [2]. Power flow calculations are performed in power systems for operational planning and operation control [4]. Active component of the current at the two end of the transmission line at E1 and E2 is:

$$I_{P1} = E_2 \sin \delta / x \qquad (1)$$

$$I_{P2} = E_1 \sin \delta / x \qquad (2)$$

Active power at the two ends at E1 and E2 is:

$$P_1 = E_1 (E_2 \sin \delta) / x \qquad (3)$$

$$P_2 = E_2 (E_1 \sin \delta) / x \qquad (4)$$

Reactive component of the current at the two end of the transmission line at E1 and E2 is:

$$I_{q1} = (E_1 - E_2 \cos \delta) / x \quad (5)$$

$$I_{q2} = (E_2 - E_1 \cos \delta) / x \quad (6)$$

Reactive power at the two end at E1 and E2 is:

$$Q_1 = E_1 (E_1 - E_2 \cos \delta) / x \quad (7)$$

$$Q_2 = E_2 (E_2 - E_1 \cos \delta) / x \quad (8)$$

Naturally P_1 and P_2 are the same:

$$P_1 = E_1 E_2 \sin \delta / x \quad (9)$$

Where,
X = is the impedance of the line,
E_1, E_2 = bus end voltage,
δ = angular difference of the end bus voltages.
Thus, varying the value of X will vary P, Q_1, and Q_2 in according with above equation [2],[5].

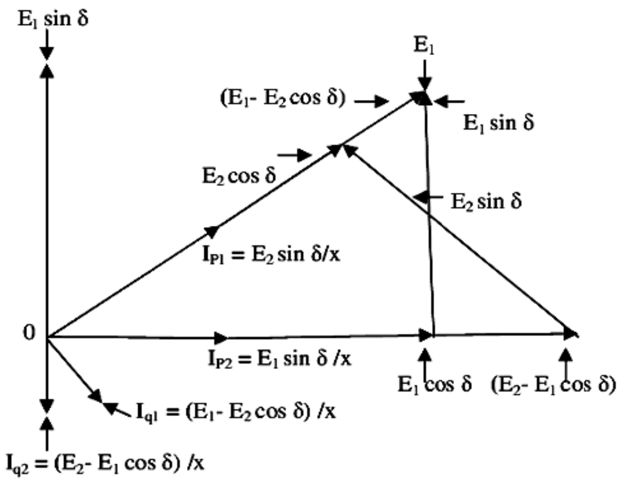

Figure 3. Active and reactive power flow phasor diagram [2].

This makes series compensation a highly effective means for up keeping or even increasing voltage stability in a heavily loaded transmission circuit and likewise, it allows additional power transmission over the circuit without upsetting voltage stability [5]. With the reactance of the capacitive element, i.e. the series capacitor equal to X_C and the inductive reactance of the line equal to X_L, we can define the degree of series compensation [6].

$$k = X_C / X_L \quad (10)$$

2. Series Compensation

The series compensation is an economic method of improving power transmission capability of the lines [7], [8], [9] VAR compensation can also be of the series type. Typical series compensation systems use capacitors to decrease the equivalent reactance of a power line at rated frequency. The connection of a series capacitor generates reactive power that, in a self regulated manner, balances a fraction of the line's transfer reactance. The result is improved functionality of the power transmission system through:

- Increased angular stability of the power corridor.
- Improved voltage stability of the corridor.
- Optimized power sharing between parallel circuits.

Like shunt compensation, series compensation may also be implemented with current or voltage source devices as shown in Figure 4 and Figure 5. The results obtained with the series compensation through a voltage source which has been adjusted again to have unity power factor operation at V2 [9]. However the compensation strategy is different when compared with shunt compensation. In this case voltage V_{COMP} has been added between the line and the load to change the angle of V2 which is now the voltage at the load side. With the appropriate magnitude adjustment of V_{COMP}, unity power factor can again be reached at V2. As can be seen from the phasor diagram of Figure 5, V_{COMP} generates a voltage with opposite direction to the voltage drop in the line inductance because it lags the current I_P [9].

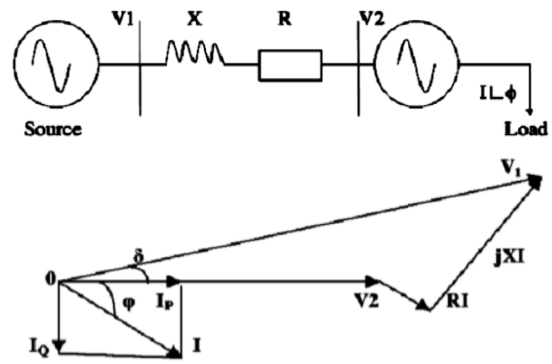

Figure 4. Power system without compensation [9].

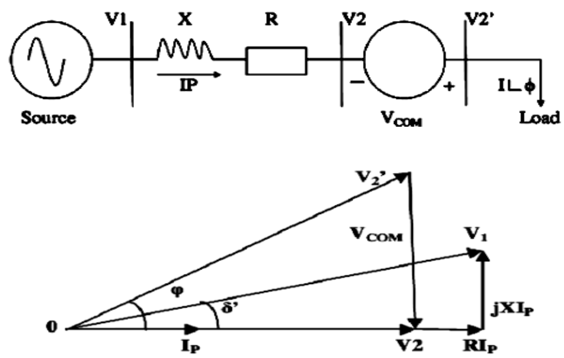

Figure 5. Principles of Series compensation with a voltage source [9].

3. Flexible AC Transmission System (FACTS)

Now a day's electrical power systems are more complex and it's require careful design of new devices are needed to improve electric power utilization while still maintaining reliability, stability, minimizing power loss and security. Thus, this needs a review of traditional methods and the creation of new concepts that emphasize a more efficient use of already existing power system resources without reduction 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.

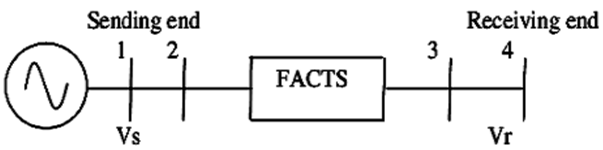

Figure 6. SMIB with FACTS device [20]

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].

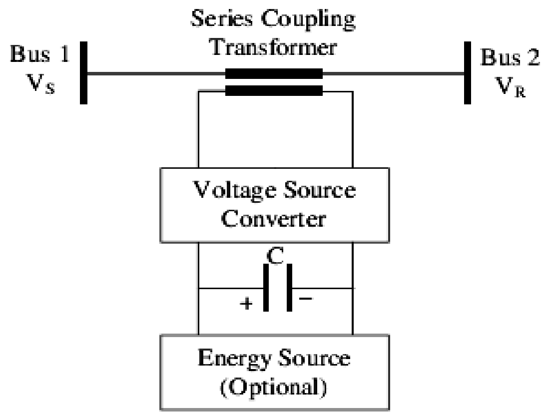

Figure 7. SSSC Configuration [21]

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].

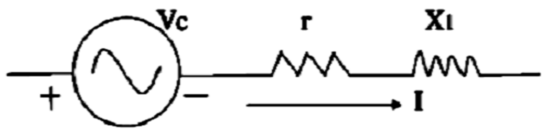

Figure 8. An Equivalent circuit of SSSC [20]

The magnitude of Vc can be controller to regulate power. The winding resistance and leakages reactance of the connecting transformer appears is series with the voltage source Vc. 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].

$$Re\,[V_c\, I^*] = 0 \qquad (11)$$

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].

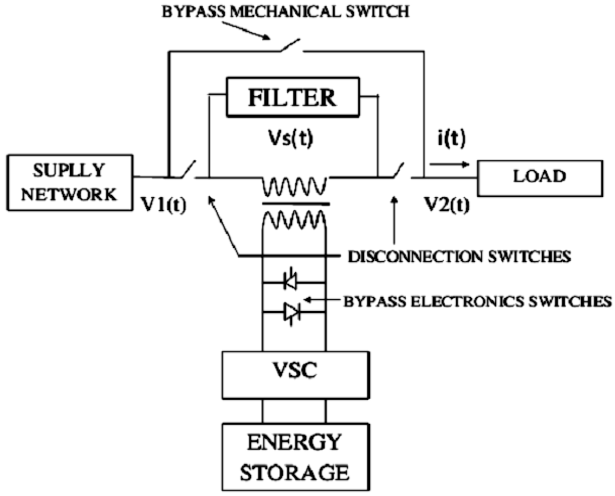

Figure 9. SSSC or SSC general structure [23]

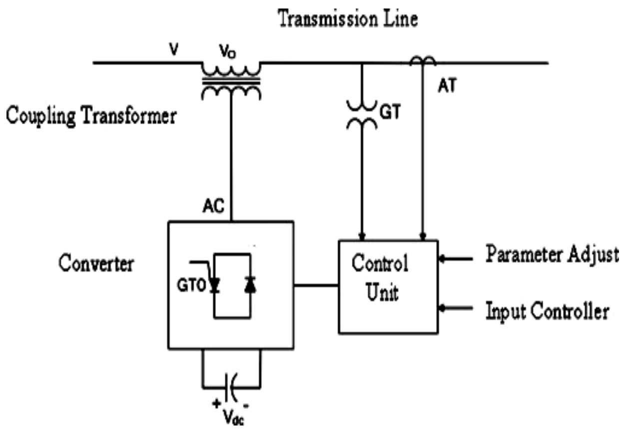

Figure 10. SSSC simplified diagram [24]

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.

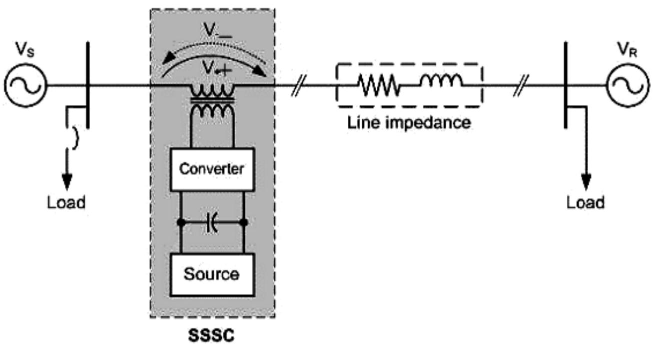

Figure 11. SSSC connected to two machine power system [25]

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)	$E = V_1(e^{j\Phi}-1) \sim jV_1\Phi$, $V_1 I_p = V_p I_2$, $V_1 I_r = I_2 V_r$	Φ
SSSC (S^{3}C) (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^{3}C 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.

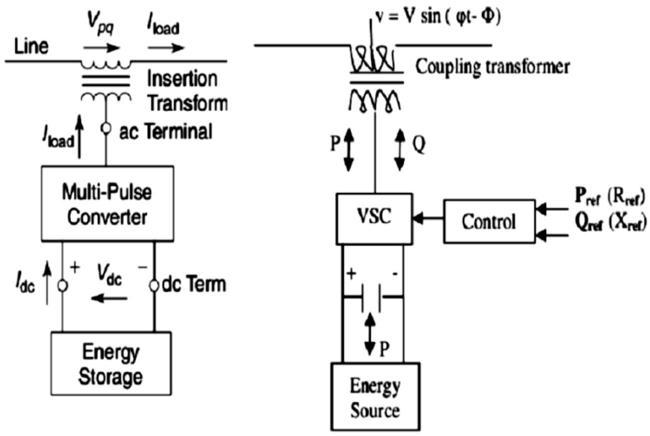

Figure 12. Generalized series connected synchronous voltage source employing multi pulse converter with an energy storage device [26] and Functional representation of active reactive power flow [7]

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 Xref 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].

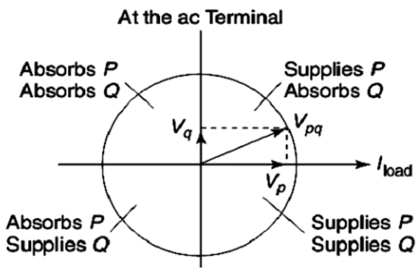

Figure 13. The different operating modes of SSSC for real and reactive power exchange [26]

Table 2. SSSC Phasor diagram description [44]

Quadrant	P and Q
I	$P = Vpq\ I_{Line}\ Cos\ \phi > 0$ $Q = Vpq\ I_{Line}\ Sin\ \phi > 0$
II	$P = Vpq\ I_{Line}\ Cos\ \phi < 0$ $Q = Vpq\ I_{Line}\ Sin\ \phi < 0$
III	$P = Vpq\ I_{Line}\ Cos\ \phi < 0$ $Q = Vpq\ I_{Line}\ Sin\ \phi > 0$
IV	$P = Vpq\ I_{Line}\ Cos\ \phi > 0$ $Q = Vpq\ I_{Line}\ Sin\ \phi < 0$

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].

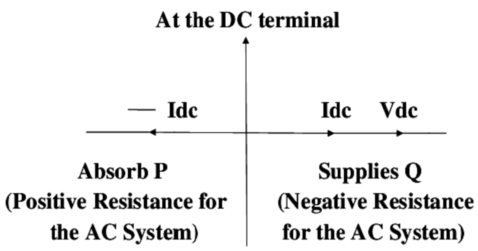

Figure 14. The different operating modes for real and reactive power exchange [26]

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 proportional 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]:

$$I_L = 2V\ Sin\delta/X + Vc/X \quad (13)$$

The corresponding line-power flow is then expressed as

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

$$P = V^2\ Sin\delta/X + VVc\ Cos(\delta/2)/X \quad (15)$$

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 Es 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].

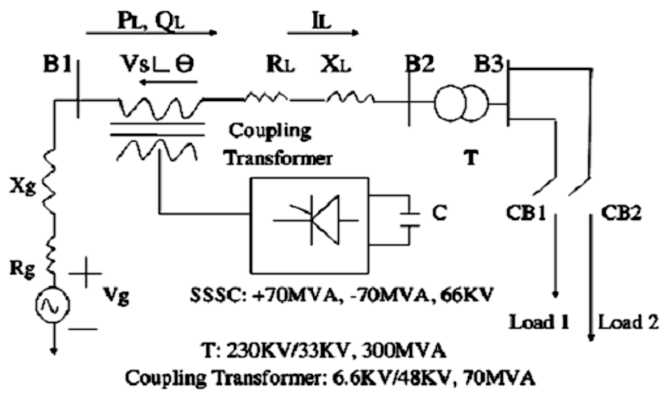

Figure 15. Schematic diagram of SSSC [50]

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].

$$P = VsVr\ Sin(\delta s - \delta r)/X_L = V^2 Sin\delta/X_L \quad (16)$$

$$Q = VsVr\ [1-Cos(\delta s - \delta r)]/X_L = V^2\ (1-Cos\delta)/X_L \quad (17)$$

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.

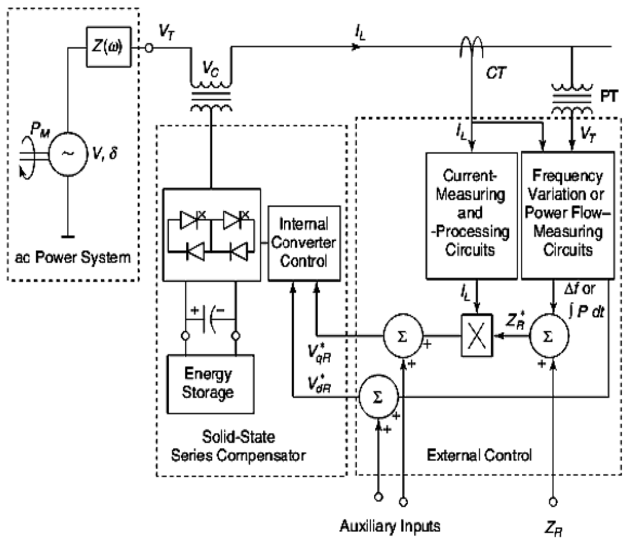

Figure 16. A basic control scheme for the solid state series compensator to control (P and Q), line impedance and improve system stability [48].

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 ZR 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].

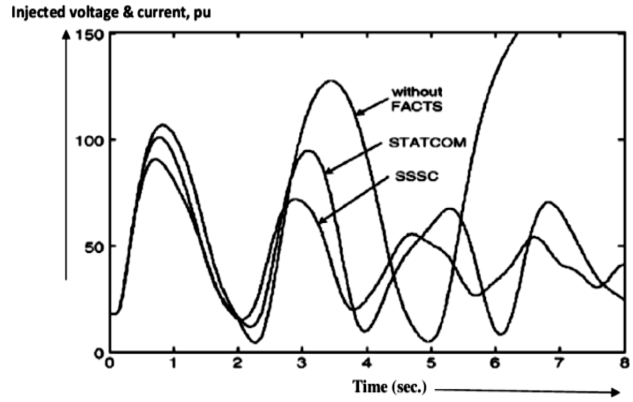

Figure 17. Swing curve of machine with and without a FACTS devices [32].

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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