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Evolve the Controller for Static Synchronous Series Compensator Based on Control Strategy of Sen Transformer

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ABSTRACT

Real and Reactive power flow in an alternating current transmission line can be independently controlled by connecting, to the transmission line, a series-compensating voltage, which is variable in magnitude and phase angle. The Static Synchronous Series Compensator (SSSC), a solid-state voltage source inverter (VSC) coupled with a transformer, is connected in series with a transmission line. An SSSC injects an almost sinusoidal voltage, of variable magnitude, in series with a transmission line. This injected voltage is almost in quadrature with the line current, thereby emulating an inductive or a capacitive reactance in series with the transmission line. This emulated variable reactance, inserted by the injected voltage source, influences the electric power flow in the transmission line. In this report, an attempt is made to evolve the model of SSSC and VSC with preliminary studies for the controller design.

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1. INTRODUCTION

1.1. Electrical Transmission Networks

An electrical power transmission network comprises mostly three-phase alternating-current (ac) transmission lines operating at different transmission voltages. With increasing requirement of power-transmission capacity and / or longer transmission distances, the transmission voltages continue to increase; indeed, increases in transmission voltages are linked closely to decreasing transmission losses.

1.2. Conventional Control Methods

The following conventional control methods are used to control the power flow in transmission line network

- Introducing the series capacitor in transmission line to control the line impedance.
- Control of bus voltage by using Automatic generation control (AGC) / Transformer tap changer
- Controlling the phase angle by using Phase-shifting transformers

1.3. Flexible AC Transmission System

Flexible AC Transmission System (FACTS) is a concept based on power-electronic controllers, which enhance the value of transmission networks by increasing the use of their capacity. As these controllers operate very fast, they enlarge the safe operating limits of a transmission system without risking stability [1], [2].

Today, it is expected that within the operating constraints of the current-carrying thermal limits of conductor, the voltage limits of electrical insulating devices, and the structural limits of the supporting infrastructure, an operator should be able to control power flows on lines to secure the highest safety margin as well as transmit electrical power at a minimum of operating cost.

In general, FACTS devices possess the following technological attributes [3]:

- Provide dynamic reactive power support and voltage control.
- Reduce the need for construction of new transmission lines, capacitors, reactors, etc which,
  - Mitigate environmental and regulatory concerns.
  - Improve aesthetics by reducing the need for construction of new facilities such as transmission lines.
- Improve system stability.
- Control real and reactive power flow.

The following FACTS controllers are used to control the power flow in transmission line network

- Thyristor-Switched Series Capacitor (TSSC)
- Thyristor-Controlled Series Capacitor (TCSC)
- Thyristor-Controlled Phase Angle Regulator (PAR)
- Static Synchronous Series Compensator (SSSC)

The Static Synchronous Series Compensator is one of the most recent FACTS devices for power transmission line series compensation. The operation and control fundamentals of the SSSC can be found in [1], [4], [5].

1.4. Static Synchronous Series Compensation (SSSC)

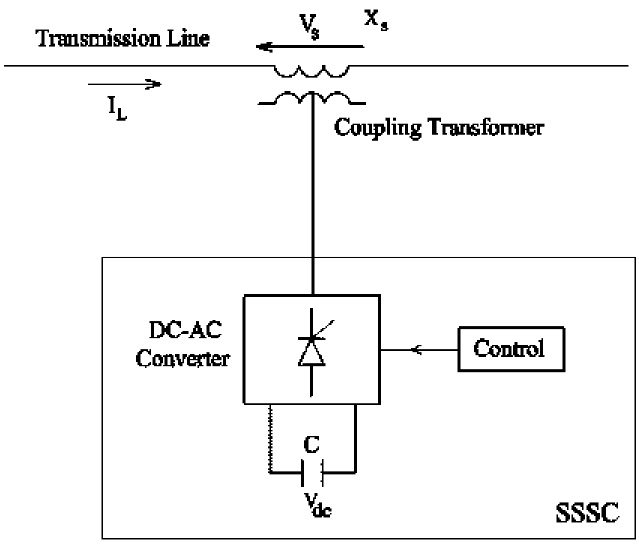

Figure 1. Basic Building block of SSSC

The basic building block of the SSSC as shown Figure 1 is a dc-ac converter which is connected in series with the transmission line by a coupling transformer. This injected voltage is almost in quadrature with the line current. A small part of the injected voltage which is in phase with the line voltage which is in quadrature with the line current emulates an inductive or a capacitive reactance in series with the transmission line. This emulated variable reactance, inserted by the injected voltage source, influences the electric power flow in the transmission line.

An impedance compensation controller can compensate for the transmission line resistance if an SSSC is operated with an energy storage system. An impedance compensation controller, when used with an SSSC and no energy storage system, is essentially a reactance compensation controller.

2. SEN TRANSFORMER AS FACTS CONTROLLER

A review of operating principle of SEN Transformer is carried out as given below.

2.1. Direct Method of Voltage Regulation

In order to regulate the voltage at any point in a transmission line, an in-phase or an out-of-phase voltage is connected in series with the line [6]. Figure 2(a) shows a voltage regulator scheme for regulating the voltage at any point in a transmission line. The exciter unit consists of a three-phase Y connected primary winding, which is impressed with the line voltage, Vs. The voltage-regulating unit consists of a total of six secondary windings (two windings in each phase for a bipolar voltage connection). The line is regulated at a voltage, Vs’, by adding a compensating voltage, Vs’s, either in- or out of phase with the line voltage, Vs. The corresponding phasor diagram is shown in Figure 2(b).

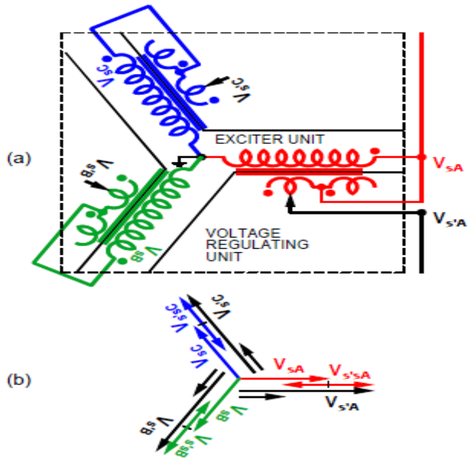

Figure 2. (a) Voltage regulator circuit (b) phasor diagram

The bipolar compensating voltage in any phase is induced, through autotransformer action, in two windings placed on the same phase of the transformer core.

2.2. Phase Angle Regulation

A Phase Angle Regulator (PAR) connects a voltage in series with the transmission line and in quadrature with the phase-to neutral voltage of the transmission line as shown in Figure 3(a). The series-connected compensating voltage introduces a phase shift, ε, [Figure 3(b)] whose magnitude (for small change) in radian varies with the magnitude of the compensating voltage in p.u where the phase-to-neutral voltage of the transmission line is the base voltage [6].

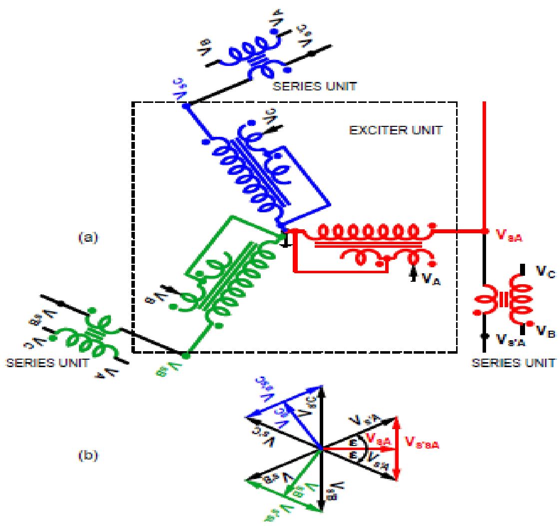

Figure 3. (a) Phase angle regulator circuit (b) phasor diagram

In a typical configuration, a PAR consists of two transformers as shown in Figure 3(a). The first transformer (exciter unit) is called a regulating transformer and is connected in shunt with the line. Its primary windings are excited from the line voltage (Vs) and a three-phase bipolar voltage is induced in the secondary windings. With the use of taps, a compensating voltage (Vs's) with variable magnitude and in quadrature with the line voltage is generated from the phase-to-phase voltage of the induced voltage of the regulating transformer. For series connection of this voltage, an electrical isolation is necessary. The second transformer (series unit) is called a series transformer and is excited from the phase-to-phase voltage of the regulating transformer. The induced voltage of the series transformer is connected in series with the line. If the series transformer is a step-down transformer, the primary windings of the series transformer as well as the secondary windings of the regulating transformer are high voltage- and low current rated so that the taps on the secondary side of the regulating transformer can operate at a low current and can ride through a high fault current.

2.3. Series Reactance Emulation

In a special case, the sending-end voltage magnitude and its phase angle can also be varied together in such a way so that the effective line reactance is changed. The indirect way to implement a variable series capacitor or a variable inductor is to connect a variable magnitude compensating voltage in series with the line and in quadrature with the line current. Through control action, the magnitude of the compensating voltage can be varied and made lagging or leading the prevailing line current in order to emulate a variable capacitor or a variable inductor. Through the use of a *Static Synchronous Series Compensator*, a variable magnitude series-connected compensating voltage source is implemented [6].

2.4. An Ideal Series-Connected Power Flow Controller

The effect of a series-connected variable magnitude and variable angle compensating voltage on the power flow in a transmission line is shown in Figure 4. A simple power transmission system with a sending-end voltage, $\mathbf{V_s}$, a receiving-end voltage, $\mathbf{V_r}$, the voltage, $\mathbf{V_X}$, across line reactance, X_L and the compensating voltage, **Vs's**, is shown in Figure 4(a). For simplicity, it is considered that $Vs = Vr = 1$ pu, the angle between them to be δ □= 30°, and $XL = 0.5$ pu. When the transmission line is uncompensated, the real power flow in the line is 1 pu and the reactive power flow at the receiving-end is 0.268 pu capacitive

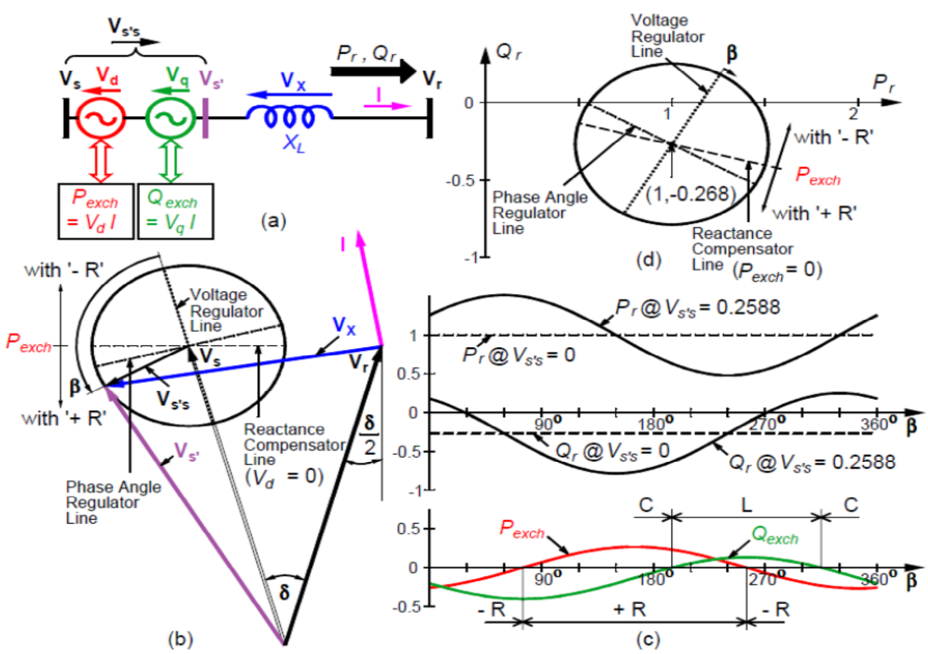

Figure 4. Effect of a series-connected voltage source on power flow in a transmission Line. (a) Power transmission system with a series-connected compensating voltage, **Vs's**, (b) phasor diagram, (c) variation of the receiving-end real and reactive power (*Pr* and *Qr*) and the exchanged compensating real and reactive power as a function of the angular rotation of the compensating voltage phasor, and (d) receiving-end *Qr* vs. *Pr*.

The voltage across the transmission line is the difference between the sending- and receiving-end voltages and it is 0.5176 pu. Figure 4(b) shows the phasor diagram related to a series-connected compensating voltage with a fixed magnitude of 0.2588 pu and its entire controllable range of $0 \leq \delta \leq 360^o$. The compensating voltage, **Vs's**, is added to the fixed sending end voltage, **Vs**, to produce the *effective* sending-end voltage, **Vs'** = **Vs** + **Vs's**. The difference, **Vs'** – **Vr**, provides the *compensated* voltage, **VX**, across *XL*. As the angle, δ, is varied over its full 360° range, the end of phasor, **Vs's**, moves along a circle with its center located at the end of phasor, **Vs**. The rotation of phasor, **Vs's**, with angle, δ, modulates both the magnitude and the angle of phasor, **VX**. The real power, *Pr*, and the reactive power, *Qr*, at the receiving-end vary with angle,δ, in a sinusoidal manner as shown in Figure 4(c).

The compensating voltage, **Vs's**, is at any angle with the prevailing line current, **I**, and, therefore, exchanges, with the line, both real power, *Pexch* (= *VdI*), and reactive power, *Qexch* (= *VqI*), where **Vd** and **Vq** are the respective real or direct and reactive or quadrature components of the compensating voltage with load convention. These exchanged real power, *Pexch*, and reactive power, *Qexch*, are also sinusoidal functions of angle, δ, as shown in Figure 4(c). For a given magnitude of a compensating voltage, the exchanged capacitive power, *Qexch*, is larger than its inductive counterpart due to the fact that the capacitive compensation produces a larger line current.

The compensating voltage, being at any angle with the prevailing line current, emulates in series with the line a capacitor (C) or an inductor (L) and a positive resistor (+R) or a negative resistor (-R). The real and reactive power flow in A compensating voltage can be in- or out-of-phase with the phase-to-neutral voltage of the transmission line to implement a voltage regulator.

- A compensating voltage can be in quadrature with the phase-to-neutral voltage of the transmission line to implement a phase angle regulator.
- A compensating voltage can be such that it provides series reactance compensation because of being in quadrature with the prevailing line current. If the circular controllable area is equally divided by the reactance compensator line (*Vd* = 0 or *Pexch* = 0), the upper and lower halves represent *Pexch* due to '-R' and '+R', respectively.

2.5. Comparison between Sen Transformer and SSSC

The Sen Transformer (ST), Figure 5, which is a single-core, three-phase transformer with a Y-connected primary winding and nine secondary windings. The ST provides two functions

- Voltage regulation
- Impedance regulation for independent control of bidirectional active and reactive power flow.

The family of Sen Transformers connects a series compensating voltage of variable magnitude at any angle with respect to the line voltage. The compensating voltage exchanges both real and reactive power with the line. Since the compensating voltage is derived from the line voltage through a transformer action with the primary windings, the exchanged real and reactive power with the line must flow through the primary windings to the line.

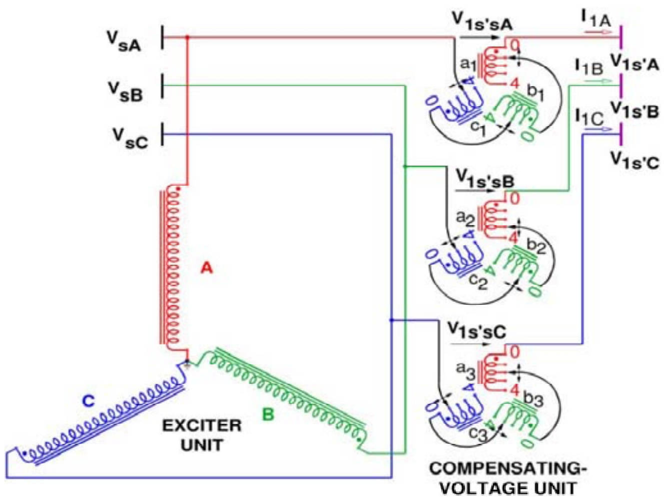

Figure 5. Schematic diagram of "ST."

In a Sen transformer, as shown in Figure 5, there are two units: exciter unit and compensating-voltage unit. The exciter unit consists of three primary windings (A, B, and C) that are Y-connected and placed on each limb of a three-limb, single-core transformer. The three-phase transmission-line voltage (V_{sA}, V_{sB}, and V_{sC}) at the sending end is applied in shunt to the exciter unit.

3. STATIC SYNCHRONOUS SERIES COMPENSATION

3.1. Theory

The indirect way to implement a variable series capacitor or a variable inductor is to connect a variable magnitude compensating voltage in series with the line and in quadrature with the line current. If the SSSC voltage, V_S, lags the line current, I_L, by 90, a capacitive series compensation is obtained and if V_S, leads I_L by 90, an inductive series compensation is obtained. By controlling the magnitude V_S and phase angle of the amount of series compensation can be adjusted.

3.2. Mathematical Model

Figure 1 shows a single line diagram of a simple transmission line with an inductive reactance, X_L, connecting a sending-end voltage source, Vs, and a receiving-end voltage source, Vr, respectively [6], [7] [8].

The real and reactive power (*P* and *Q*) flow at the receiving-end voltage source are given by the expressions

$$P = \frac{V_s V_r}{X_L}\sin(\delta s - \delta_r) = \frac{V^2}{X_L}\sin\delta \qquad -1(a)$$

and

$$Q = \frac{V_s V_r}{X_L}\left(1 - \cos(\delta s - \delta_r)\right) = \frac{V^2}{X_L}(1 - \cos\delta) \qquad -1(b)$$

Where Vs and Vr are the magnitudes and δs and δs□ are the phase angles of the voltage sources Vs and Vr, respectively. For simplicity, the voltage magnitudes are chosen such that Vs=Vr=V and the difference between the phase angles is δ□= δs-δr.

An SSSC, limited by its voltage and current ratings, is capable of emulating a compensating reactance, Xq, (both inductive and capacitive) in series with the transmission line inductive reactance, X_L. Therefore, the expressions for power flow given in equation (1) become

$$P_q = \frac{V^2}{X_{eff}}\sin\delta = \frac{V^2}{X_L\left(1 - X_q / X_L\right)}\sin\delta \qquad -2(a)$$

and

$$Q_q = \frac{V^2}{X_{eff}}(1 - \cos\delta) = \frac{V^2}{X_L\left(1 - X_q / X_L\right)}(1 - \cos\delta) \qquad -2(b)$$

Where X_{eff} is the effective reactance of the transmission line between its two ends, including the emulated variable reactance inserted by the injected voltage source of the SSSC. The compensating reactance, *Xq*, is defined to be negative when the SSSC is operated in an inductive mode and positive when the SSSC is operated in a capacitive mode.

Figure shows an example of a simple power transmission system with an SSSC operated both in inductive and in capacitive modes and the related phasor diagrams. The line current decreases from *I*0% to *I*-100%, when the inductive reactance compensation, - Xq/X_L, increases from 0% to 100%. The line current increases from *I*0% to *I*33%, when the capacitive reactance compensation, Xq/X_L, increases from 0% to 33%. From equations (1) and (2), the expressions for the normalized power flow in the transmission line and the normalized effective reactance of the transmission line can be written as

$$\frac{P_q}{P} = \frac{Q_q}{Q} = \frac{1}{\left(1 - X_q / X_L\right)} \qquad -(3)$$

$$\frac{X_{eff}}{X_L} = 1 - \frac{X_q}{X_L} \qquad -(4)$$

The effects of the compensating reactance, Xq, on the normalized power flow in the transmission line and the normalized effective reactance of the transmission line are shown. When the emulated reactance is inductive, the power flow, Pq and Qq, decrease and the effective reactance, Xeff, increases as the reactance compensation, $-Xq/X_L$, increases. When the emulated reactance is capacitive, the power flow, Pq and Qq, increase and the effective reactance, Xeff, decreases as the reactance compensation, Xq/X_L, increases.

4. METHODOLOGY

4.1. Voltage Source Converter (VSC)

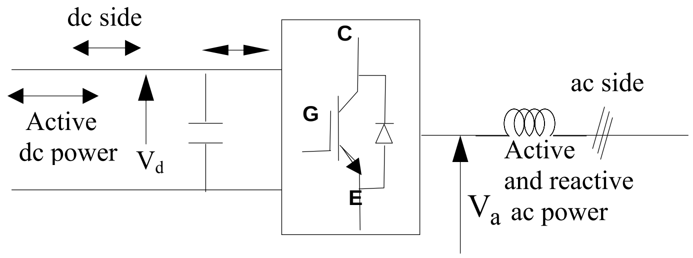

Figure 6. Basic principles of VSC

Voltage fed converter means [1], [9], it receives the dc voltage at one side and convert it to ac voltage on the other side. The ac voltage frequency maybe variable or constant depends on the applications. The voltage – fed inverter should have a stiff voltage source at the input, that is, its Thevenin impedance should ideally zero. If the input voltage is not stiff a large DC capacitor can connect at the input side irrespective of DC voltage variations. In this simulation studies also large value of capacitor (splits into two) is connected in front of the converter.

Figure 6 shows the block diagram representation of VSC. The basic concept of voltage source converter and current source converter has been studied [1] in details.

4.2. Principle of operation of VSC

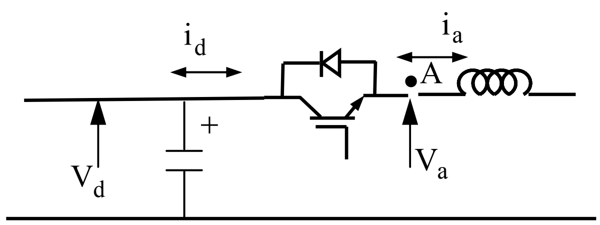

Figure 7. Single valve operation

Figure 7 shows the principle of operation of an IGBT based single valve connection diagram. Gating instant is not shown in Figure 3.2, for simplicity of explanation.

The capacitor voltage V_d is assumed to be a constant, supported by a large capacitor. With the positive terminal of the capacitor is connected to the collector of the IGBT. When IGBT is turned ON, the positive dc terminal is connected to an ac terminal at 'A' and the ac voltage would jump to V_d. If the current happens to flow from $+V_d$ to 'A' (through IGBT), the power would flow from the dc side to ac side (inverter action). However, if the current happens to flow from 'A' to $+V_d$ it will flow through the diode even the IGBT is ON, and power will flow from ac side to dc side (rectifier action). Thus the valve with combinations of diode can handle the power flow in direction, this valve and its capability to act as a rectifier or as an inverter with instantaneous current flow in positive or negative direction respectively, is basic to voltage source converter concepts.

4.3. Basic Control of SSSC

The basic building block of the SSSC as shown in figure 8 is a dc-ac converter which is connected in series with the transmission line by a coupling transformer. If the SSSC voltage, V_S, lags the line current, I_L, by 90º, capacitive series compensation is obtained and if V_S leads by I_L 90º, inductive series compensation is obtained. By controlling the magnitude of the amount of series compensation can be adjusted [10], [11].
The only way to control the magnitude of the converter ac voltage is by the input dc voltage. The dc capacitor voltage control is achieved by a small phase displacement, Δα, real power flows from the SSSC to the transmission line and the dc capacitor is discharged. Similarly, real power flows from the transmission line to the SSSC and the dc capacitor is charged. Besides, a small amount of real power from the transmission line is required to compensate the converter switching and coupling transformer losses.

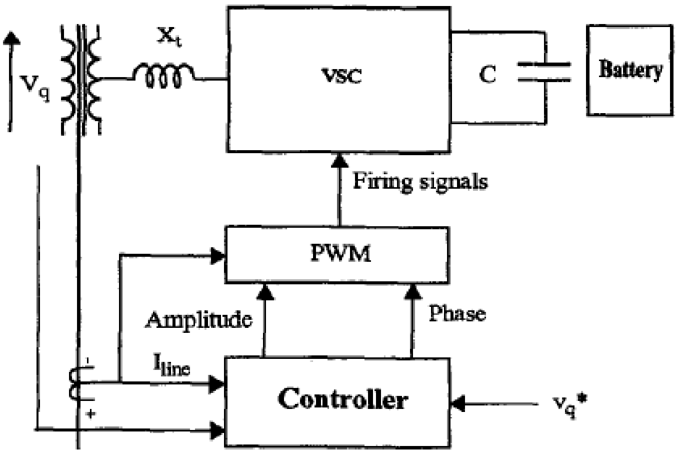

Figure 8. Basic Control block of SSSC

4.4. Proposed Power Flow Control using SSSC

The main function of the SSSC is to control the real power flow. This can be achieved either by direct control of the line current or power, or alternatively by indirect control of the compensating reactance, Xs, or series voltage, Vs. Because of practical considerations, sometimes the reactance control may be preferred. [12] [13].

The degree of series compensation, S, is usually expressed as the ratio of the series injected reactance, X_S, to the transmission line reactance, X_L. Therefore, $S = (X_S/X_L)$ and the reference reactance is SX_L which is negative for capacitive and positive for inductive compensation. Figure shows the basic control structure of the SSSC, with the series injected reactance, X_S, as the reference value as shown in figure 9.

The Phase-Locked Loop (PLL) system provides the basic synchronization signal,ϕ, which is the phase angle of the line current. X_{Ref} is compared with X_S and the error is passed to a PI controller that generates the required phase angle displacement, Δα. The final output of the control system is the phase angle of the SSSC voltage.

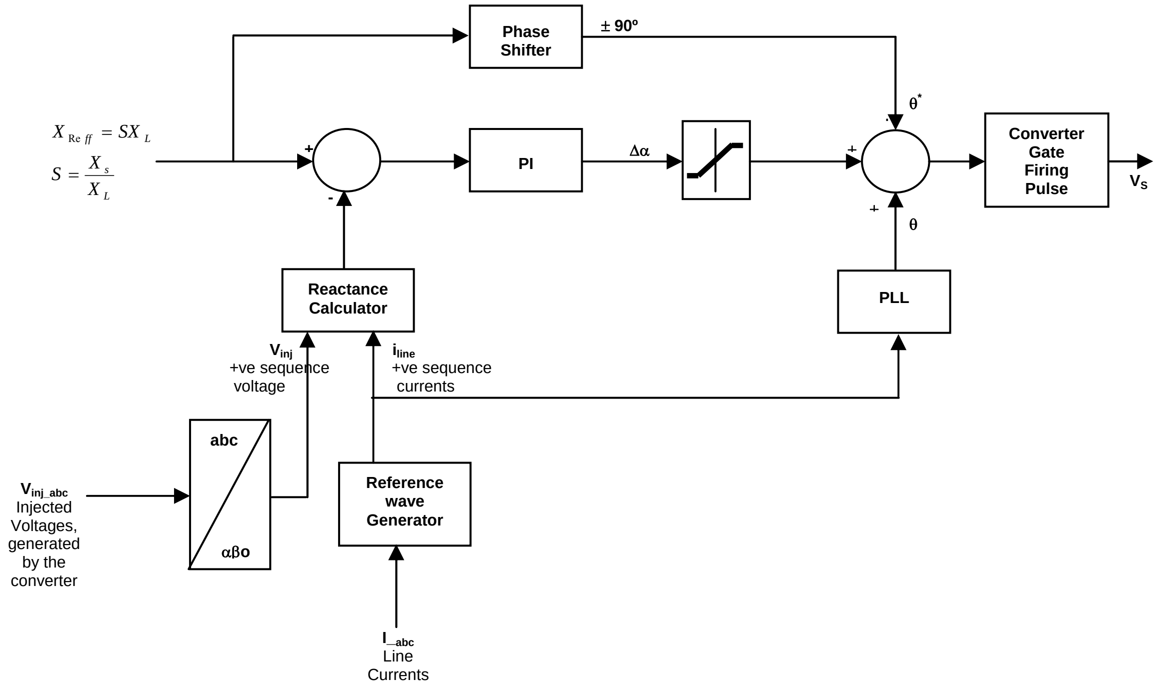

Figure 9. Basic Control Block for SSSC

X_{Reff} is the effective reactance of the transmission line between its two ends, including the emulated variable reactance inserted by the injected voltage source of the SSSC. The compensating reactance, X_S, is defined to be negative when the SSSC is operated in an inductive mode and positive when the SSSC is operated in a capacitive mode.

5. CONCLUSION

In this paper, an attempt is made to review the model of SSSC and VSC with preliminary studies for the controller design. The power flow in the transmission line always decreases when the injected voltage by the SSSC emulates an inductive reactance in series with the transmission line and the power flow in the transmission line always increases when the injected voltage by the SSSC emulates a capacitive reactance in series with the transmission line. An attempt has been made to evolve a better control strategy to control the power flow in the transmission line using voltage source converter. The power flow control using sen transformer discussed in [5], is considered as reference for evolving control strategy for SSSC.

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