

Power Oscillation Damping of Multi-Area Power System Using SSSC

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ABSTRACT: The main aim of this work is to damp out power system oscillations, which has been recognized as one of the major concerns in power system operation. In a Static Synchronous Series Compensator (SSSC), a controllable AC voltage is generated by a voltage-source converter. There are two control channels for controlling the magnitude and phase of the voltage. This work describes the damping of power oscillations by static synchronous series compensator (SSSC) based damping controllers. The advantage of this approach is that it can handle the nonlinearities, at the same time it is faster than other conventional controllers and it improve the reactive power of the system. Simulation studies will be carried out in Matlab/Simulink environment to evaluate the effectiveness of the proposed Static synchronous series compensator (SSSC) of multi-area power system. Results will show that the proposed SSSC based damping controllers improve the damping performance in the event of a major disturbance.

KEYWORDS: PST (Phase Shifting Transformer), Thyristor Controlled Series Compensator (TCSC), Static Synchronous Series Compensator (SSSC), Static Synchronous Compensator (STATCOM), Unified Power Flow Controller (UPFC)

I. INTRODUCTION

The technology of power system utilities around the world has rapidly evolved with considerable changes in the technology along with improvements in power system structures and operation. The ongoing expansions and growth in the technology, demand a more optimal and profitable operation of a power system with respect to generation, transmission and distribution systems [1].

In the present scenario, most of the power systems in the developing countries with large interconnected networks share the generation reserves to increase the reliability of the power system. However, the increasing complexities of large interconnected networks had fluctuations in reliability of power supply, which resulted in system instability, difficult to control the power flow and security problems that resulted large number blackouts in different parts of the world. The reasons behind the above fault sequences may be due to the systematical errors in planning and operation, weak interconnection of the power system, lack of maintenance or due to overload of the network [2].

In order to overcome these consequences and to provide the desired power flow along with system stability and reliability, installations of new transmission lines are required. However, installation of new transmission lines with the large interconnected power system are limited to some of the factors like economic cost, environment related issues. These complexities in installing new transmission lines in a power system challenges the power engineers to research on the ways to increase the power flow with the existing transmission line without reduction in system stability and security.

In this research process, in the late 1980's the Electric Power Research Institute (EPRI) introduced a concept of technology to improve the power flow, improve the system stability and reliability with the existing power systems. This technology of power electronic devices is termed as Flexible Alternating Current Transmission Systems (FACTS) technology. It provides the ability to increase the controllability and to improve the transmission system operation in terms of power flow, stability limits with advanced control technologies in the existing power systems [3, 4].

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The main objective to introduce FACTS Technology is as follows:

1. To increase the power transfer capability of a transmission network in a power system.
2. To provide the direct control of power flow over designated transmission routes.
3. To provide secure loading of a transmission lines near the thermal limits.
4. To improve the damping of oscillations as this can threaten security or limit usage line capacity [5].

FACTS technology is not a single power electronic device but a collection of controllers that are applied individually or in coordination with other devices to control one or more interrelated power system parameters such as series impedance, shunt impedance, current, voltage and damping of oscillations. These controllers were designed based on the concept of FACTS technology known as FACTS Controllers [5].

FACTS controllers are advanced in relation to mechanical control switched systems that are controlled with ease. They have the ability to control the power flow and improve the performance of the power system without changing the topology. Since 1980s, a number of different FACTS controllers with advanced control techniques proposed as per the demand of the power systems [5].

Unified Power Flow Controller (UPFC) is one among the different FACTS controllers introduced to improve the power flow control with stability and reliability. It is the most versatile device introduced in early 1990s designed based on the concept of combined series-shunt FACTS Controller. It has the ability to simultaneously control all the transmission parameters affecting the power flow of a transmission line i.e. voltage, line impedance and phase angle [2].

II. POWER FLOW CONTROL IN POWER SYSTEMS

2.1 POWER SYSTEM OPERATION

A power system is a large interconnected network with components converting nonelectrical energy into the electrical form to meet the demanded high quality power supply to the end users. A power system is an electrical network divided into three sub-systems. The three sub-systems are the generation stations, the transmission systems and the distributed systems. Electric power produced by a generator unit transmitted from generators to loads by transmission system. The transmission systems are the connecting link between generating stations and the distributed systems that leads to other power system over interconnections as shown in the block diagram in Figure 2.1.1 [6].

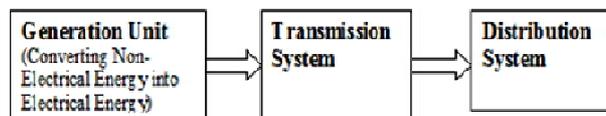


Fig. 2.1.1 Block Diagram of Power System Operation

- **Generation Unit:** The generation unit includes the generating plants that produce energy fed through the transformers to a high voltage transmission network interconnecting to other generating plants. It converts non-electrical energy such as coal, water, natural gas, hydroelectric, solar and geothermal sources etc., into electrical energy.
- **Transmission Systems:** In transmission systems, electricity generated from power generation unit is transferred to substations. It performs voltage transformation, power switching, measurement and control [6].
- **Distribution Systems:** This is the final stage in the delivery of electricity to the end users. A distribution system carries electricity from the transmission system and delivers it to the end users [6].

2.2 POWER FLOW CONTROL

Today most of the electrical power systems in the world are widely interconnected due to economic reasons to reduce the cost of electricity and to improve system stability and reliability. Because of the increasing complexity of power

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system design, the challenge to meet the high quality power supply in a power system is highly desirable. The factors considered for the smooth functionality of power system operation and control as follows:

- Power system operating in a synchronous mode maintains the power quality with a controlled phase between all the interconnected networks.
- The voltage level in a power system should maintain within limits. Any variations in the voltage level cause damage to electric motors and dielectric components, which is not acceptable and leads to overloading of many electric components.
- Transmission lines of power systems should operate with minimum losses by using the most efficient transmission paths capable of handling the loads.
- In practical power engineering it is not possible to operate a power system without any single faults. When faults naturally occur protective relaying systems are used to detect the faults and restore the system operation.
- Whenever there are disturbances in the power system because of system failure, the part of the system that remains operable may not have sufficient capacity to serve the loads without becoming overloaded. In such cases, the major control objective of power system is to manage the overloads that may results from disturbances to the normal operation of the system.

2.3 POWER SYSTEM LIMITATIONS

- Theoretically, power engineers have taken lot of measures to avoid the limitations and maintain the power system to work with stability and reliability. However, it is very hard to predict the power system limitations that affect the system operation. Following are the some of the limitations considered in power system: Thermal, Voltage and Transient Stability limits.
- **Thermal limit:** Thermal limits are due to the thermal capability of power systems. As power transfer increases, current magnitude increases which is key to thermal damage. For example, in a power system, the sustained operation of units beyond the maximum operation limits will result in thermal damage [8].
- **Voltage limit:** Power systems are designed to operate at a nominal supply voltage. Variations in nominal voltage can adversely affect the performance as well as cause serious damage to the system. Current flowing through the transmission lines may produce an unacceptably large voltage drop at the receiving end of the power system. This voltage drop is primarily due to the large reactive power loss, which occurs as the current flows through the systems [8].
- **Transient Stability:** It is defined as the ability of power system to maintain synchronism when it is subjected to severe transient disturbance. In general, power systems with long transmission lines are most susceptible to transient instability. The best way to analyze the transient stability limit is to study the change of rotor angle of all synchronous machines connected to the system after the system subjected to large disturbance [8].

2.4 POWER CONTROLLING DEVICES

1. Phase Shifting Transformer (PST)
2. High Voltage Direct Current (HVDC)
3. Flexibility of Ac Transmission Systems (FACTS)

III. THE STATIC SYNCHRONOUS SERIES COMPENSATOR (SSSC)

3.1 INTRODUCTION

The SSSC, sometimes called the S3C, 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 real and reactive power with the transmission system [35]–[36], [37]–[38]. For instance, if the injected voltage is in phase with the line current, then the voltage would exchange real power. On the other hand, if a voltage is injected in quadrature with the line current, then reactive power—either absorbed or generated—would be exchanged.

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The SSSC emerges as a potentially more beneficial controller than the TCSC because of its ability to not only modulate the line reactance but also the line resistance in consonance with the power swings, thereby imparting enhanced damping to the generators that contribute to the power oscillations.

The SSSC comprises a multi-phase VSC with a dc-energy storage controller, as shown in Fig. 3.1.1(a). Here, the controller is connected in series with the transmission line. The operating modes of the SSSC are illustrated graphically in Fig. 3.1.1(b).

3.1 THE PRINCIPLE OF OPERATION

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:

$$\overline{V}_C = -jkX\overline{I}_L \quad (3.1)$$

Where, \overline{V}_C = the injected compensating voltage

\overline{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 [39], [40]:

$$I_L = \frac{2V \sin \delta/2}{X} + \frac{V_C}{X} \quad (3.2)$$

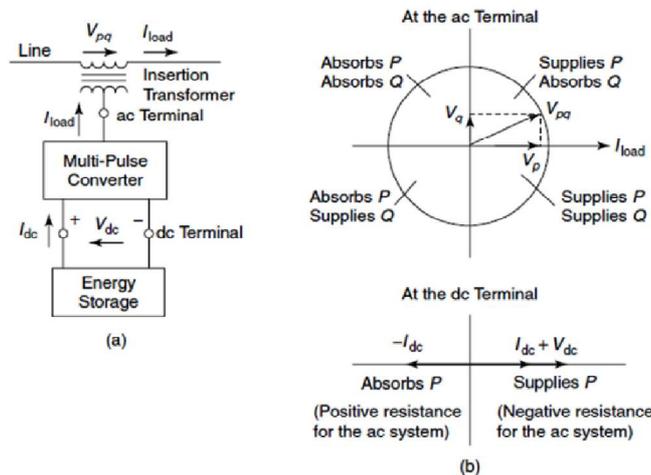


Fig. 3.1.1 (A) Generalized Series-Connected Synchronous-Voltage Source Employing A Multi-Pulse Converter With An Energy-Storage Device; (B) The Different Operating Modes For Real- And Reactive-Power Exchange.

Where, V = The magnitude of voltage (assumed to be the same) at the two ends of the transmission line

same) at the two ends of the transmission line

δ = The angular difference across the line

The corresponding line-power flow is then expressed as:

$$P = VI_L \cos \delta/2 \quad (3.3.a)$$

or

$$P = \frac{V^2 \sin \delta}{X} + \frac{VV_C}{X} \cos (\delta/2) \quad (3.3-b)$$

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A series-compensation scheme using the SSSC is depicted in Fig. 4.1.2. Normally, the SSSC-output voltage lags behind the line current by 90° to provide effective series compensation. In addition, the SSSC can be gated to produce an output voltage that leads the line current by 90° , which provides additional inductive reactance in the line. This feature can be used for damping power swings and, if the converter has adequate rating, for limiting short-circuit currents.

A typical SSSC controller connected in a transmission line is shown in Fig. 4.1.3 [41]. This controller comprises a VSC in which its coupling transformer is connected in series with the transmission line.

The valve-side voltage rating is higher than the line-side voltage rating of the coupling transformer to reduce the required current rating of the gate turn-off (GTO) thyristor valves.

The valve-side winding is delta-connected to provide a path for 3rd harmonics to flow. Solid-state switches are provided on the valve side to bypass the VSC during periods of very large current flow in the transmission line or when the VSC is inoperative.

The basic dc voltage for conversion to ac is provided by the capacitor, and the dc to ac conversion is achieved by pulse width-modulation techniques [42], [43].

The dc-capacitor rating is chosen to minimize the ripple in the dc voltage. An MOV is installed across the dc capacitor to limit its voltage and provide protection to the valves.

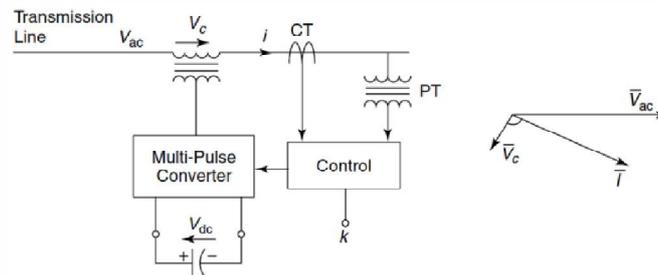


Fig. 3.1.2 A Synchronous-Voltage Source Employing A Multi-Phase DC To AC Converter That Is Operated As A Series-Capacitive Compensator

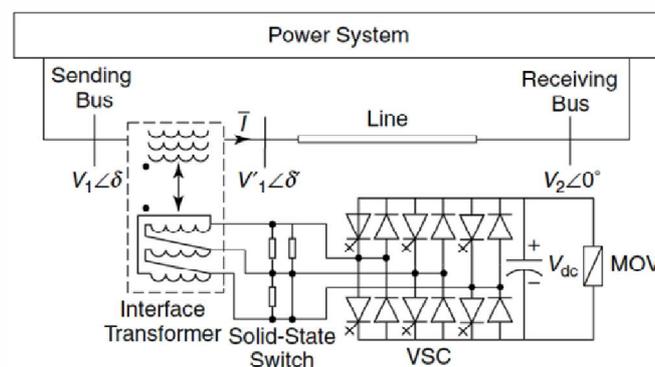


Fig. 3.1.3 A Line Compensated With An SSSC

3.1.1 THE CONTROL SYSTEM

A typical SSSC control system is depicted in Fig. 4.1.1.1 [39]. It accomplishes the following functions:

1. The introduction of desired series-reactive compensation (capacitive or inductive).
2. The damping of power-swing oscillations and enhancement of transient stability.

3. The control of current in the SSSC-compensated line.

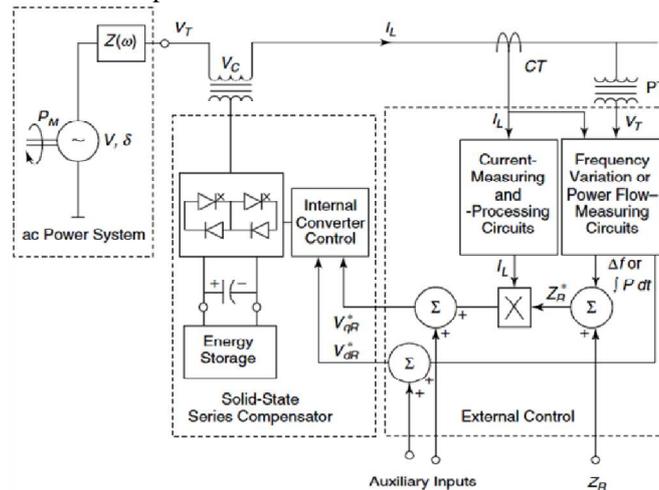


Fig. 3.1.1.1 A Basic Control Scheme For The Solid-State Series Compensator To Control (Reactive And Real) Line Impedance And Improve System Stability

- 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} . 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 bus frequency or line-power signals are representative of the generator-rotor oscillations, $(d\delta/dt)$, as follows:
 1. If $(d\delta/dt) > 0$ —that is, the generators accelerate—the signal V^*_{qr} controls the SSSC output to increase the power drawn from the generator, thereby decreasing its kinetic energy. This action is achieved by enhancing the series-capacitive compensation provided by SSSC.
 2. If $(d\delta/dt) < 0$ —that is, the generators decelerate—the signal V^*_{qr} , effectively inserts an inductive reactance in the line to decrease the power transmitted from the generator.
- 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. It thus controls the real-power exchange between the SSSC and the system and is particularly effective when the SSSC is equipped with an energy-storage device such as the one shown in the Fig. 4.4. To damp power swings, the modulation signal representing $(d\delta/dt)$ is used to modulate V^*_{dr} , as follows:
 1. If $(d\delta/dt) > 0$ —that is, the generators accelerate—the signal V^*_{dr} controls the SSSC to absorb real power from the system. It effectively introduces a positive (apparent) resistance in the transmission network.
 2. If $(d\delta/dt) < 0$ —that is, the generators decelerate—the signal V^*_{dr} instructs the SSSC to inject real power into the system. This action is equivalent to the introduction of a negative (virtual) resistance in the transmission circuit.
- The SSSC can also be used to balance the currents in parallel lines. This objective is attained by implementing an additional current loop in which the measured current is compared with the desired reference value. The error signal is then employed to modulate Z_R to effect the required current flow in the compensated line.

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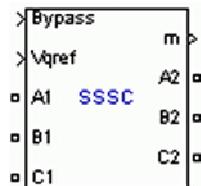
3.1.2 APPLICATIONS

1. Power-Flow Control
2. SSR Mitigation

IV. SIMULATION RESULTS

4.1 MODELING OF SSSC

Description



The Static Synchronous Series Compensator (SSSC) is a series device of the Flexible AC Transmission Systems (FACTS) family using power electronics to control power flow and improve power oscillation damping on power grids [1]. The SSSC injects a voltage V_s in series with the transmission line where it is connected.

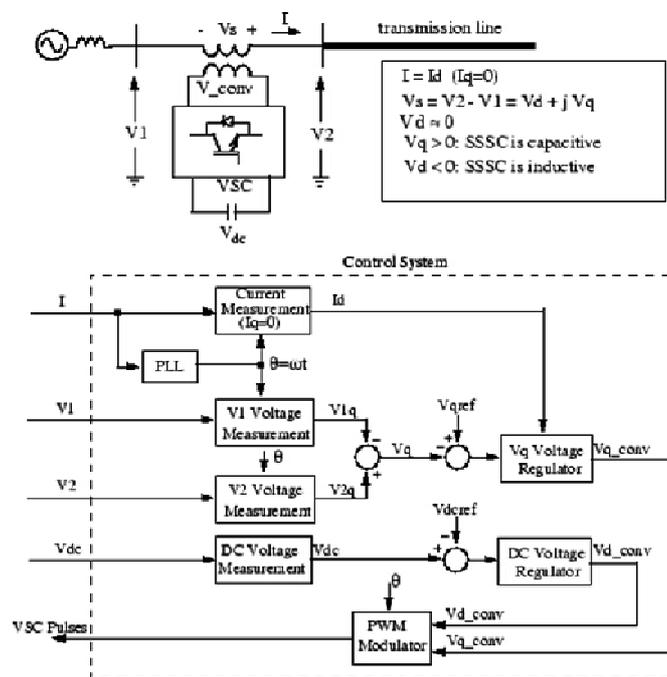


Fig. 4.1.1 Single-Line Diagram Of A SSSC And Its Control System Block Diagram

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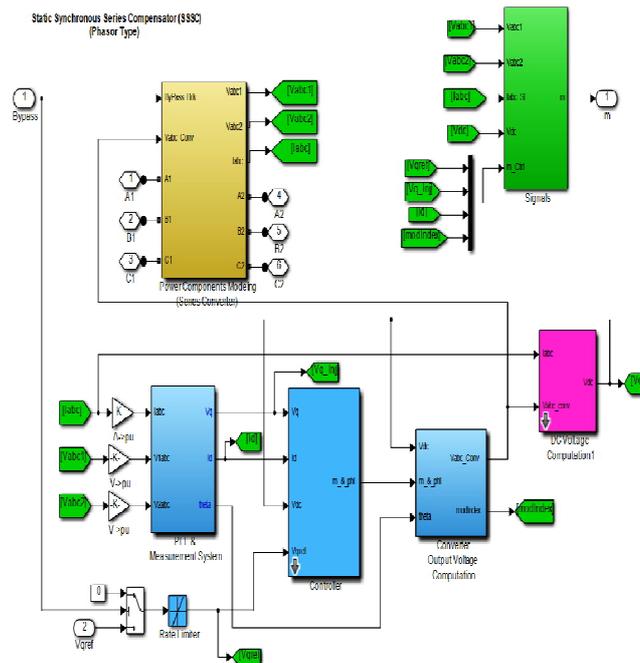


Fig. 4.1.2 MATLAB Implementation of SSSC

- As the SSSC does not use any active power source, the injected voltage must stay in quadrature with line current. By varying the magnitude V_q of the injected voltage in quadrature with current, the SSSC performs the function of a variable reactance compensator, either capacitive or inductive.
- The variation of injected voltage is performed by means of a Voltage-Sourced Converter (VSC) connected on the secondary side of a coupling transformer. The VSC uses forced-commutated power electronic devices (GTOs, IGBTs or IGCTs) to synthesize a voltage V_{conv} from a DC voltage source.
- A capacitor connected on the DC side of the VSC acts as a DC voltage source. A small active power is drawn from the line to keep the capacitor charged and to provide transformer and VSC losses, so that the injected voltage V_s is practically 90 degrees out of phase with current I . In the control system block diagram V_d_{conv} and V_q_{conv} designate the components of converter voltage V_{conv} which are respectively in phase and in quadrature with current. Two VSC technologies can be used for the VSC:
- VSC using GTO-based square-wave inverters and special interconnection transformers. Typically four three-level inverters are used to build a 48-step voltage waveform. Special interconnection transformers are used to neutralize harmonics contained in the square waves generated by individual inverters. In this type of VSC, the fundamental component of voltage V_{conv} is proportional to the voltage V_{dc} . Therefore V_{dc} has to varied for controlling the injected voltage.
- VSC using IGBT-based PWM inverters. This type of inverter uses Pulse-Width Modulation (PWM) technique to synthesize a sinusoidal waveform from a DC voltage with a typical chopping frequency of a few kilohertz. Harmonics are cancelled by connecting filters at the AC side of the VSC. This type of VSC uses a fixed DC voltage V_{dc} . Voltage V_{conv} is varied by changing the modulation index of the PWM modulator.
- The SSSC (Phasor Type) block models an IGBT-based SSSC (fixed DC voltage). However, as details of the inverter and harmonics are not represented, it can be also used to model a GTO-based SSSC in transient stability studies.

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- The control system consists of:
 - A phase-locked loop (PLL) which synchronizes on the positive-sequence component of the current I. The output of the PLL (angle $\Theta = \omega t$) is used to compute the direct-axis and quadrature-axis components of the AC three-phase voltages and currents (labeled as V_d , V_q or I_d , I_q on the diagram).

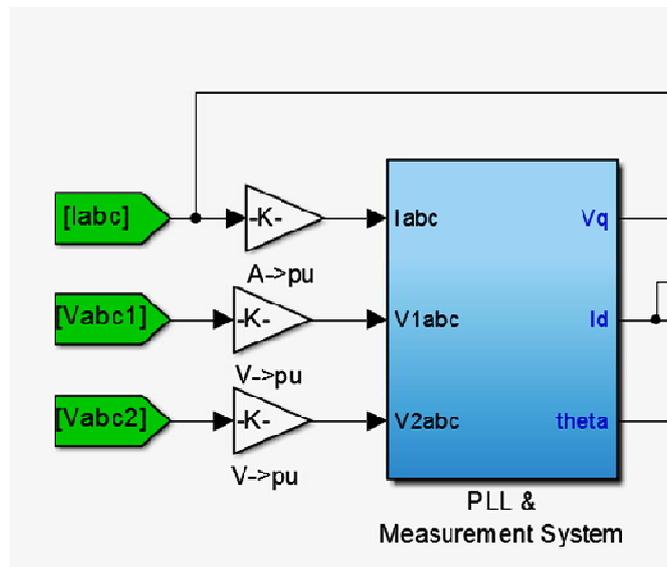


Fig.4.1.3 PLL & Measurement System

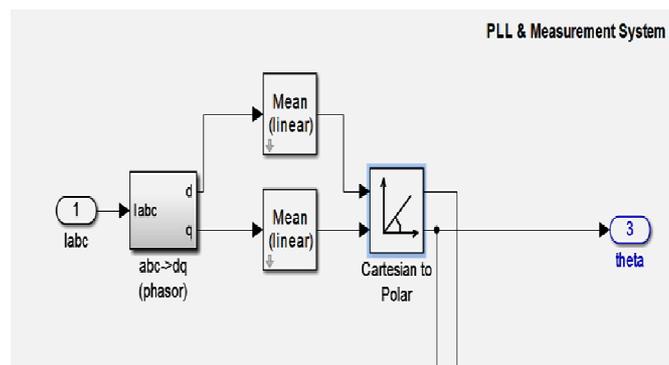


Fig.4.1.4 Phase Locked Loop (PLL)

Measurement systems measuring the q components of AC positive-sequence of voltages V_1 and V_2 (V_{1q} and V_{2q}) as well as the DC voltage V_d .

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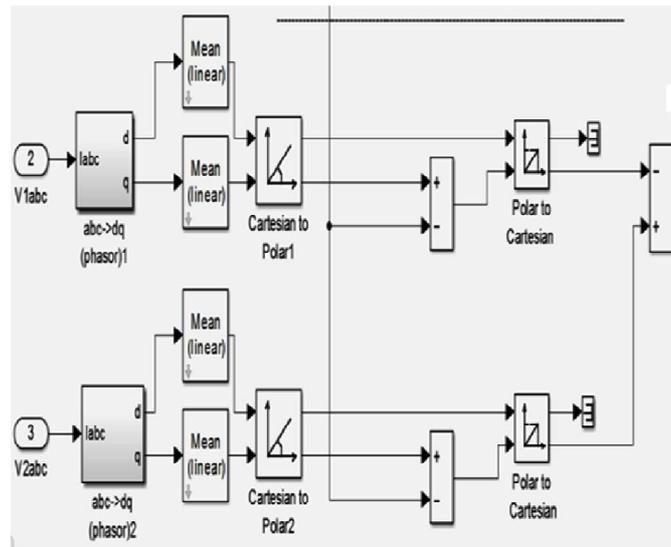


Fig.4.1.5 Measurement System

AC and DC voltage regulators which compute the two components of the converter voltage (V_{d_conv} and V_{q_conv}) required to obtain the desired DC voltage (V_{dc_ref}) and the injected voltage (V_{q_ref}). The V_q voltage regulator is assisted by a feed forward type regulator which predicts the V_{conv} voltage from the I_d current measurement.

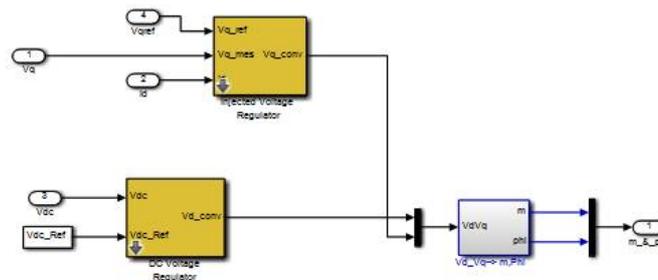


Fig.4.1.6 VSC Voltage Controller

Dialog Box and Parameters

The SSSC parameters are grouped in two categories: Power data and Control parameters. Use the **Display** listbox to select which group of parameters you want to visualize.

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Power Data Parameters.

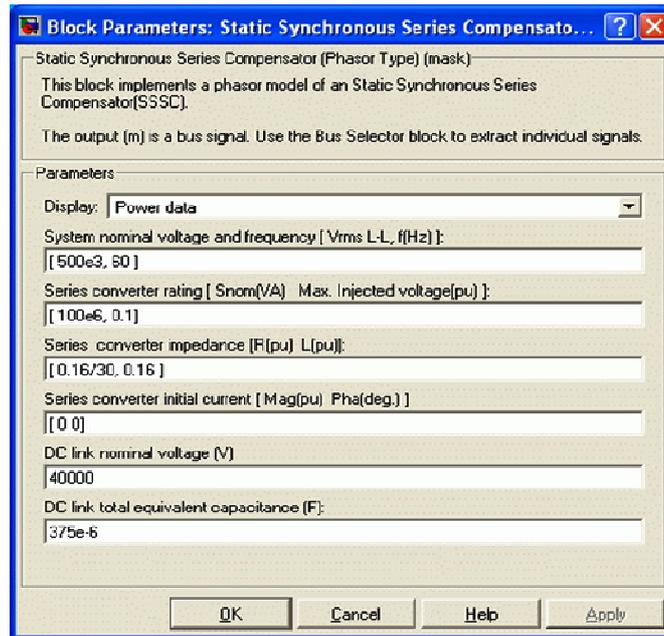


Fig. 4.1.7 Power Data Parameters

- **System nominal voltage and frequency [Vrms f]**
The nominal line-to-line voltage in Vrms and the nominal system frequency in hertz.
- **Series converter rating [Snom, Max. Injected voltage]**
The nominal rating of the series converter in VA and the maximum value of the injected voltage V_{conv} on the VSC side of the transformer (see single line diagram), in pu of nominal phase-to-ground voltage.
- **Series converter impedance [R L]**
The positive-sequence resistance and inductance of the converter, in pu based on the nominal converter rating and nominal voltage. R and L represent the resistance and leakage inductance of the coupling transformer plus the resistance and inductance of the series filtering inductors connected at the VSC output.
- **Series converter initial current [Mag Phase]**
The initial value of the positive-sequence current phasor (Magnitude in pu and Phase in degrees). If you know the initial value of the current corresponding to the SSSC operating point you may specify it in order to start simulation in steady state. If you don't know this value, you can leave [0 0]. The system will reach steady-state after a short transient.
- **DC link nominal voltage**
The nominal voltage of the DC link in volts.
- **DC link total equivalent capacitance**
The total capacitance of the DC link in farads. This capacitance value is related to the SSSC converter rating and to the DC link nominal voltage. The energy stored in the capacitance (in joules) divided by the converter rating (in VA) is a time duration which is usually a fraction of a cycle at nominal frequency. For example, for the default parameters, $(C \cdot V_{dc}^2 / 2) / S_{nom}$ is 3.0 ms, which represents 0.18 cycle for a 60 Hz frequency. If you change the default values of the nominal power rating and DC voltage, you should change the capacitance value accordingly.

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This analysis for supply current. It has THD of 20.68%.

Now for load current analysis. It has THD of 9.19%.

Control Parameters

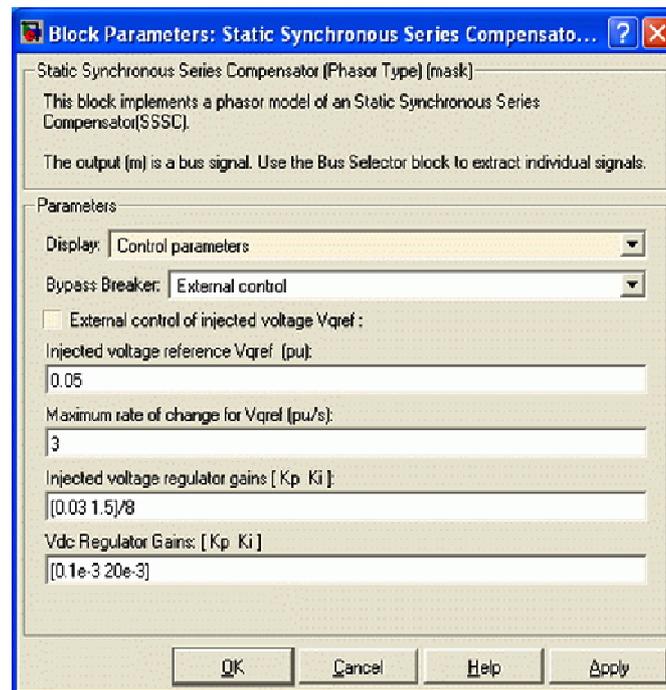


Fig. 5.1.8 Control Parameters

- Bypass Breaker**
 Specifies the status of the bypass breaker connected inside the block across terminals A1, B1, C1 and A2, B2, C2. Select either External Control, Open or Closed. If the bypass breaker is in external control, a Simulink[®] input named Bypass appears on the block, allowing to control the status of the bypass breaker from an external signal (0 or 1).
- External control of injected voltage V_{qref}**
 If this parameter is checked, a Simulink input named V_{qref} appears on the block, allowing to control the injected voltage from an external signal (in pu). Otherwise a fixed reference voltage is used, as specified by the parameter below.
- Injected voltage reference V_{qref}**
 This parameter is not visible when the **External control of injected voltage V_{qref}** parameter is checked. Specify the quadrature-axis component of the voltage injected on the VSC side of the series transformer, in pu.
- Maximum rate of change for V_{qref}**
 Maximum rate of change of the V_{qref} voltage, in pu/s.
- Injected voltage regulator gains: [Kp Ki]**
 Gains of the PI regulator which controls the injected voltage. Specify proportional gain Kp in (pu of V_{q_conv})/(pu of V), and integral gain Ki, in (pu of V_{q_conv})/(pu of V)/s, where V is the V_q voltage error and V_{q_conv} is the quadrature-axis component of the voltage generated by the VSC. The feed forward gain is computed from the **Series converter impedance [R L]** parameters.
- Vdc regulator gains: [Kp Ki]**
 Gains of the DC voltage PI regulator which controls the voltage across the DC bus capacitor. Specify proportional gain Kp in (pu of V_{d_conv})/Vdc, and integral gain Ki, in (pu of V_{d_conv})/Vdc/s, where Vdc is the DC voltage error and V_{d_conv} is the direct-axis component of the voltage generated by the converter.

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- **Inputs and Outputs**

- A1 B1 C1 are the three input terminals of the SSSC.

- A2 B2 C2 are the three output terminals of the SSSC.

This input is visible only when the **Bypass Breaker** parameter is set to External Control.

Apply a simulink logical signal (0 or 1) to this input. When this input is high the bypass breaker is closed.

- **V_{qref}**

This input is visible only when the **External control of injected voltage V_{qref}** parameter is checked.

Apply a simulink signal specifying the reference voltage, in pu. These signals are either voltage and current phasors (complex signals) or control signals. They can be individually accessed by using the Bus Selector block. They are, in order:

Signal	Signal Group	Signal Names	Definition
1-3	Power Vabc1 (cmplx)	Va1 (pu) Vb1 (pu) Vc1 (pu)	Phasor voltages (phase to ground) Va, Vb, Vc at the SSSC input terminals A1, B1, C1 (pu)
4	Power	Vdc (V)	DC voltage (V)
5-7	Power Vabc2 (cmplx)	Va2 (pu) Vb2 (pu) Vc2 (pu)	Phasor voltages (phase to ground) Va, Vb, Vc at the SSSC output terminals A2, B2, C2 (pu)
8-10	Power Vabc_Inj (cmplx)	Va_Inj (pu) Vb_Inj (pu) Vc_Inj (pu)	Phasors of injected voltages Vs= V2-V1 (pu)
11-13	Power Iabc (cmplx)	Ia (pu) Ib (pu) Ic (pu)	Phasor currents Ia, Ib, Ic flowing out of terminals A2, B2, C2 (pu)
14	Control	Vqref (pu)	Reference value of quadrature-axis injected voltage (pu)
15	Control	Vqinj (pu)	Measured injected voltage in quadrature-axis (pu)
16	Control	Id(pu)	Measured current (pu)
17	Control	modindex	The modulation index m of the PWM modulator. A positive number $0 < m < 1$. $m=1$ corresponds to the maximum voltage V _{conv} which can be generated by the series converter without over modulation.

Table 1 Signal Specification

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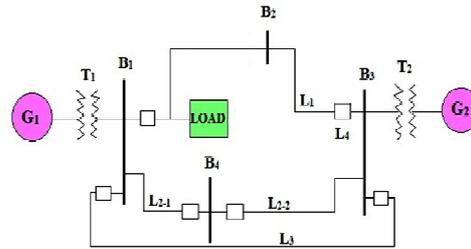


Fig.4.2.1 Single line diagram of a two-machine system without SSSC

4.2 POWER SYSTEM UNDER STUDY

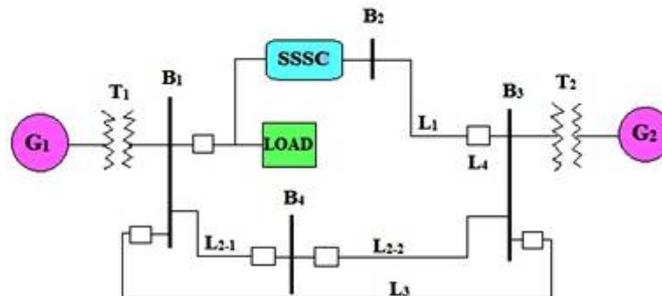


Fig.4.2.2 Single line diagram of a two-machine system with SSSC

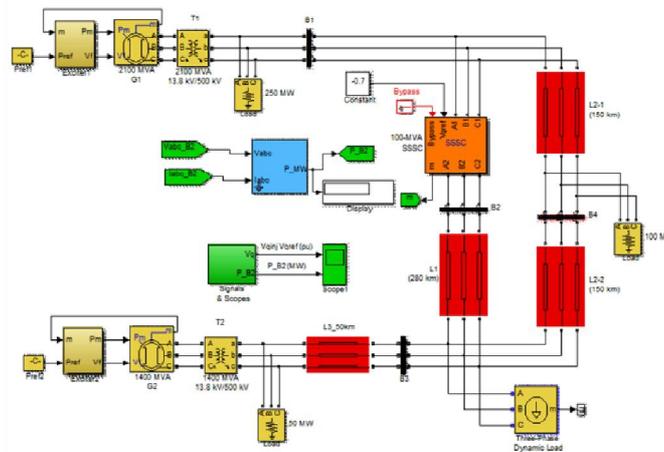


Fig.4.2.4 MATLAB Implementation

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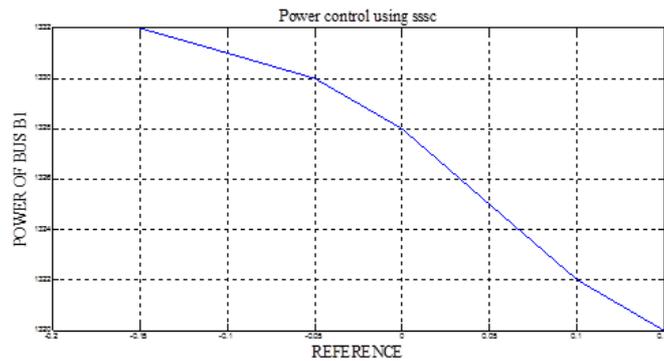


Fig.4.2.5 Variation of Power at Bus B₁ With Change in Compensation

- As shown in fig. with positive compensation, power of bus B₁ decreases while with negative compensation, power of bus B₁ increases.

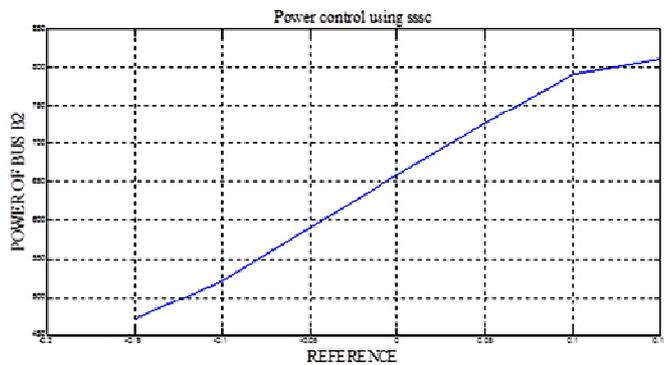


Fig.4.2.6 Variation of Power at Bus B₂ With Change in Compensation

- As shown in fig. with positive compensation, power of bus B₂ increases while with negative compensation, power of bus B₂ decreases.

Table 2 Simulation Results With Variation of % Compensation With SSSC

V _{qref} (v)	PB1 (w)	PB2(w)	PB3(w)	PB4(w)
-0.15	1332	470.3	982.6	749.6
-0.1	1331	521.3	983	699
-0.05	1330	590.8	983.4	629.3
0	1328	659.4	983.6	559.9
0.05	1325	726.4	983.5	491.1
0.1	1322	791.5	983.2	423.2
0.15	1320	811.2	983	402.4

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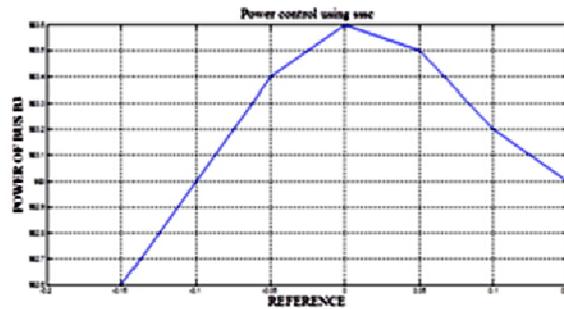


Fig.4.2.7 Variation of Power at Bus B₃ With Change in Compensation

- As shown in fig. with positive compensation, power of bus B₃ decreases while with negative compensation, power of bus B₃ increases.

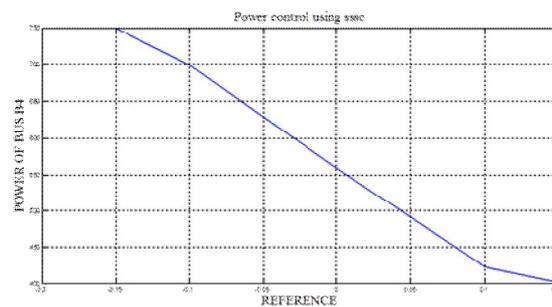


Fig.4.2.8 Variation of Power at Bus B₄ With Change in Compensation

- As shown in fig. with positive compensation, power of bus B₄ decreases while with negative compensation, power of bus B₄ increases.

4.3 SIMULATION RESULTS OF POWER FLOW CONTROL

4.1 MODELING OF SSSC

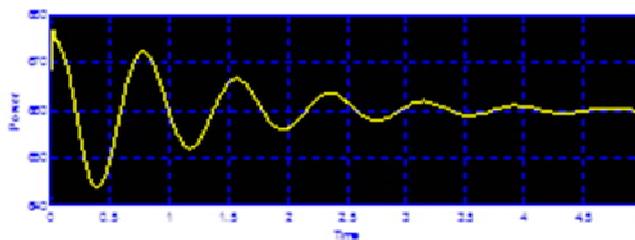


Fig.4.3.1 Power Flow Control Through a Line Without SSSC

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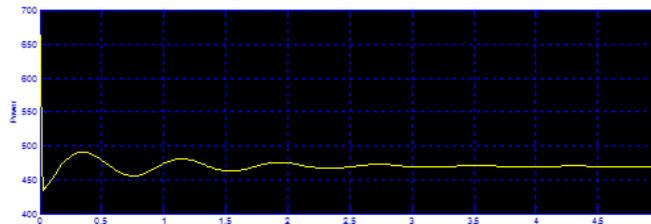


Fig.4.3.2 Power Flow Control Through a Line With SSSC

IV. MATHEMATICAL MODEL OF SSSC

Consider a single machine infinite bus system with a SSSC as shown in Fig. 5.1.1(A). The equivalent circuit of the system is shown in Fig. 5.1.1(C) where the SSSC is represented by a variable synchronous voltage source of V_s and the generator is modeled by a constant voltage source behind transient reactance. Reactance X_1 represents the sum of generator transient reactance and transformer leakage reactance and X_2 represents the equivalent reactance of the parallel lines. The leakage reactance of the series transformer of SSSC can be included either in X_1 or X_2 . The phasor diagram of the system is shown in Fig. 5.1.2 for various operating conditions of the SSSC. It can be seen in Fig. 5.1.2 that, for given E' and V , the SSSC voltage V_s changes only the magnitude of the current but not its angle.

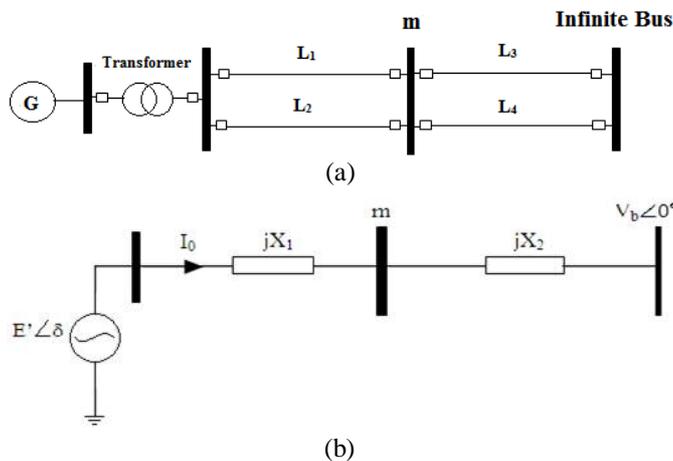
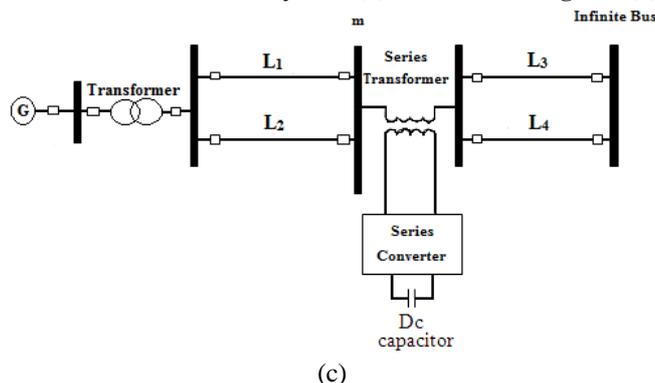


Fig. 5.1.1 Single Machine Infinite Bus System (a) Schematic Diagram (b) Equivalent Circuit



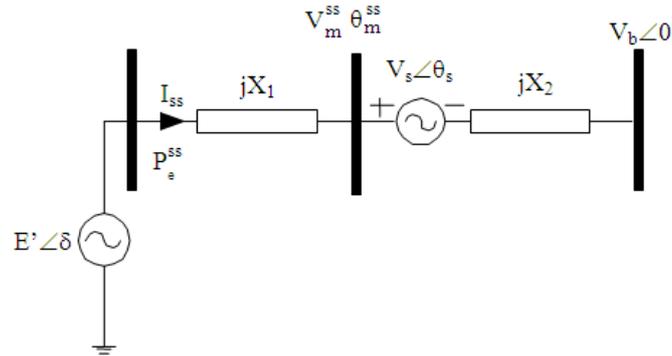
(c)

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(d)

Fig. 5.1.1 Single Machine Infinite Bus System With A SSSC (c) Schematic Diagram (d) Equivalent Circuit Of System With A SSSC Represented By A Series Voltage Injection

When $V_s = 0$, the current I_0 of the system can be written as:

$$I_0 = \frac{E' - V}{jX} \quad (5.1)$$

Here, $X = X_1 + X_2$. The angle θ of the current can be written as:

$$\theta = \tan^{-1} \left(\frac{V - E' \cos \delta}{E' \sin \delta} \right) \quad (5.2)$$

From Fig. (B), the general equation of the current can be written as:

$$I = \frac{E' - V_s - V}{jX} = \left(\frac{E' - V}{jX} \right) + \left(\frac{-V_s}{jX} \right) = I_0 + \Delta I \quad (5.3)$$

Here ΔI is an additional term appears because of the SSSC voltage V_s . The electrical output power P_e of the generator can be written as:

$$P_e = \Re\{E' I^*\} = P_{e0} + \Delta P_e \quad (5.4)$$

Here, P_{e0} is the generator output power without SSSC ($V_s = 0$) and is given by:

$$P_{e0} = P_{\max} \sin \delta \quad (5.5)$$

Where, $P_{\max} = E' V / X$.

The additional power term ΔP_e appears in (4) is due to the SSSC voltage V_s and can be written as:

$$\Delta P_e = \Re\left\{E' \left(\frac{-V_s}{jX}\right)^*\right\} = \frac{E' V_s}{X} \sin(\delta - \alpha) \quad (5.6)$$

When V_s lags the current by 90° ($\alpha = \theta - 90^\circ$), ΔP_e becomes:

$$\Delta P_e = \frac{E' V_s}{X} \cos(\delta - \theta) \quad (5.7)$$

Now, ΔP_e can be expressed as:

$$\Delta P_e = C V_s P_{e0} \quad (5.8)$$

Thus the electrical output power of the generator in the presence of a SSSC becomes:

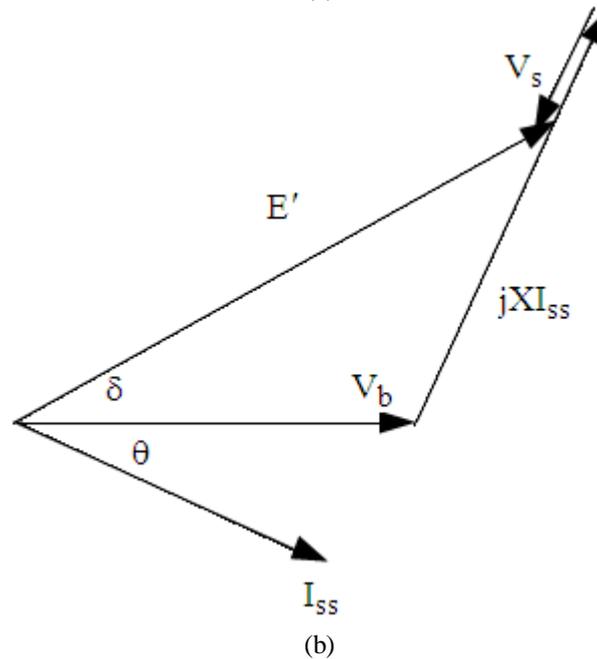
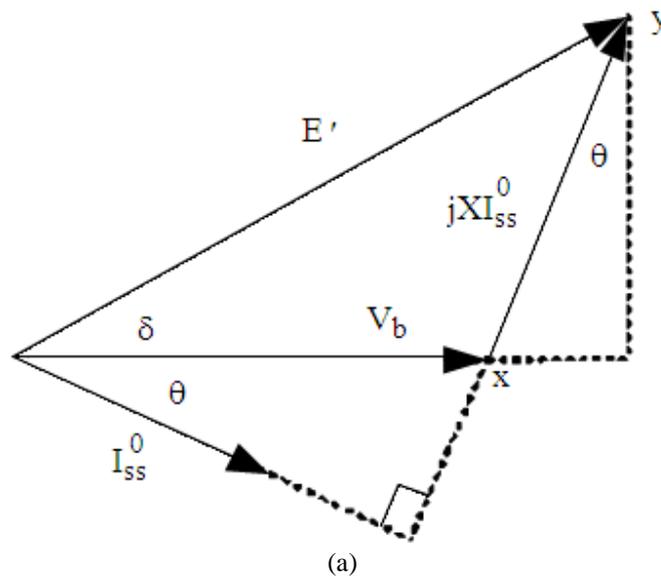
$$P_e = P_{e0} + C V_s P_{e0} \quad (5.9)$$

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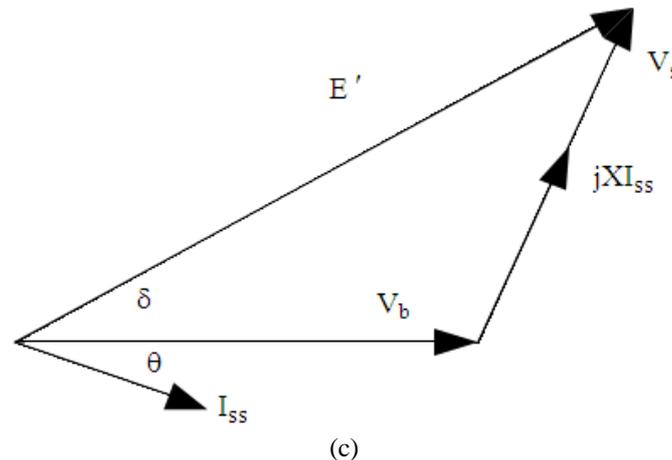


Fig. 5.1.2 Phasor Diagram (a) Without A SSSC (b) With A SSSC Operating In Capacitive Mode (c) With A SSSC Operating In Reactive Mode

V. CONCLUSION

The SSSC which is a voltage source inverter injects an almost sinusoidal voltage in series with the transmission line.

This injected voltage is almost in quadrature with the line current, thereby emulating an inductive reactance or a capacitive reactance in series with the transmission line.

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. Hence by using SSSC we can control the power flow through any bus, thereby we can load the line upto its maximum loading point. Similarly using SSSC we can prevent the line to be over loaded.

The SSSC can be used for power oscillation damping and stability enhancement. From above simulation analysis we came to know that by keeping active filter there is reduce in harmonic in RL load.

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