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Dynamic operation and control schemes for hybrid static synchronous series compensator

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This paper presents a modeling and simulation of Neutral Point Clamped (NPC) Voltage Source Converter (VSC) based Hybrid Static Synchronous Series Capacitive Compensator (HSSSC) with direct and indirect control schemes is presented. The hybrid scheme is a combination of Static Synchronous Series Compensator (SSSC) and a fixed capacitor in series with the transmission line. The hybrid scheme is reduces the size and ratings of the SSSC in a transmission line system. The effectiveness of the schemes is to analysing the performance characteristics of HSSSC with direct and an indirect controller is evaluating using the MATLAB/SIMULINK^{TM}.

Keywords: *FACTS devices, NPC, VSC, SSSC, HSSSC, fixed capacitor, power flow.*

1.0 INTRODUCTION

A Voltage Source Converter (VSC) can be used as a sinusoidal voltage source with controllable amplitude and angle. When placed in series with a transmission line, this source can control the flow of active and/or reactive power in the line thereby operating as a series compensator [1]. To increase the power transfer capability in an AC transmission system it's necessary to incorporate the power electronics based controller called Flexible AC Transmission System (FACTS). FACTS Controllers provides an avenue to utilize the existing system to its limits without endangering the stability of the system, thus providing efficient utilization of the existing system [2].

FACTS devices can be broadly classified into two types, namely (a) Variable Impedance type devices, e.g. Static Var Compensator (SVC) or Thyristor Controlled Series Capacitor (TCSC) and (b) Switching Converter type devices which generally use Voltage Source Converters, e.g. Static Synchronous Series Compensator (SSSC) or Unified Power Flow Controller (UPFC). The dynamic performance of VSC based FACTS devices have been observed to be better than that of the variable impedance type FACTS devices [3]. Among the VSC based FACTS devices, the SSSC is capable of controlling the parameters that effect power flow in a transmission line either simultaneously or selectively. But the main constraint in the use of the SSSC is its cost. The VSC especially for the transmission voltage level comes at a very high cost. There are reportedly very few installations of SSSC around the world [4], as compared to the number of installations of SVC and TCSC which are comparatively cheaper.

Series capacitive compensation is a very economical way for increased transmission capacity and improved transient stability of the transmission grid [5]. The SSSC is implemented by a voltage source converter to provide independently controllable series compensation.

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SSSC is the series connected synchronous voltage source that can vary effective impedance of the line by injecting a voltage. This injected voltage is almost in quadrature with the line current, with a small component in phase with the line current to replenish the losses in the inverter. This injected voltage can emulate either an inductive or capacitive reactance in series with the transmission line; by controlling the size of this emulated reactance, the SSSC can influence the power flow in the line [6]. While it may be convenient to consider series compensation as a means of reducing the line impedance, in reality it is really a means of increasing the voltage across the given impedance of the transmission line.

In this paper, modeling and simulation of Neutral Point Clamped (NPC) VSC based HSSSC with direct and indirect control schemes is presented. The proposed scheme is to analysing the performance characteristics of HSSSC with Direct and indirect controllers are evaluating using the MATLAB/SIMULINK^{TM}. The effectiveness of the proposed schemes is compared with SSSC.

2.0 STATIC SYNCHRONOUS SERIES COMPENSATOR

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 [7]. 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.

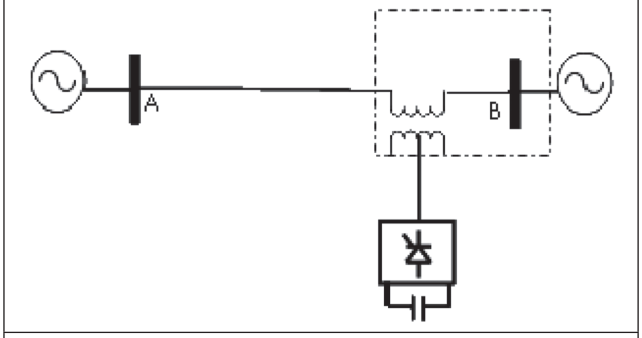

FIG. 1 STATIC SYNCHRONOUS SERIES COMPENSATOR

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 a SSSC is operated with an energy storage system. An impedance compensation controller, when used with a SSSC and no energy storage system, is essentially a reactance compensation controller [8].

The principle of operation of SSSC

$$Vc = -jkXI_L \qquad ....(1)$$

Vc = Injected compensating voltage

X = Series reactance of the line

k = Degree of series compensation

SSSC when connected to the transmission line through a coupling transformer in series with the line. Hence the power flow equation:

$$I_L = \frac{2V\sin\frac{\delta}{2}}{X} + \frac{V_c}{X} \qquad ....(2)$$

$$P = VI_L\cos\frac{\delta}{2} \qquad ....(3)$$

$$P = \frac{V^2}{X}\sin\delta + \frac{VV_C}{X}\cos\frac{\delta}{2} \qquad ....(4)$$

In this paper, a 3-level NPC VSC based SSSC is used. This topology is suitable for high power applications and when compared to a 2-level topology, it has smaller DC capacitors, lower switch blocking voltage and lower switching losses.

3.0 NEUTRAL POINT CLAMPED VOLTAGE SOURCE CONVERTER

The VSC topology, a large number of semiconductor devices must be connected in series to provide the required switch voltage rating. Therefore, appropriate gating and snubber circuits must be applied to minimize the switching stress on each device [9].

In this paper, a 3-level NPC VSC is used. A VSC with NPC topology with one or more phases, comprises an intermediate DC circuit having at least a first and a second capacitance connected in series between a positive terminal and a negative terminal, providing a central tap terminal between both capacitances, and at least one sub-circuit for generating one phase of an alternating voltage, each sub-circuit comprising an AC terminal for supplying a pulsed voltage; a circuit arrangement of the form of a conventional NPC converter, with a first series connection of at least two switches between AC terminal and positive terminal, a second series connection of at least two switches between AC terminal and negative terminal, and switchable connections from central tap terminal to the centers of both two-switch series connections; and additional first and second auxiliary switches assigned to two-switch series connections [10].

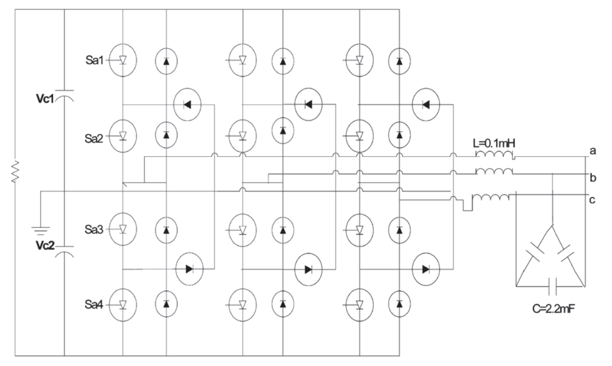

FIG. 2 NEUTRAL-POINT-CLAMPED VOLTAGE SOURCE CONVERTER

A three level NPC VSC is used as shown in Figure 2. This topology is suitable for high power applications and when compared to a two level topology, it produces lesser harmonics, has smaller DC capacitors, lower switch blocking voltage and lower switching losses. The drawbacks of the three levels NPC topology are: requirement for a large number of switches, different duties for semiconductor switches and a requirement for balancing the DC capacitor voltages. Figure 1 shows a 3-phase, 3-level NPC VSC; the circuit consists of 12 valves and 2 DC capacitors C_1 and C_2. Each valve consists of a switch with turn-off capability and an anti-parallel diode. The diodes ensure the bidirectional current flow; therefore, the converter is capable of operating in both rectifier and inverter modes [11].

4.0 HYBRID STATIC SYNCHRONOUS SERIES COMPENSATION

The hybrid scheme is a combination of Static Synchronous Series Capacitive Compensation (HSSSC) and a fixed series capacitor in series with the transmission line as shown Figure 3. Since existing equipment is fully utilized, the hybrid topology requires considerably lower total ratings of the system. Series capacitive compensation is a very economical way for increased transmission capacity and improved transient stability of the transmission grid.

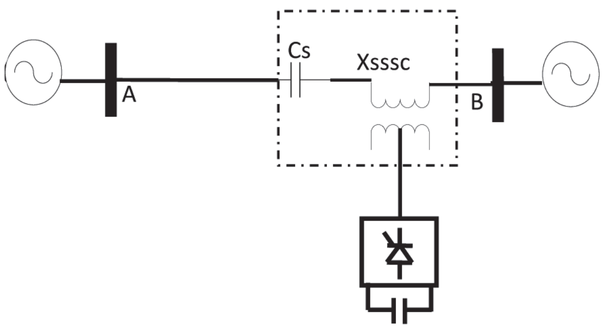

FIG. 3 HYBRID SSSC

At the power frequency, the total series reactance between buses A and B in Figure 3 is given by

$$X_{AB} = \frac{1}{j\omega C_s} - jX_{SSSC} \qquad ....(5)$$

Where $-jX_{sssc}$ is the effective capacitive reactance of HSSSC

The principle of operation of HSSSC

$$V_c = -jkX_{AB}I_L \qquad ....(6)$$

Vc = injected compensating voltage

X_{AB} = total series reactance between buses A and B

I_L= Line current

k = degree of series compensation

HSSSC when connected to the transmission line through a coupling transformer in series with the line.

Hence the power flow equation:

$$I_L = 2V\sin\frac{\delta}{2} + \frac{V_c}{X_{AB}} \qquad ....(7)$$

$$P = VI_L\cos\frac{\delta}{2} \qquad ....(8)$$

$$P = \frac{V^2}{X}\sin\delta + \frac{VVc}{X}\cos\frac{\delta}{2} \qquad ....(9)$$

5.0 CONTROL STRATEGY FOR NPC VSC BASED HSSSC

In order to control the impedance characteristic of the transmission line external injection is required. In this paper HSSSC is designed to control the injecting impedance by two methods. Indirect control method the phase angle of line injecting voltage is varied keeping the magnitude of it constant. Whereas the other controller named direct control in which both magnitude of injecting voltage as well as phase angle Φ with respect line current is controlled [12]. Here both the controllers are used to control power flow in the transmission line and the results are compared.

5.1 INDIRECT METHOD

In this method keeping the modulation index and the DC side voltage constant only the angular position of three phase injected voltages are being varied. As shown in Figure 4 three phase injecting voltages, transmission line currents, line voltages are taken as reference feedback signals for the controller [13].

Block 1: Converting the 3-phase voltages (V_{inja}, V_{injb}, V_{injc}) into $V_{\alpha\beta0}$ by Clarke's transformation.

$$\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \sqrt{\frac{3}{2}} \begin{bmatrix} 1 & \frac{-1}{2} & \frac{-1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{-\sqrt{3}}{2} \\ 1 & \frac{1}{\sqrt{2}} & \frac{-1}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \\ i_o \end{bmatrix} \qquad ....(10)$$

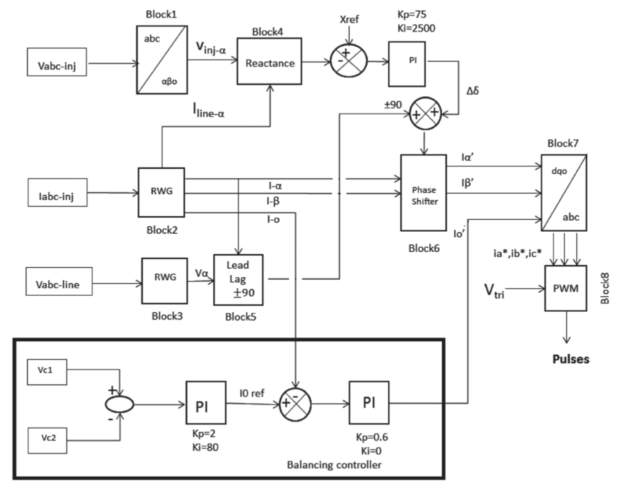

FIG. 4 INDIRECT CONTROL SCHEME

Block 2: Line currents (I_{a1}, I_{b1}, I_{c1}) and Line voltages (V_{a1}, V_{b1}, V_{c1}) are transformed into αβ0 coordinates.

$$\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \sqrt{\frac{3}{2}} \begin{bmatrix} \frac{2}{3} & 0 & \frac{\sqrt{2}}{3} \\ \frac{-1}{3} & \frac{\sqrt{3}}{3} & \frac{-\sqrt{2}}{3} \\ \frac{-1}{3} & \frac{-\sqrt{3}}{3} & \frac{\sqrt{2}}{3} \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \\ i_o \end{bmatrix} \qquad ....(11)$$

The i_α, i_β are fed to the phase shifter block 6 while the zero sequence current is fed to balancing controller. If the phase currents in abc coordinates are sinusoidal then i_α and i_β are also sinusoidal and orthogonal.

Block 4: It receives the positive sequence $V_{inj-\alpha}$ and positive sequence of line current α and computes the injected line reactance X_{inj} then sends to the reactance controller block.

Block 5: Lead/Lag block receives the reference signal of line voltage V_α and reference signal i_α and computes the 90 degree phase shift and its sign. This information is summed with the output angle Δδ from the reactance controller.

Block 6: Phase shifter changes the phase angle by adding ± (90-Δδ) degree angle to ωt radians to generate modified reference signals $i_{\alpha'}$, $i_{\beta'}$.

Block 7: is used to convert αβ0 to abc by inverse Clark's transformation. Thus the required reference signals for SPWM modulation trigger unit are obtained. These signals are fed to PWM unit to generate required pulses for the VSC converter.

With this controller DC voltage is not varied. In fact only the phase angle of reference current signals is varied to control the phase angle of injected voltages.

5.2 Direct Control

Similar to the indirect control technique described earlier, Phase angle of injected voltage is varied in addition to control in magnitude of V_{inj}. This is to control the reactance of transmission line. In this technique, two control loops are provided one to control magnitude and the other for controlling the phase angle Φ. The voltage V_{dc} is kept constant by the DC voltage controller which regulates the phase angle Φ. Reactance control loop to vary the magnitude of voltage injection.

This scheme is more suitable for providing both active and reactive power line compensation if an External Energy Storage (EES) system exists in the DC side of converter. Similar to Indirect control technique, in reactive power compensation mode, the injected voltage leads/lags by almost 90 degrees. A small change in angle is due to active power requirement to meet VSC losses.

From Figure 5, block diagram is similar to indirect controller. In addition to that two more blocks for park's transformation and inverse park's transformation are applied after phase shifter block. This will control the magnitude of reference current signals to PWM trigger unit.

Block 7: of Indirect controller is replaced by two blocks which achieve a transformation from αβ0-abc coordinates via an intermediary dqo stage.

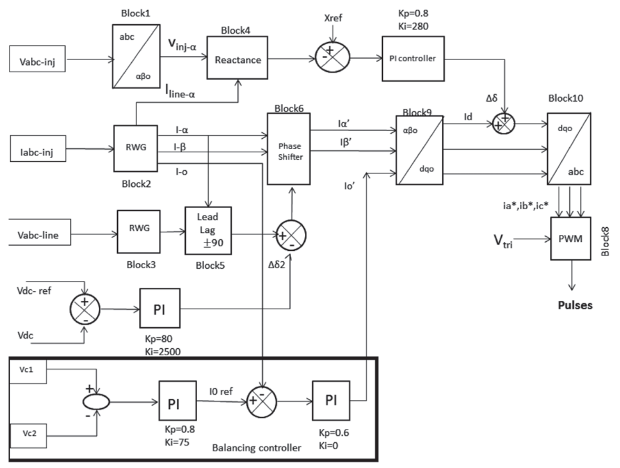

FIG. 5 DIRECT CONTROL SCHEME

Reactance controller: The injected reactance X_{inj} is compared to reference reactance X_{ref} and a PI controller amplifies the error. The resultant from reactance controller is added to the d-component of the desired reference waveform $i_{d'}$.

5.2.1 Reference Wave Generator

The synchronizing signals are based on symmetrical component transformation.

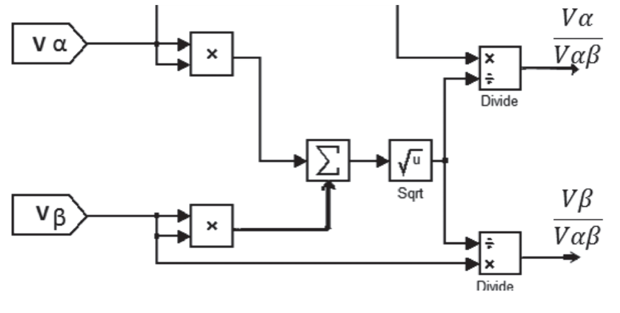

FIG. 6 BLOCK DIAGRAM FOR RWG

A RWG block shown in Figure 6 was introduced to generate clean synchronizing signals which are similar to Phase Locked Loop (PLL). The transmission line currents and voltages are transformed into positive and negative sequence components by matrix conversion and these αβo components are subsequently passed through normalizing and wave-shaping blocks in order to obtain original waveform even under severe system distortion conditions. Delay compensation can be given after normalizing and wave shaping if system is required.

5.2.2 Lead / Lag

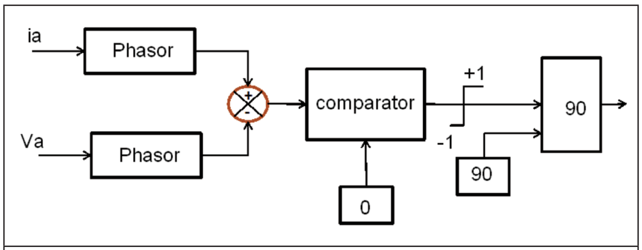

FIG. 7 LOGIC FOR LEAD/LAG COMPARISON

If the line current is leading line voltage then +90 degree will be generated otherwise if current is lagging line voltage -90 degree will be generated. It is shown in Figure 7.

5.2.3 Phase shifter

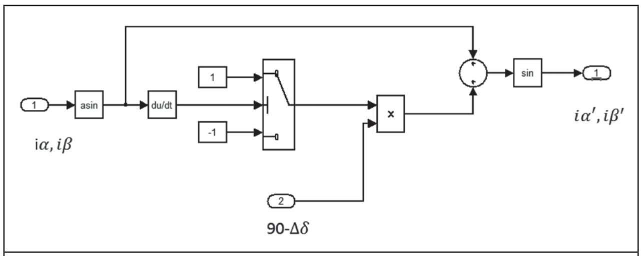

FIG. 8 PHASE SHIFTER BLOCK

Phase angle of reference sinusoidal waveforms i_α, i_β are varied by addition of ± (90-Δδ) degrees shown in Figure 8. Δδ is the change in load angle with respect to the changes in load or change in line reactance.

Balancing Controller Block: Both capacitor voltages are compared from VSC. If the capacitor voltages are unbalanced, a zero sequence reference current i_{oref} is generated by a PI controller. It is compared with actual i_o current of VSC's output and acted upon by another PI controller. This produces i_o that joins i_α, i_β components.

$$\begin{bmatrix} i_d \\ i_q \\ i_o \end{bmatrix} = \begin{bmatrix} \frac{i_\alpha}{i_{\alpha\beta}} & \frac{i_\beta}{i_{\alpha\beta}} & 0 \\ -\frac{i_\beta}{i_{\alpha\beta}} & \frac{i_\alpha}{i_{\alpha\beta}} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \\ i_o \end{bmatrix} \qquad ....(12)$$

$$\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \begin{bmatrix} 1 & 0 & \frac{1}{\sqrt{2}} \\ \frac{-1}{2} & \frac{\sqrt{3}}{2} & \frac{1}{\sqrt{2}} \\ \frac{-1}{2} & \frac{-\sqrt{3}}{2} & \frac{1}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} \frac{i_\alpha}{i_{\alpha\beta}} & -\frac{i_\beta}{i_{\alpha\beta}} & 0 \\ -\frac{i_\beta}{i_{\alpha\beta}} & \frac{i_\alpha}{i_{\alpha\beta}} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} i_d \\ i_q \\ i_o \end{bmatrix} \qquad ....(13)$$

5.2.4 Pulse Width Modulation

This block provides firing pulses for the 3-level NPC VSC switches. The three phase input to the PWM block is

$$V_n = V_m \sin\left(wt + \phi_n\right) \qquad ....(14)$$

Where n=(a, b, c) and V_m is the peak value of waveform.

The PWM uses 2 input triangular 1.8 kHz carrier waves is shown in Figure 9.

$V_{tri\text{-}H}$, $V_{tri\text{-}L}$ and modulation index is defined as

$$k = \frac{V_m}{V_{tri}} \qquad ....(15)$$

Logic for generating pulses under single arm of NPC voltage source converter is suppose for phase a,

If Va>$V_{tri\text{-}H}$, switch Sa_1 is ON, else Sa_1 is OFF.

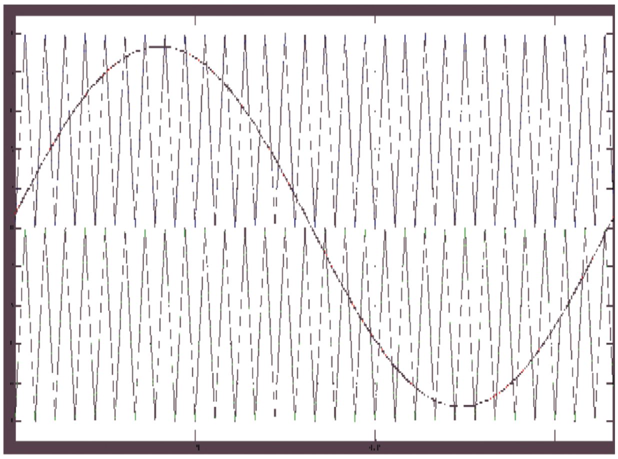

FIG. 9 SPWM FOR PULSE GENERATION

If Va>$V_{tri\text{-}L}$, switch Sa_2 is ON, else Sa_2 is OFF. Operating frequency f_s = 60 Hz, Switching frequency f_c = 1.8 kHz

6.0 METHODOLOGY

Transmission line consists of 3 bus bars as shown in Figure 10. Three phase voltages and currents are obtained from AC grid. Three phase line voltage and line currents are taken from bus1. HSSSC is connected to the transmission line through a coupling transformer in series with the line. Reactive load is connected after the Bus 3 with step down transformer. Now the HSSSC is injecting a generated 15 MVA, 36 kV power in series with the line.

All the Values are measured in per unit system with 230 kV Base voltages and 100 MVA base power with the line. Reactive load is connected after the bus 4 with step down transformer. Now the HSSSC is injecting a generated ±15 MVA, 36 kV power in series with the line. All the values are measured in per unit system with 230 kV Base voltage and 100 MVA.

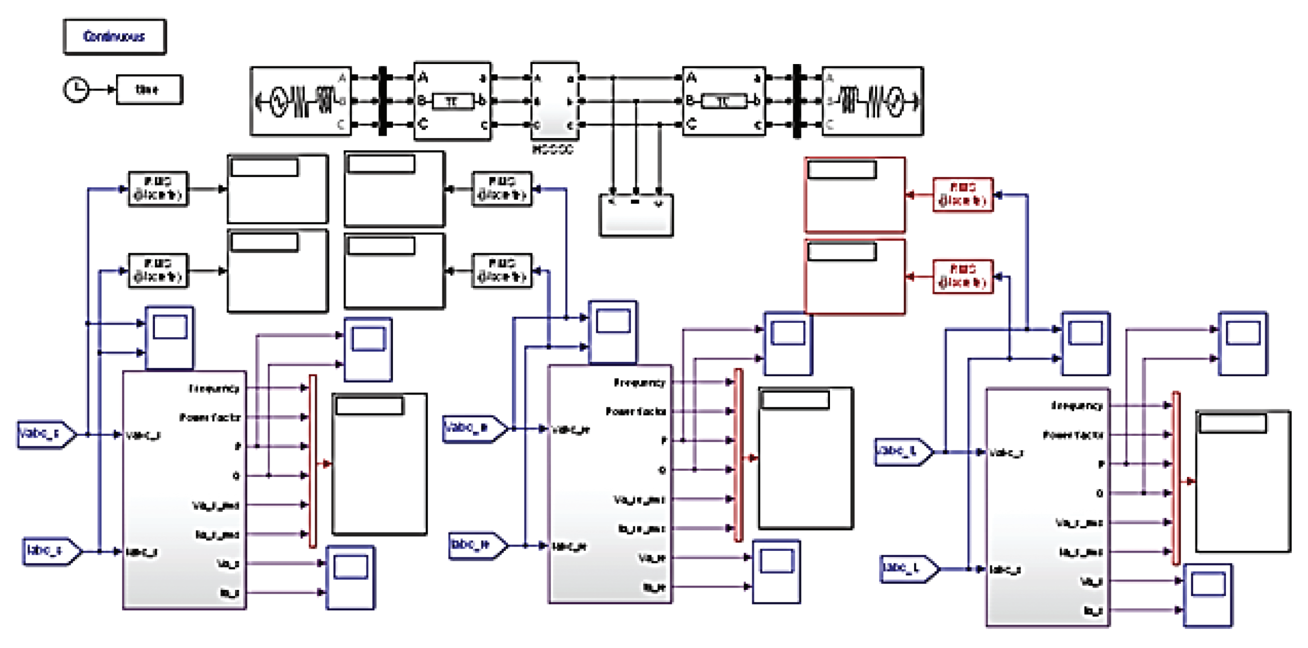

FIG. 10 SIMULATION MODEL

Hybird static synchronous series compensator consists of voltage source converter. Here VSC used is a neutral point clamped 3 level PWM converter. This topology is better suited for high power applications. NPC VSC converter has smaller DC capacitors lower switch blocking voltage and hence switching losses. For Direct control C_1=C_2=20 mF, Indirect control C_1=C_2=30 mF [14-15].

But the drawbacks with this topology are: requirement of large number of semiconductor switches. Fig. 2 shows the 3-phase 3 level NPC consists of twelve valves and two DC capacitors C_1 and C_2. Each valve consists of a switch with turnoff capability and an anti-parallel diode.

7.0 SIMULATION

To evaluate the performance of NPC VSC based HSSSC control in transmission line simulation is done by using MATLAB / SIMULINK^{TM}. The Radial system utilizes a small HSSSC, rated at base power.

6.6 kV and ±15 MVA, for injecting voltage into the system. Both direct and indirect controllers are used and compared in this section. The controllers compensate transmission line reactance in capacitive mode of operation. The following two tests were conducted to evaluate the performance of controllers and to investigate the system behavior. These tests are compared simultaneously for the direct and indirect type of controllers.

1. Impact of load variation on SSSC.
2. Step change in reference value of injected reactance.

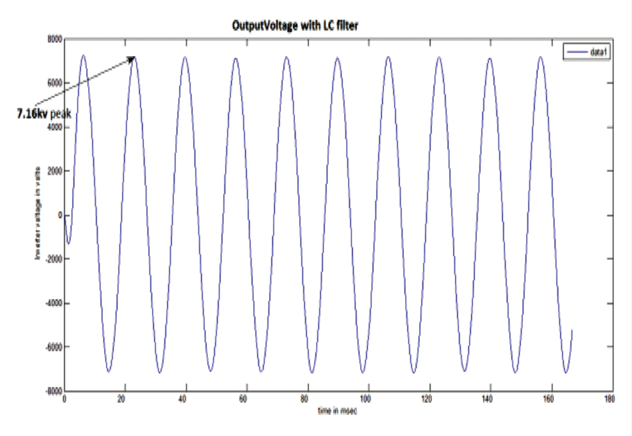

FIG. 11 NPC CONVERTER V_{AB} VOLTAGE WITH LC FILTER

A pure sinusoidal waveform of output voltages to inject to the transmission line with a LC filter is designed to eleminate 5th and 7th hormonics is shown in Figure 11.

The SSSC dynamic behavior is observed by adding a balanced load with active power P=0.4 pu and reactive power Q=0.25 pu, from 0.4 sec to 0.7 sec at the receiving end of transmission line. This test is applied on both the Direct and Indirect control and is used to investigate system behavior.

7.1 Impact of load variation on HSSSC

The dynamic behavior of the SSSC is verified by adding a balanced load with active power P=0.4 pu and reactive power Q=0.25 pu, from 400-700 ms at the receiving-end of the transmission line. For a SSSC with a direct (Figure 12) and an indirect controller (Figure 13), the following results are observed:

a. These signals show the injected reactance into the transmission line. A large change 0.4 pu in the load causes a small transient that is damped quickly within 100 ms and only the steady state injected reactance stays virtually constant.

b. These signals show the rms value of the injected voltages with the two controllers, and that the system takes about 80 ms for settling down with either controller.

c. These signals show the fluctuations of the rms value of the transmission line currents. Again very similar behavior is observed with both controllers.

d. These signals illustrate the phase angle between the injected voltage and transmission line current. The angle is about 83° with the direct controller and almost 90 with the indirect controller. At 400 ms, the phase angle transiently decreases and the VSC absorbs more active power from the transmission line.

e. These show the DC-side voltage of the VSC. When the load increases, the DC voltage rises to provide the required injected reactance with the Indirect controller. But with the direct controller, the DC voltage remains practically constant. This shows the effectiveness of the direct controller in comparison to the indirect controller.

7.1.1 Impact of load variation on HSSSC with Indirect control

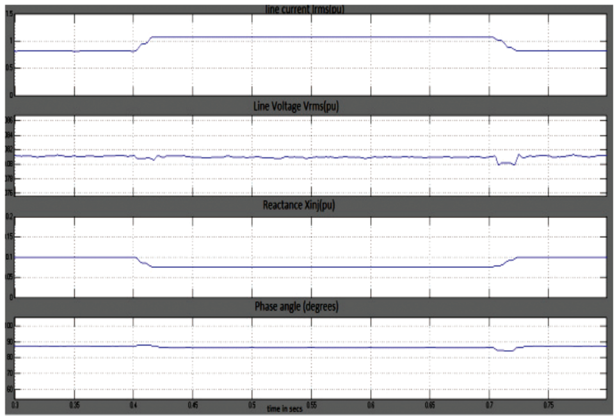

FIG. 12 A. LINE CURRENT I_{RMS} B. INJECTING VOLTAGE INTO TRANSMISSION LINE C. INJECTING REACTANCE X_{INJ} D. INJECTING VOLTAGE PHASE ANGLE Φ.

7.1.2 Impact of load variation on HSSSC with Direct control

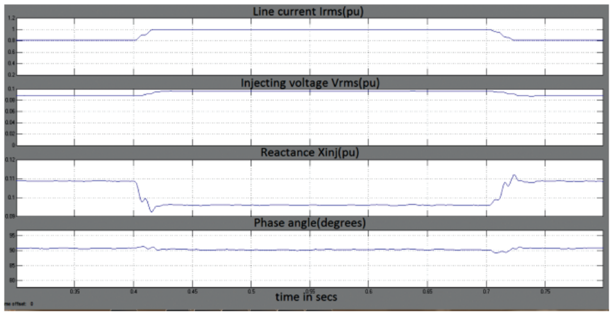

FIG.13 A. LINE CURRENT I_{RMS} B. INJECTING VOLTAGE V_{RMS} INTO TRANSMISSION LINE C. INJECTING REACTANCE X_{INJ} D. INJECTING VOLTAGE PHASE ANGLE Φ.

7.2 Step change in reference value of injected reactance

The dynamic behavior of the two controllers is investigated by applying a 10% step change in the reference value of the injected reactance from Figure 14 and 15 shows the comparative results of a SSSC with the Direct and Indirect controllers respectively:

a. These signals show the 10% reactance reference step decrease and the corresponding controller responses. The dynamic response is stable and it takes about 50 ms for the settling time for the two controllers, although the response with the indirect controller displays a transient overshoot.

b. These signals show the rms value of the injected voltage into the line during the step period and, therefore, the degree of compensation increases during this period.

c. These signals illustrate the rms value of the transmission line current. By decreasing the injected reactance at 400 ms, the line current effectively increases.

d. These signals show the phase angle between the injected voltage and the transmission line current. At 400 ms, when the reference reactance step is applied, the phase angle decreases to absorb active power to charge the DC-side capacitor. With the Direct controller, the system phase angle is slightly raised to maintain the DC voltage constant.

e. These signals demonstrate clearly the differences in the VSC DC-side voltages. With the Direct controller, this DC voltage remains effectively constant. However, with the indirect controller, the DC voltage rises to increase the magnitude of the injected voltage into the line.

7.2.1 Impact of change in reference value of injected reactance on HSSSC with Indirect control

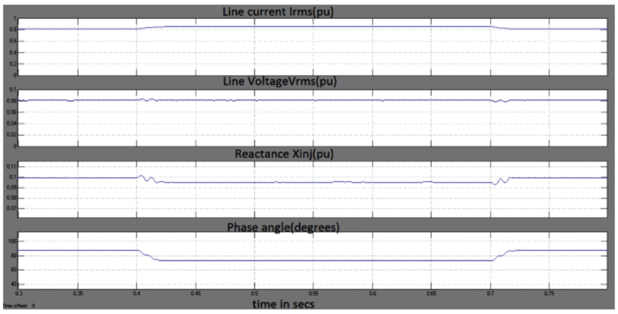

FIG. 14 A. LINE CURRENT IRMS B. INJECTING VOLTAGE V_{RMS} INTO TRANSMISSION LINE C. INJECTING REACTANCE X_{INJ} D. INJECTING VOLTAGE PHASE ANGLE Φ.

7.2.2 Impact of step change in reference injected reactance on HSSSC with direct control

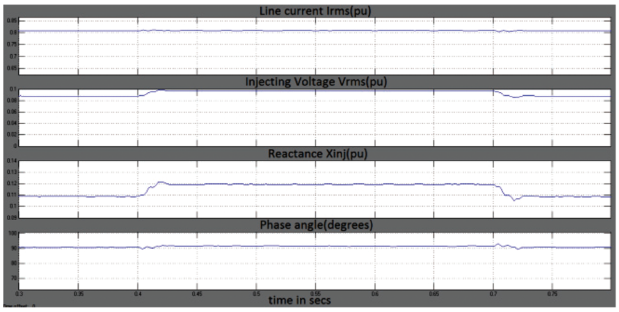

FIG. 15 A. LINE CURRENT I_{RMS} B. INJECTING VOLTAGE INTO TRANSMISSION LINE C. INJECTING REACTANCE X_{INJ} D. INJECTING VOLTAGE PHASE ANGLE Φ.

8.0 CONCLUSION

The paper presents a detailed model of a neutral point clamped voltage source converter based hybrid static synchronous series compensator by using the MATLAB/SIMULINK™ simulation package. The performance of HSSSC Simulink based model with two types of controllers, Indirect and direct type have been presented in this paper. The behavior with the two controllers has been compared. The HSSSC is designed to control the impedance characteristic of a transmission line. A 3-level NPC VSC has been used for converter as it is considered suitable for a high voltage application. The two tests were conducted to evaluate the performance of controllers one is Impact of load variation on HSSSC and another one the step change in reference value of injected reactance. Based on two tests the NPC VSC a based HSSSC system behavior was investigated. These tests are compared simultaneously for the Direct and Indirect type of controllers.

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