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Computer Simulation of Complex Power Systems

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ABSTRACT

Main contribution of this paper is to present the results of time domain computer simulation studies, which are needed to investigate the performance of a compensation scheme in damping power system oscillations in multi machine power systems. Hardware in loop simulations is very expensive and computer simulations are preferred for system evaluations. Using MATLAB simulation the performance of the scheme in damping oscillation for different faults and the line power flows are simulated. This shows that the single phase thyristor controlled series capacitor (TCSC) compensation scheme is quite effective for different load conditions.

Keywords: Generating stations, Thyristor controlled series capacitor, Transmission lines, MATLab simulation

1. INTRODUCTION

Any System means number of components or equipments connected in a sequence manner to perform a specific function. In electric power system, electrical components [1] are connected in a sequence from generating stations to distribution stations. An example of an electric power system is the network that supplies power to different consumers like big industry, domestic consumers, agriculture etc. Smaller power systems are also found in industry, hospitals, commercial buildings and homes. With power for sizeable regions, this power system is known as the grid and can be broadly divided into the generators that supply the power, the transmission system that carries the power from the generating centers to the load centers and the distribution system that feeds the power to nearby homes and industries. Basically these systems are 3ϕ AC power, the standard for large scale power transmission and distribution across the world. These power systems are not directly related to aircraft, electric rail systems, ocean liners and automobiles.

2. POWER SYSTEMS DESCRIPTION

The differential equations of the system components are derived by developing individually the mathematical models which represent the various components of the system, namely the synchronous generator, the excitation system, the transmission line and the system load. Fig.1 shows the single line diagram for power system modeling [2].

These electric power systems consist of three large generating stations (G_1, G_2 and G_3) supplying to two substations (S_1 and S_2) through five 400KV transmission lines. The two double circuit transmission lines L_1 and L_2 are series compensated with fixed capacitor banks located at the middle of the lines. The compensation degree of L_1 and L_2 is 50%. The compensation degree is defined as the ratio $\frac{X_c}{X_L}*100\%$ for

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fixed capacitor compensated phases and $\frac{X_{cc} + X_{TCSC}}{X_L} * 100\%$ for the single phase TCSC with fixed capacitor compensated phase[3].

Fig. 2 shows the block diagram of the synchronous machine in [4]. The stator circuit consists of a 3ϕ winding which produces a sinusoidal space distributed magneto motive force. The rotor of the machine

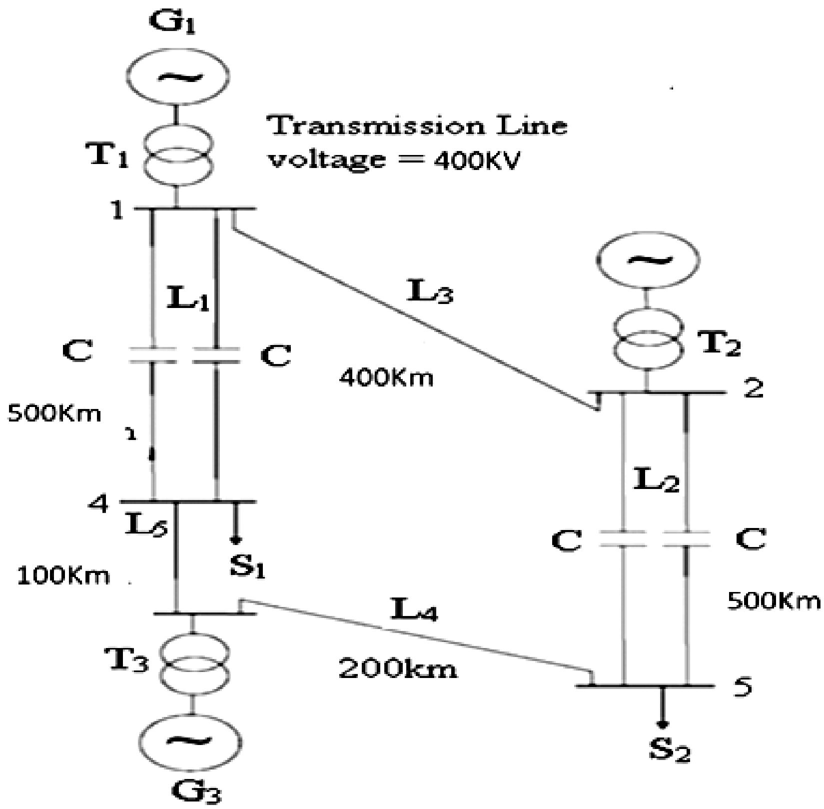


Figure 1: Single line diagram for power system modeling

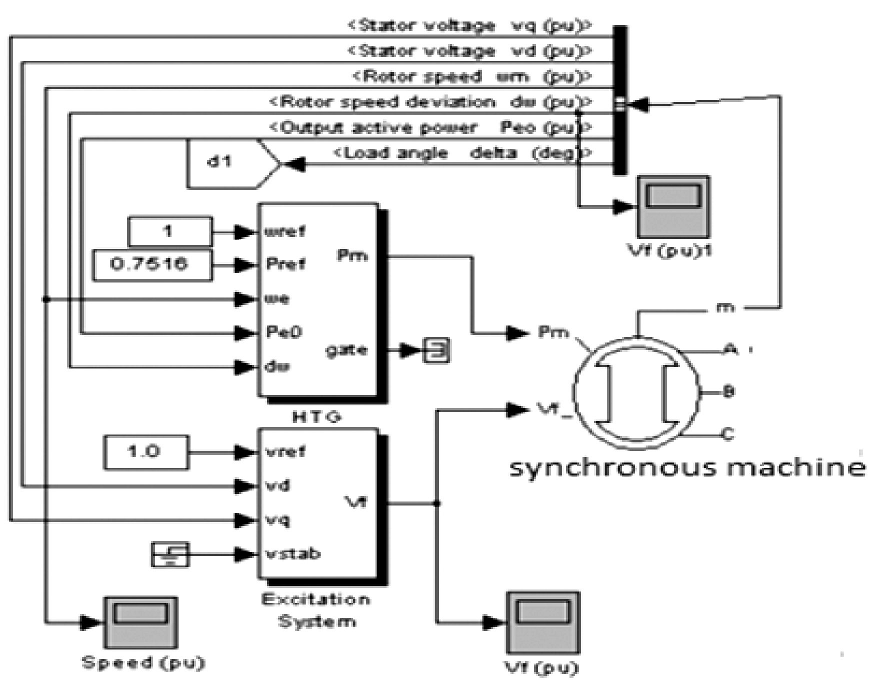


Figure 2: Block diagram of synchronous machine.

carries the field excitation winding which is excited by a DC voltage. The electrical damping is due to the eddy currents in the solid rotor. In other cases the damper winding is represented by three equivalent damper circuits one on the direct axis (d axis) and the other two on the quadrature axis (q axis). The performance of the synchronous machine can be described by the equations given below in the d-q reference frame. In these equations, the convention adopted for the signs of the voltages and currents are that V is the impressed voltage at the terminals and that the direction of positive current I corresponds to generation. The sign of the currents in the equivalent damper windings is taken positive when they flow in a direction similar to that of the positive field current. With time t expressed in seconds, the angular velocity ω expressed in radian/s and the other quantities expressed in per unit, the stationary part equations become

$$e_d = \frac{1}{\omega_0}\frac{d\psi_d}{dt} - \frac{\omega}{\omega_0}\psi_q - R_a i_d \tag{1}$$

$$e_d = \frac{1}{\omega_0}\frac{d\psi_q}{dt} + \frac{\omega}{\omega_0}\psi_d - R_a i_q \tag{2}$$

The rotating part equations become,

$$e_{fd} = \frac{1}{\omega_0}\frac{d\psi f_d}{dt} + R_{fd} i_{fd} \tag{3}$$

$$0 = \frac{1}{\omega_0}\frac{d\psi_{1d}}{dt} + R_{1d} i_{1d} \tag{4}$$

$$0 = \frac{1}{\omega_0}\frac{d\psi_{1q}}{dt} + R_{1q} i_{1q} \tag{5}$$

$$0 = \frac{1}{\omega_0}\frac{d\psi_{2q}}{dt} + R_{2q} i_{2q} \tag{6}$$

Stationary part flux linkage equations now become,

$$\psi_d = -L_a i_d + L_{ad} i_{fd} + L_{ad} i_{1d} \tag{7}$$

$$\psi_q = -L_q i_q + L_{aq} i_{1q} + L_{aq} i_{2q} \tag{8}$$

Physical System is,

The rotating flux linkage equations now become:

$$\psi_{fd} = L_{ffd} i_{fd} + L_{ad} i_{1d} - L_{ad} i_d \tag{9}$$

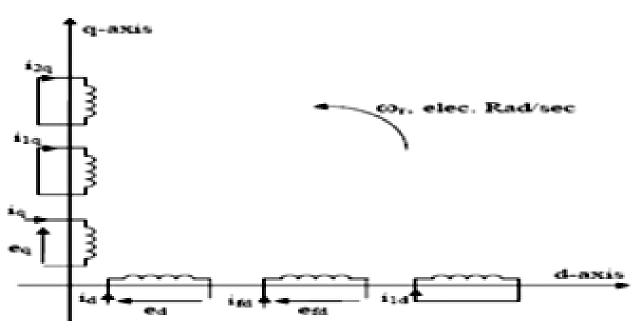


Figure 3: Physical Model of the synchronous machine (d-q axes)

$$\psi_{1d} = L_{ad} i_{fd} + L_{11} i_{1d} - L_{ad} i_d \tag{10}$$

$$\psi_{1q} = L_{11q} i_{1q} + L_{aq} i_{2q} - L_{aq} i_q \tag{11}$$

$$\psi_{2q} = L_{aq} i_{1q} + L_{22q} i_{2q} - L_{aq} i_q \tag{12}$$

The torque equation is given by

$$\tau_{ELEC} = \psi_d i_q - \psi_q i_d \tag{13}$$

The overall differential equations which describe the transient performance of the synchronous machine are given by the following matrix differential equations

$$\left[\frac{dX_{syn}}{dt}\right] = \left[At_{syn}\right]\left[X_{syn}\right] + \left[Bt_{syn}\right]\begin{bmatrix} V_{td} \\ V_{tq} \\ V_{fd} \end{bmatrix}$$

Where,

$$[X_{syn}] = [i_d\ i_q\ i_{fd}\ i_{1q}\ i_{1d}\ i_{2q}]^T \tag{14}$$

$$[\mathrm{A}t_{syn}] = L^{-1}\,[Qt] \tag{15}$$

$$[\mathrm{B}t_{syn}] = L^{-1}\,[Rt] \tag{16}$$

$$[L] = \begin{bmatrix} -L_d & 0 & L_{ad} & 0 & L_{ad} & 0 \\ 0 & -L_q & 0 & L_{aq} & 0 & L_{aq} \\ -L_{ad} & 0 & L_{ffd} & 0 & L_{ad} & 0 \\ 0 & -L_{aq} & 0 & L_{11q} & 0 & L_{aq} \\ -L_{aq} & 0 & L_{ad} & 0 & L_{11q} & 0 \\ 0 & -L_{aq} & 0 & L_{aq} & 0 & L_{22q} \end{bmatrix}$$

$$[Qt] = \begin{bmatrix} \omega_0 R_a & -\omega L_q & 0 & \omega L_{aq} & 0 & \omega L_{aq} \\ \omega L_d & \omega_0 R_a & -\omega L_{ad} & 0 & -\omega L_{ad} & 0 \\ 0 & 0 & -\omega_0 R_{fd} & 0 & 0 & 0 \\ 0 & 0 & 0 & -\omega_0 R_{1q} & 0 & 0 \\ 0 & 0 & 0 & 0 & -\omega_0 R_{1d} & 0 \\ 0 & 0 & 0 & 0 & 0 & -\omega_0 R_{2q} \end{bmatrix}$$

$$[Rt] = \begin{bmatrix} \omega_0 & 0 & 0 \\ 0 & \omega_0 & 0 \\ 0 & 0 & \omega_0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} 0$$

Where T represents the matrix transposes, the synchronous machine swing equation can be written as:

$$\frac{2H}{\omega_0}\frac{d\omega}{dt} = \tau_{MECH} - \tau_{ELEC} \qquad (17)$$

$$\frac{d\delta}{dt} = \omega - \omega_0 \qquad (18)$$

Where

ω – Represents the radians per second,

H – Represents the inertia constant is in joule/VA

δ – Represents the load angle in radians,

ω_o – Represents the synchronous frequency 377rad/sec, mechanical and electrical torques and are in per unit.

In developing the equations of multimachine systems, the equations of each synchronous machine expressed in its own d-q reference frame which rotates with its rotor must be expressed in a common reference frame. Usually, a reference frame rotating at synchronous speed is used as the common reference. Axis transformation equations are used to transform between the individual machine (d-q) reference frames and the common (R-I) reference frame [5].

2.1. High voltage transmission

High voltage transmission lines are used to transmit electric power over relatively long distances, from a generating station to load centers or substations. They are also used for electric power transmission from one substation to another for load sharing. Operating voltages of these lines are between 138KV to 765KV. Basically these lines are made up of either copper or Aluminum. One of the important factors in these lines is power loss; it is also called line loss or transmission loss. The voltage can be stepped up at the generating station, transmitted through the transmission grid to a load center, and there stepped down to the lower voltages required by distribution lines.

2.2. Thyristor controlled series capacitor

The main advantage of TCSC is to vary the degree of compensation k at mains frequency 50Hz with rapidity limited only by the speed of response of the electronic scheme used in the TCSC. This opens up for applications previously not encountered in conjunction with series compensation, such as post contingency power flow control and damping of active power oscillations, the TCSC concept is very useful as a tool for extending the possibilities for AC power interconnection between regions, both as far as amounts of power and geographical distances are concerned.

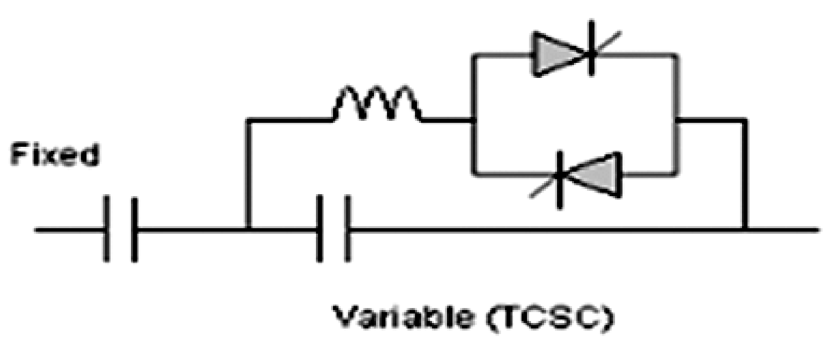


Figure 4: Sigle line diagram of TCSC

3. COMPUTER SIMULATION RESULTS

It is installed in all circuits of lines L_1 and L_2. Each TCSC provides 50% of the total capacitive compensation and the disturbance is a three cycles, 3ϕ fault at bus 4. Here four different combinations of stabilizing signals are examined in order to determine the combination that would result in the best system transient time responses. The final results of the time domain simulation studies from the generator load angles, measured with respect to G_1 load angle, during and after fault clearing are presented. The transfer functions of the TCSC supplemental controllers for the four combinations [6].

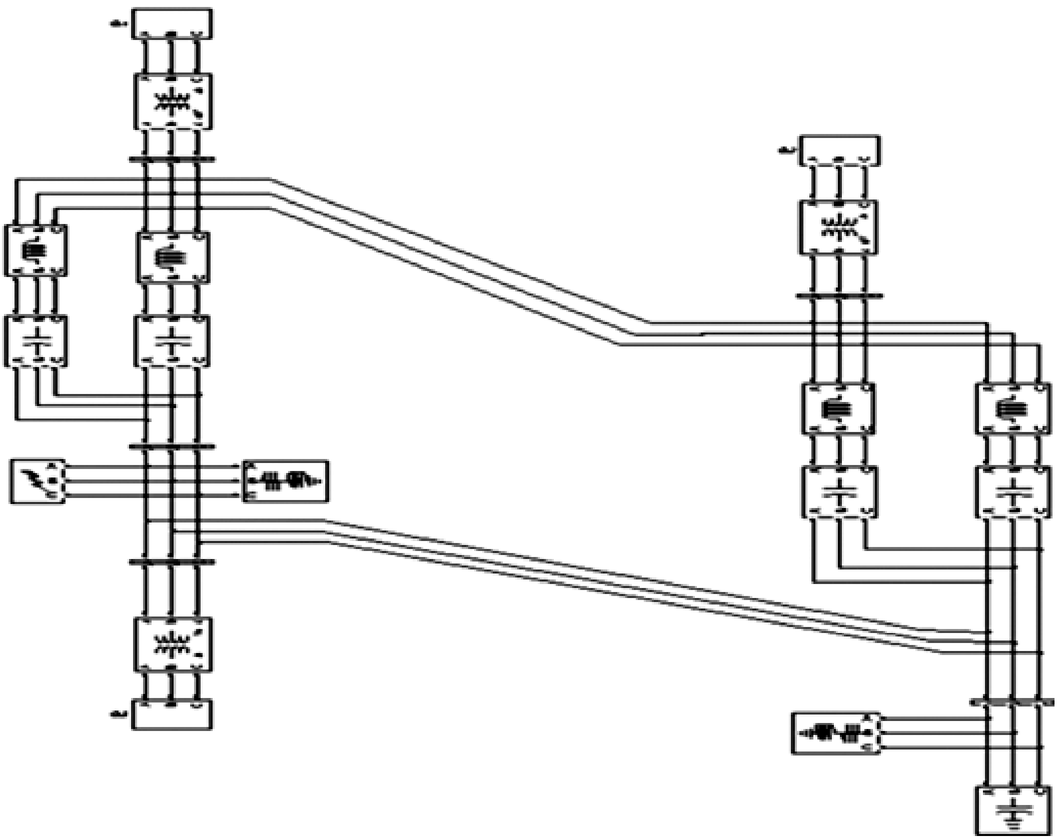


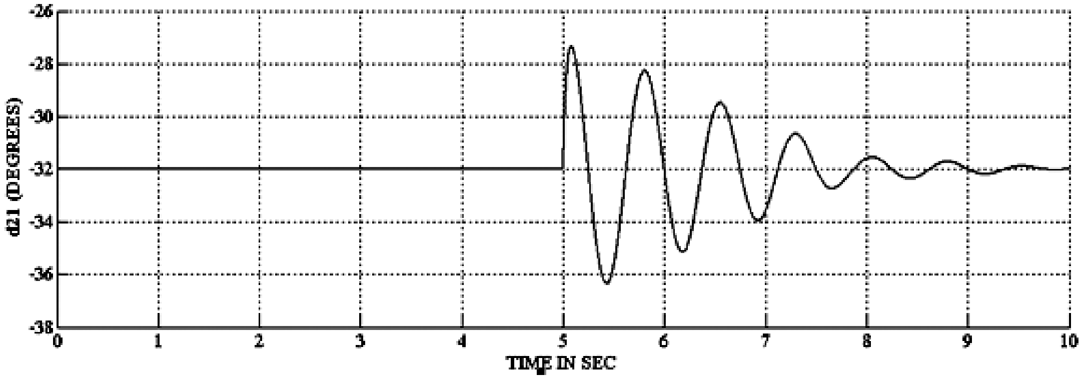
Figure 5: The simulation diagram for single phase TCSC compensation scheme

Table 1
The four examined combinations of stabilizing signals

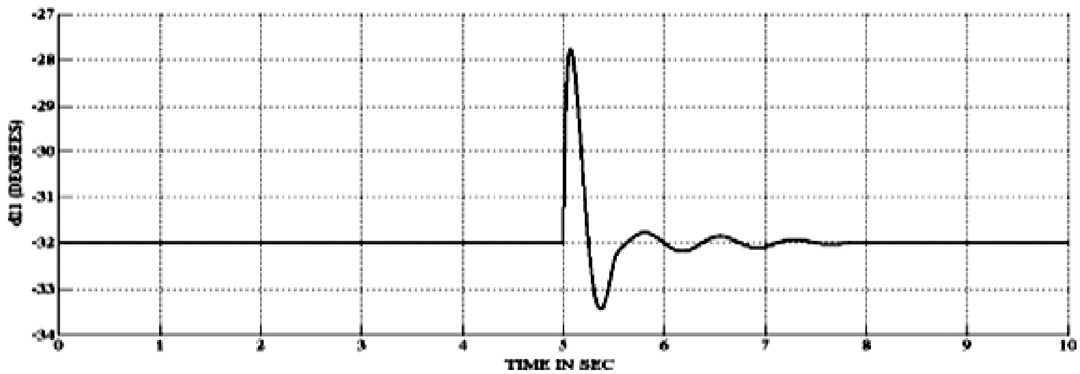
Combination	*TCSC in L_1*	*TCSC in L_2*
1	d_{21}	d_{21}
2	d_{31}	d_{21}
3	d_{31}	P_{L2}
4	P_{L1}	d_{21}

Transfer functions of the TCSC supplemental controllers for comparing the responses of the fixed series capacitor compensation to the single phase TCSC compensation scheme. The best damping of the relative load angle responses are achieved with the δ_{31}-δ_{21} combination. The second best damped responses are obtained with the $\delta_{31}\delta_{21}$ combination. These results should be expected due to the direct relationship between the relative load angles and the generators that yield the problem. The worst damped responses are obtained with $P_{L1}\delta_{21}$ combination which results also in the increase of the first swings [7]. The load angles of substations are given below:

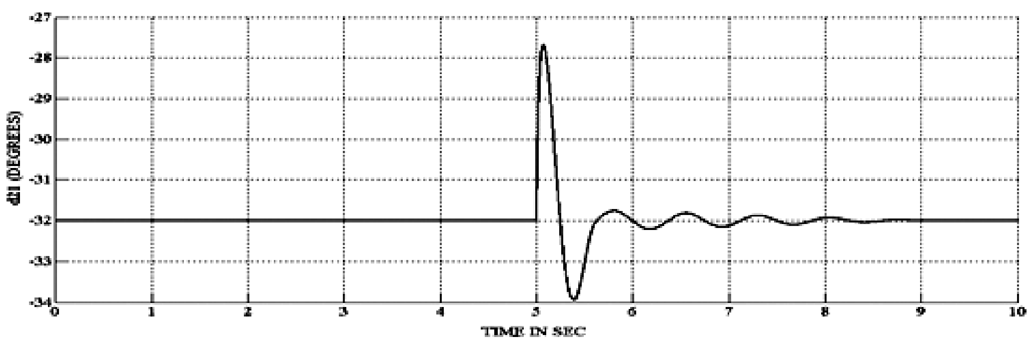
3.1. Substation S_1



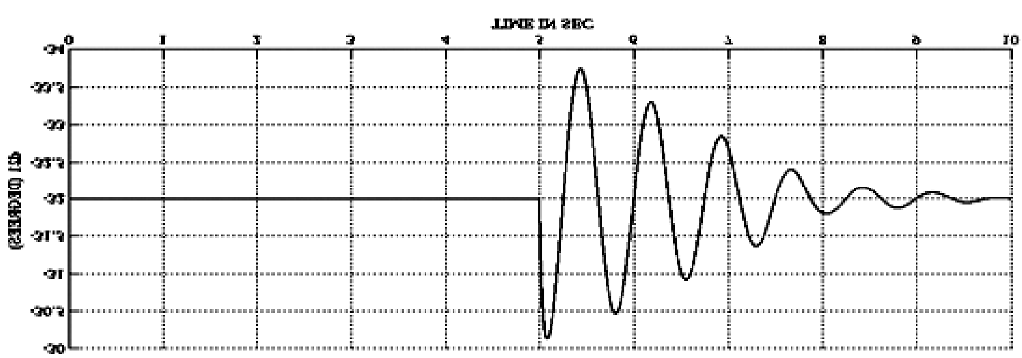
i. Using fixed series capacitor



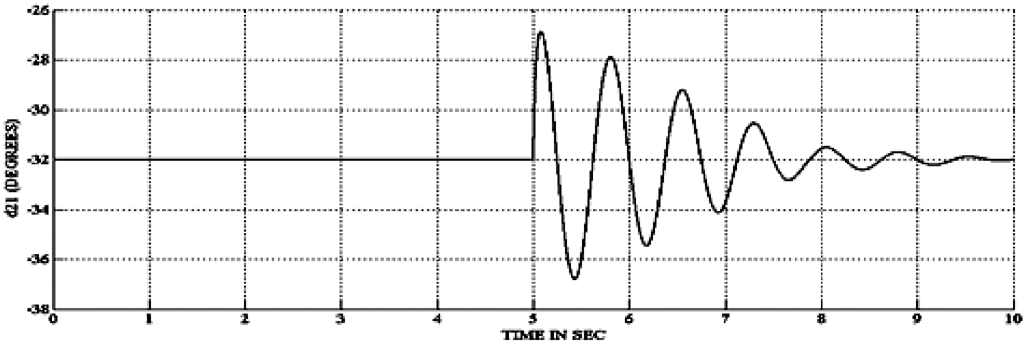
ii. Using single phase TCSC ($d_{21}d_{21}$ Controller)



iii. Using single phase TCSC ($d_{31}d_{21}$ Controller)

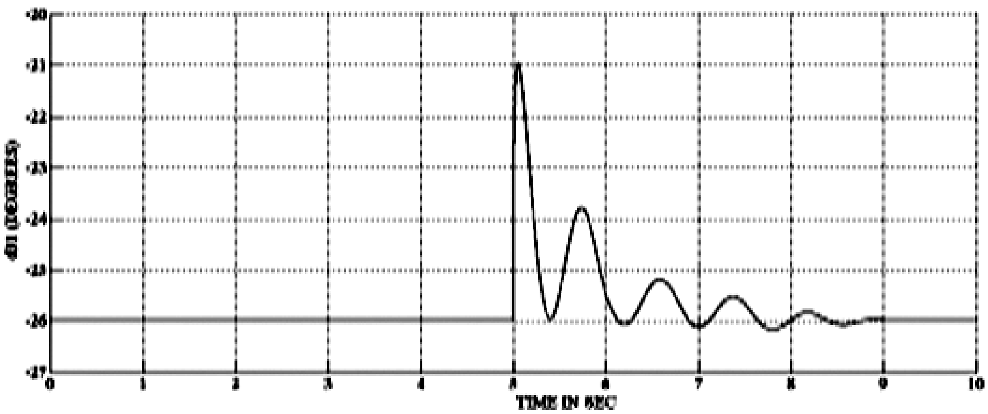


iv. Using single phase TCSC ($d_{31}P_{L2}$ Controller)

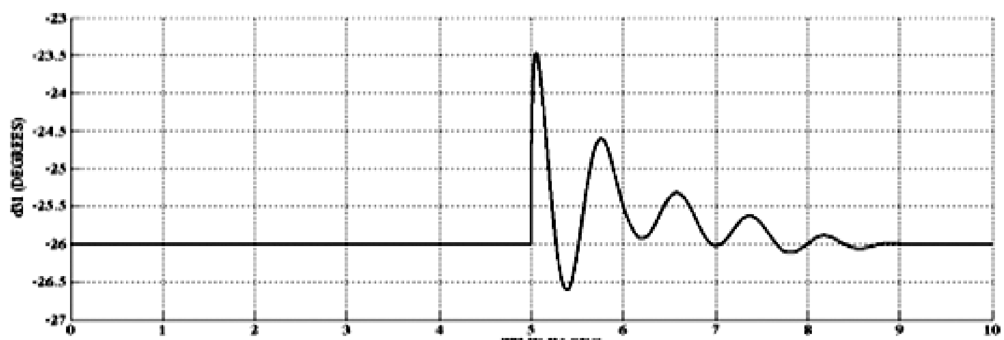


v. Using single phase TCSC ($P_{L1}d_{21}$ Controller)

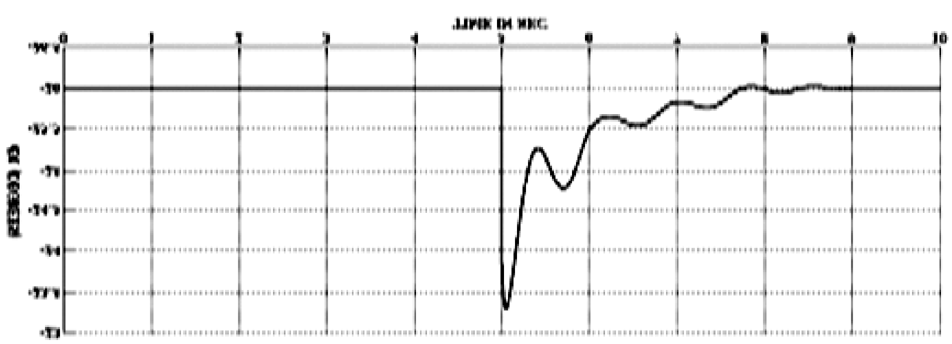
3.1.1. Load Angles



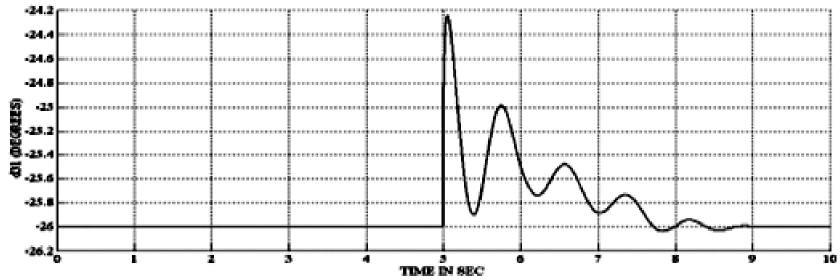
i. Using fixed series capacitor



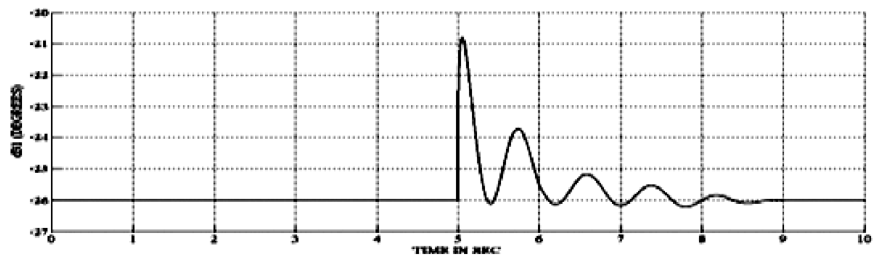
ii. Using single phase TCSC ($d_{21}d_{21}$ Controller)



iii. Using single phase TCSC ($d_{31}d_{21}$ Controller)



iv. Using single phase TCSC ($d_{31}P_{L2}$ Controller)



v. Using single phase TCSC ($P_{L1}d_{21}$ Controller)

Figure 6: Generator load angles, measured with respect to generator 1 load angle, during and after clearing a 3f fault at bus 4

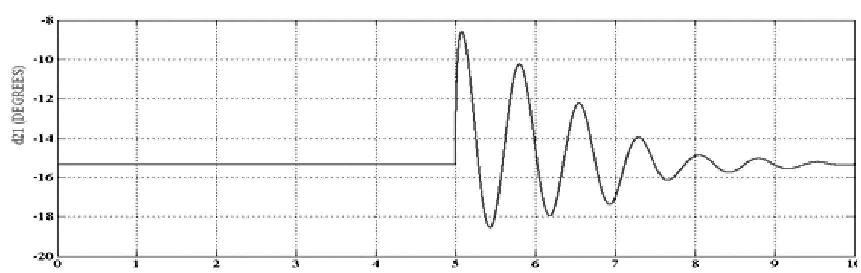
3.2. Substation S_2

Each TCSC provides 50% of the total capacitive compensation and the stabilizing signal is δ_{21}. Moreover, the disturbance is a three cycle, 3ϕ fault at bus 4. Load S_1 is increased by 600MW while load S_2 is reduced by the same amount. The comparison between this fig (i) and (ii) illustrates the generator load angles, measured with respect to generator 1 load angle, during and after fault clearing. The transfer functions of the TCSC supplemental controllers are given in Table 1. It can be seen from fig (ii), at this loading condition, the single phase TCSC scheme provides again a better damping performance to system oscillations compared to fixed capacitor compensation. It is observed, however, that there is a slight increase in the first swing of δ_{21} [8].

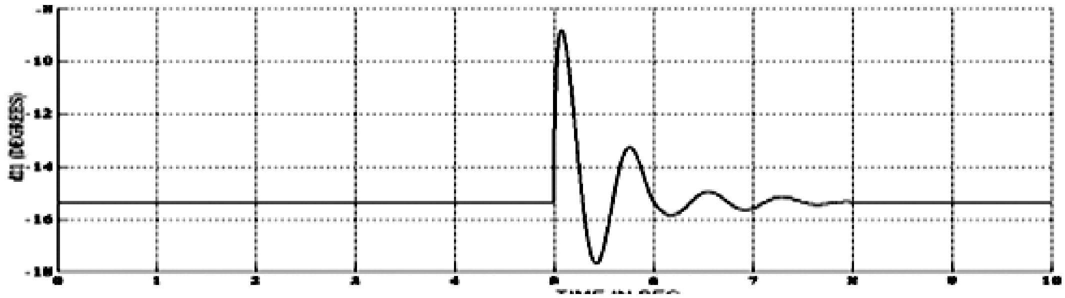
Table 2
Transfer functions of the TCSC supplemental controllers for substation 2

Each TCSC in L_1	$G(s) = 0.3\frac{10}{(s+100)}\frac{3s}{(3s+1)}$
Each TCSC in L_2	$G(s) = 0.15\frac{10}{(s+100)}\frac{3s}{(3s+1)}$

Output wave forms of S_2



i. Using fixed series capacitor



ii. Using single phase TCSC ($d_{21}d_{21}$ Controller)

3.3. Analysis of Results with Two Signals

Any of the four signals, δ_{21}, δ_{31}, P_{L1} and P_{L2} contains the system's two natural modes of oscillations and can be used to add damping to these modes as it has been demonstrated at substation I. The sum of two properly selected signals, however, should result in a more effective damping. The reason is that the two natural modes of oscillations are, in general, not in phase. A two channel controller would adjust separately the gain and phase of each mode of oscillations and, thus, provides a better damping [9]. In damping power system oscillations is examined using the six pairs of signals given in Table 3. Investigations are conducted on the test benchmark system at substation 2.

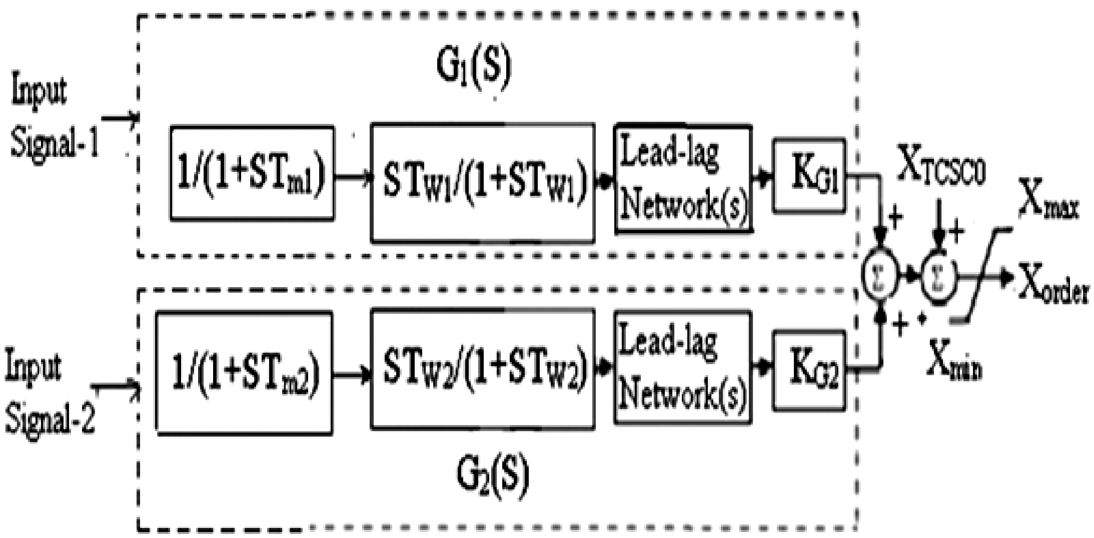


Figure 7: Structure of a two channel power oscillations damping controller

Table 3
The six examined combinations of stabilizing signals for two channel controller

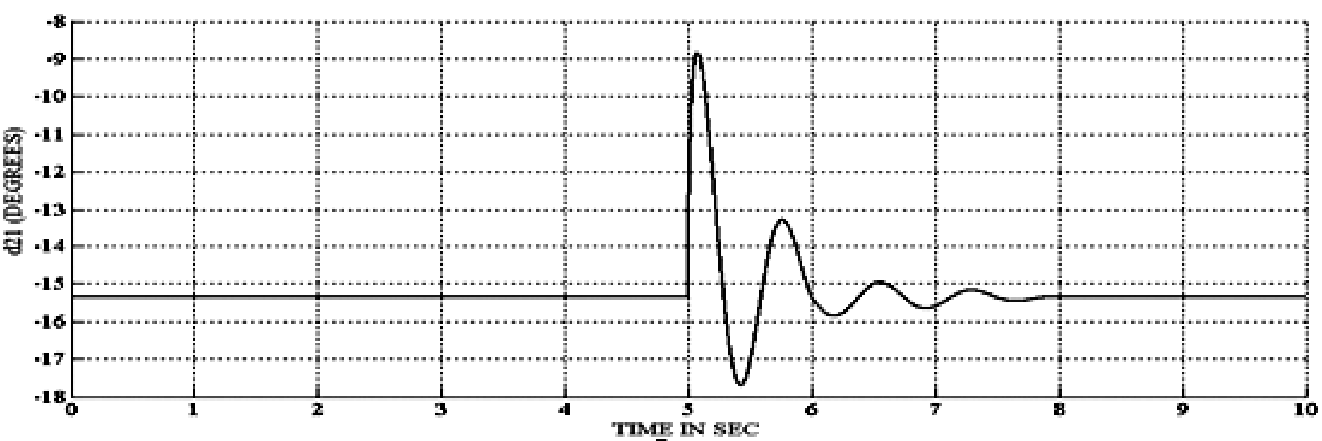
Pair number	*Each TCSC (input signal-1, input signal-2)*
1	δ_{21}, d_{31}
2	δ_{21}, P_{L1}
3	$\delta_{21,}$ P_{L2}
4	$\delta_{21,}$ P_{L1}
5	δ_{21}, P_{L1}
6	P_{L1}, P_{L2}

The final results of the time domain simulation studies (controllers tuning) show that the best and second best damped responses are obtained with pairs 2 and 5. The transfer functions of the TCSC supplemental controllers for the six pairs of signals are given in Table 3 the generator load angles, measured with respect to generator 1 load angle, during and after fault clearing. These results are compared to the single channel [10].

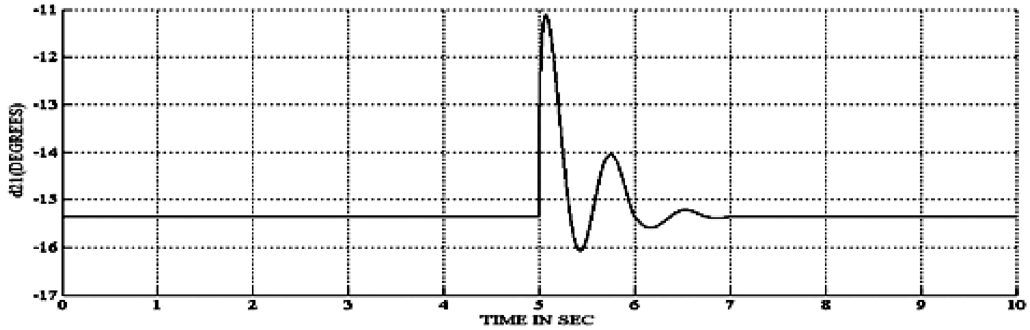
Table 4
Transfer functions of the TCSC supplemental controllers

Pair 2Each TCSC in L_1	$G_1(s)=0.25\frac{10}{(s+10)}\frac{0.5s}{(0.5s+1)}$
	$G_2(s)=0.5\frac{60}{(s+60)}\frac{0.01s}{(0.01s+1)}$
Pair 2Each TCSC in L_2	$G_1(s)=0.25\frac{10}{(s+10)}\frac{0.5s}{(0.5s+1)}$
	$G_2(s)=0.5\frac{60}{(s+60)}\frac{0.01s}{(0.01s+1)}$
Pair 5Each TCSC in L_1	$G_1(s)=-0.28\frac{10}{(s+10)}\frac{3s}{(3s+1)}$
	$G_2(s)=-0.25\frac{60}{(s+60)}\frac{0.01s}{(0.01s+1)}+\frac{(s+0.1)(s+0.5)}{(s+0.2)(s+3)}$
Pair 5Each TCSC in L_2	$G_1(s)=-0.26\frac{10}{(s+10)}\frac{s}{(s+1)}$
	$G_2(s)=2\frac{60}{(s+60)}\frac{0.01s}{(0.01s+1)}+\frac{(s+0.1)(s+0.5)}{(s+0.2)(s+3)}$

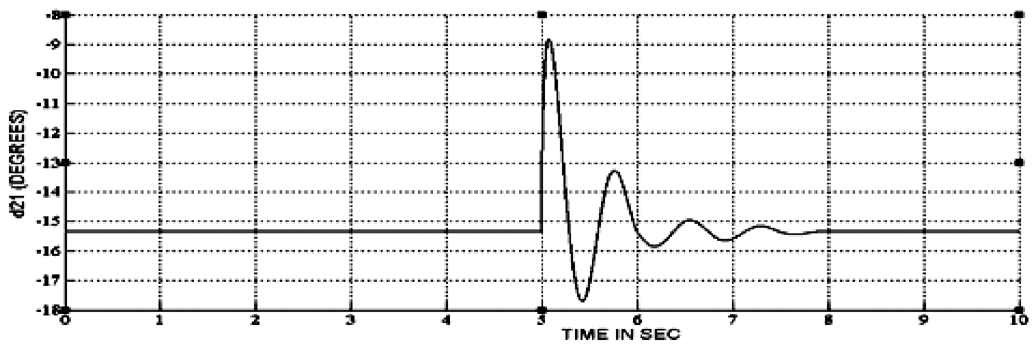
Output wave forms of two Chanal performance



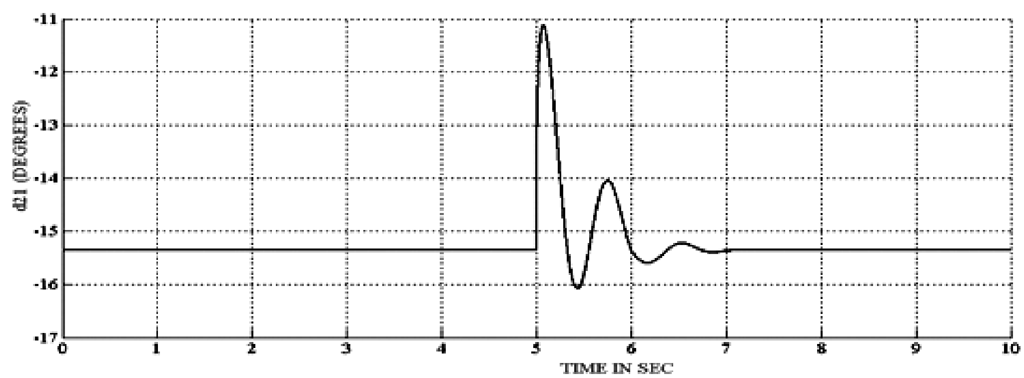
i. Using single phase TCSC (d_{21} for pair 2)



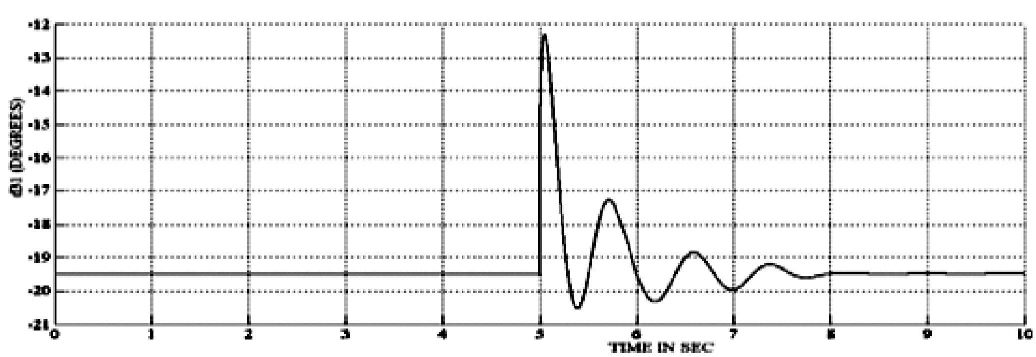
ii. Using single phase TCSC with two channel controller (d_{21} for pair 2)



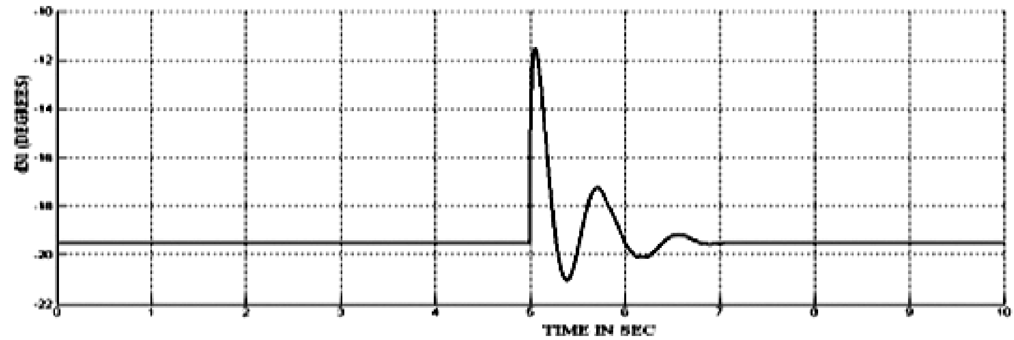
iii. Using single phase TCSC (d_{21} for pair 5)



iv. Using single phase TCSC with two channel controller (d_{21} for pair 5)



v. Using single phase TCSC (d_{31} for pair 5)



vi. Using single phase TCSC with two channel controller(d_{31} for pair 5)

Figure 8: Generator load angles, measured with respect to generator 1 load angle, during and after clearing a 3ϕ fault at bus4 (two channel controller)[11]

4. CONCLUSIONS

Computer simulation is found to be very effective in studying the system behavior for different parametric conditions. The following are very obvious conclusions one could draw from the simulations. A two channel TCSC supplemental controller is more effective in damping power system oscillations than a single channel controller. In this regard, the best two signals are found out to be the deviation of generator 2 load angles, with respect to generator 1 load angle and the real power flow in line L_1. The reduction of the generator first swings depends on the proportion of the single phase TCSC compensation scheme to the total fixed capacitor compensation in the system. It is observed, however, that in one case there is a slight increase in the first swing of one generator. It should be emphasized here that the main task of the supplemental controller of the single phase TCSC compensation scheme is to damp power system oscillations in the already stable system under study which has come out of computer simulation.

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