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Presenter

4th International Power Engineering and Optimization Conference (PEOCO), 23-24 June 2010

Effect of TCSC Parameters and Control Structure on Damping of Sub-Synchronous Resonance

Assoc. Prof. Dr. Ismail Musirin
Chair, PEOCO 2010

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Effects of TCSC Parameters and Control Structure on Damping of Sub-Synchronous Resonance

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Abstract— **Series compensation of transmission lines using fixed series capacitors can cause sub-synchronous resonance (SSR) between electrical and mechanical systems. This phenomenon leads to severe damages to turbine generator shafts. Thyristor controlled series compensator (TCSC) is one of the FACTS devices which can be utilized to damp electromechanical and sub-synchronous oscillations. This device can perform flexible series compensation and SSR damping. The effect of different parameters of the TCSC is studied using complex torque coefficient method. Open loop and closed-loop constant current and constant power control methods are simulated using PSCAD/EMTDC software package. First IEEE benchmark model for sub-synchronous resonance studies and a complete model of TCSC is used to analyze the effect of different parameters and control structure on the SSR damping capability of the TCSC.**

Index Terms— **Series compensation, sub-synchronous resonance, SSR, thyristor controlled series capacitor, thyristor controlled series compensator, TCSC, damping torque coefficient.**

I. Introduction

Compensation of transmission lines using series capacitor has many advantages for power system such as enhancing transient stability limits, increasing power capacity and etc [1]. However, sub-synchronous resonance (SSR), which can lead to significant mechanical damages, has been observed when compensation degree of lines is high [2]. Performing series compensation by Thyristor Controlled Series Compensator (TCSC) can reduce the risk of SSR. Generally, TCSC can be used for controlling power follow, damping of Power Swing (PS) and SSR [3]. However, utilization of power electronic switches in TCSC structure causes nonlinear behavior of this device and analysis difficulties.

Several methods have been suggested to analyze the possibility of occurrence and effects of SSR phenomena in power systems. Frequency sweep method presents the electrical system equivalent impedance from generator neutral point as a function of frequency. The impedance of the overall system is the series combination of electrical and mechanical impedance of generator. Positive and negative equivalent impedance means positive and negative damping [4].

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978-1-4244-7126-3/10/$26.00 2010 IEEE.

Singular values of linearized system shows the effect of compensation degree and system configuration on damping of resonance modes. However, this method has limiting assumptions and can not be used to analyze large signal perturbations and nonlinear characteristics of the system components [4].

Time domain simulation methods can be used to fully analyze effects of nonlinear devices such as TCSC on SSR. Complex torque method is a time domain procedure for computing electrical and mechanical damping of a power system [5]. In this method, TCSC power and control structures can be modelled in detail using modelling softwares. So, no simplification is necessary and all nonlinear features of the system under study can be analyzed. However, long simulation time is a disadvantage of this method [6].

In this parer the effects of structural parameters of TCSC and its synchronization block on damping of SSR is studied using complex torque coefficient method. Generator speed modulation method is utilized to find damping coefficient of the electrical system at frequencies between 5 and 55 Hz [7]. A detailed model of the TCSC with no simplification is considered and using PSCAD/EMTDC, first IEEE benchmark system for SSR studies is simulated.

Section II presents a mathematical model of TCSC and defines parameters which their variations are under study. In Section III the concept of complex torque method is introduced and damping torque coefficient is defined. In Section IV a power system with two buses based on first IEEE benchmark system for SSR studies is presented to perform simulations. Section V consist simulation results as well as their analyzes. Finally Section VI concludes the discussions.

II. TCSC Model

As shown in Fig. 1, TCSC is made of a fixed capacitor and a thyristor controlled reactor (TCR). The operation of TCSC depends on impedance of capacitor bank ($X_C = -1/(\omega_n C)$) and TCR branch ($X_V = \omega_n L_e$). Where ω_n is system angular frequency and L_e is effective inductance of TCR. The resonance frequency of TCSC (ω_R) can be calculated as:

$$\omega_R = \frac{1}{\sqrt{LC}} = \omega_n \sqrt{\frac{-X_C}{X_V}} \tag{1}$$

The ratio of TCSC resonance frequency and system angular frequency is defined by λ:

$$\lambda = \frac{\omega_R}{\omega_n} = \sqrt{\frac{-X_C}{X_V}} \tag{2}$$

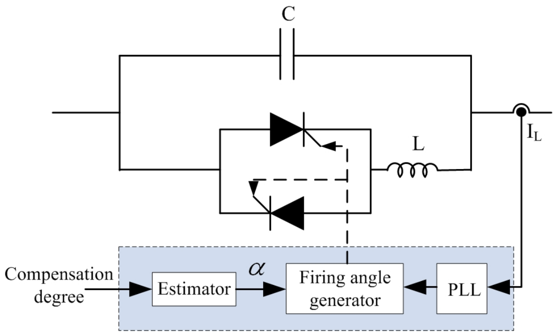

Fig. 1. Configuration of TCSC with open loop control method

Considering f_n as system nominal frequency, thus:

$$\omega_n = 2\pi f_n \tag{3}$$

Apparent impedance of TCSC is defined as follows

$$X_{app} = Z_{TCSC} = Im\{\frac{V_{C1}}{I_{L1}}\} \tag{4}$$

where V_{C1} and I_{L1} are fundamental frequency components of capacitor voltage and line current. Generally, TCSC has four operational modes, in each mode it has different behavior. The boost factor of TCSC (K_b) can be defined as follow:

$$K_b = \frac{X_{app}}{X_C} \tag{5}$$

Considering these definitions, operational modes can be presented as:

- Blocking mode: When the thyristor valves are not triggered and the thyristors are kept in non-conducting state the TCSC is operating in blocking mode. The line current passes only through the capacitor bank ($K_b = 1$).
- Bypass mode: If the thyristor valves are triggered continuously the valves stay conducting all the time and the TCSC behaves like a parallel connection of the series capacitor bank with the inductor of the thyristor valves ($K_b = -1/(\lambda^2 - 1)$).
- Capacitive boost mode: If a trigger is supplied to the thyristor having forward voltage just before the capacitor voltage crosses the zero line, a capacitor discharge current pulse will circulate thorough the parallel inductive branch. The discharge current pulse adds to the line current through the capacitor bank. It causes a capacitor voltage that adds to the voltage caused by the line current.
- Inductive boost mode: In this condition the circulating current in the thyristor branch is bigger than the line current.

Generally, TCSC operates in capacitive boost mode to compensate line inductivity, so that increases power transfer capability.

III. Complex Torque Method

Torque variation of a synchronous generator in response to small rotor perturbations is defined as ΔT_e [5],

$$\Delta T_e = [u_{fo} - (x_d - x_q(p))i_{do}]\Delta i_q + (x_d - x_q(p))i_{qo}\Delta i_d \tag{6}$$

where u_{fo} is nominal excitation voltage, x_d and x_q are generator reactance on d and q axises, i_{do} and i_{qo} are steady state line currents in dq reference frame. Finally Δi_d and Δi_q are their variations around nominal value. When the rotor oscillation frequency is γf_n the p operator can be replaced by $p = j\gamma$. Supposing $\underline{\varepsilon}$ as phasor representation of rotor speed, $\Delta\underline{T}_e$ can be rewritten

$$\Delta\underline{T}_e = k_e(j\gamma)\underline{\varepsilon} \qquad \Delta T_e = Re[\Delta\underline{T}_e] \tag{7}$$

where

$$k_e(j\gamma) = \frac{\Delta\underline{T}_e}{\underline{\varepsilon}} = K_e + j\gamma D_e \tag{8}$$

The term $k_e(j\gamma)$ is "complex torque coefficient". If there is no series capacitor, $k_e(j\gamma)$ is called "complex synchronizing coefficient". The real part (K_e) of $k_e(j\gamma)$ is electrical spring constant and the imaginary part after dividing by γ , D_e, is the electrical damping constant. Values of K_e and D_e are depend on power system configuration, operating point, excitation system control method and the number of parallel generators.

Considering a single transmission line and an n-mass shaft, eigenvalues of the system can be expressed as,

$$p_i = -\frac{1}{\tau_i} \pm j\gamma_i \tag{9}$$

A negative time constant , τ_i, can cause oscillations with the frequency $\gamma_i f_n$. If all of the time constants are positive, interactions will not be amplified.

To simplify this method for large systems, mechanical complex torque coefficients are defined as follow:

$$k_m(j\gamma) = K_m + j\gamma D_m \tag{10}$$

where K_m and D_m are mechanical spring and damping constants. These coefficients depend on shaft dynamics. Considering frequency response of mechanical and electrical system as:

$$[k_e(j\gamma) + k_m(j\gamma)] = 0 \tag{11}$$

This equation can be used for analyzing oscillations of interaction phenomenon. Substituting Equations (8) and (10) in (11):

$$K_e + K_m + j\gamma(D_m + D_e) = 0 \tag{12}$$

When there is no damping in the system , $D_e + D_m = 0$, following constraint must be satisfied for shaft oscillation frequencies:

$$K_e + K_m = 0 \tag{13}$$

The frequencies which excite (13) are candidate for resonance between electrical and mechanical systems. If the total damping of the system is negative in mentioned frequencies, an interaction will occur, ie.,

$$K_e + K_m \cong 0 \qquad D_e + D_m < 0 \tag{14}$$

By analyzing all possible frequencies, D_e and D_m can answer to all questions about possibility of torsional interaction [4].

In this paper generator speed modulation method is used to calculate D_e [7]. Generator speed oscillations due to external disturbances are observable in electrical torque ,T_e. Damping coefficient can be shown as:

$$D_e = Re\left\{\frac{\Delta T_e}{\Delta \omega_n}\right\} = \frac{|\Delta T_e|}{|\Delta \omega_n|} cos(\angle \Delta T_e - \angle \Delta \omega_n) \quad (15)$$

Negative damping coefficient shows insufficient electrical damping. In this method electrical and mechanical sub-systems can be analyzed independently, so the generator's rotor can be considered as a single mass during calculation of electrical damping [8].

IV. Benchmark System

A modified version of first IEEE benchmark model for SSR studies (Fig. 2) is used to study the effects of TCSC on damping of power system sub-synchronous oscillations [9]. In this circuit FSC is a fixed series capacitor, R_L and X_L are line resistance and reactance, X_R and X_{inf} are transformer and infinite bus reactance. Benchmark system parameters are presented in Table I. The TCSC is implemented by thyristor switches. When open loop control system is utilized, active power exchange between generator and infinite bus is set to zero by proper choice of voltage angles [6].

This system has unstable torsional modes that can be excited depending on the degree of series compensation. Table II shows resonance frequencies and the capacitance of the fixed series capacitor (X_{FSC}) that causes the oscillations. Complex torque method is used to calculate electrical damping coefficients of the system in these frequencies to analyze SSR possibility. Mechanical damping coefficients can be calculated using an eigenvalue program. Table III. shows the system eigenvalues and the resonance frequencies. The overall system has four unstable torsional modes. If unstable sub-synchronous electrical and mechanical modes meet, a torsional interaction occurs between two systems. Eigenvalues No. 9 and 10 related to torsional mode 1 show a negative damping. This means that the system encounter growing oscillations at 15.71 Hz [10].

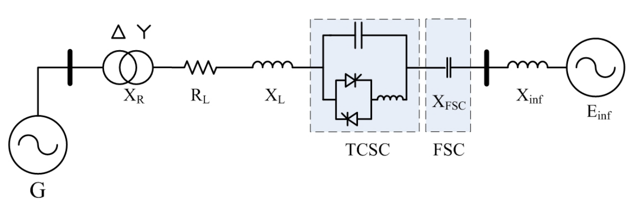

Fig. 2. First IEEE benchmark model for SSR studies.

TABLE I
Benchmark system parameters

Parameter	Value
Generator rating	892.4 MVA
Generator voltage	15 kV (V_{L-L})
System frequency	60 Hz
Transformer voltages	26/539 kV
X_R	0.14 p.u.
X_L	0.50 p.u.
R_L	0.02 p.u.
X_{inf}	0.06 p.u.

V. Simulation Results

The PSCAD/EMTDC software is used to analyze the TCSC damping effects on the benchmark system. Supposing 30%, 50% and 65% degree of compensation, capacitance of the TCSC is calculated.

A. Open loop control case

A-1) Effect of boost factor (K_b): To examine the effect of boost factor on sub-synchronous resonance damping, K_b is altered between 1.1 and 2. The degree of compensation is 35% and TCSC inductance is calculated considering $\lambda = 2.5$.

Fig. 3 depicts damping torque coefficient variations in respect to K_b. The system resonance frequencies are indicated by vertical lines on 15.71, 20.21, 25.55 and 32.28 Hz. The electrical damping has a large negative value around 32.28 Hz when fixed capacitor is used to compensate the line, so SSR occurrence is possible. Using TCSC has considerably increased D_e around 32.28 Hz however, damping is reduced at lower frequencies.

As shown in Fig. 3, increasing K_b decreases the damping at frequencies below 10 Hz but increases it at higher frequencies. So higher degree of compensation leads to higher possibility of SSR at lower frequencies.

Using FSC to perform a part of compensation can reduce the total cost. Considering overall degree of compensation to be 70%, the effect of K_b on electrical damping of the system is depicted in Fig. 4. Raising of K_b increases damping at higher frequencies and diminishes it at lower frequencies.

A-2) Effect of λ on sub-synchronous damping: Damping coefficient for λ =2, 3 and K_b =1.1, 1.2 is shown in Fig. 5. Compensation degree is 35%. In each step desired value of K_b is gained by changing firing angle of TCSC. Greater λ increases damping at higher frequencies and reduces it at

TABLE II
Mechanical resonance modes

Mode	Frequency (Hz)	X_{FSC} (p.u.)
Torsional 1	15.71	0.472
Torsional 2	20.21	0.378
Torsional 3	25.55	0.285
Torsional 4	32.28	0.184

TABLE III
Eigenvalues of first IEEE benchmark for SSR studies tuned to torsional mode No. 1.

Eigenvalues				Damping Factor	Oscillation Frequency (Hz)
No.	Mode	Real	Imaginary		
1,2	Torsional 5	0	±298.17	0	47.4563
3,4	Torsional 4	-0.0026	±202.8207	0	32.2799
5,6	Torsional 3	-0.0026	±160.4460	0	25.5358
7,8	Torsional 2	-0.0001	±126.9205	0	20.2
9,10	Torsional 1	5.0553	±99.1944	-0.0509	15.7873
11,12	Electromechanical	-0.8344	±229657	0.0696	1.9044
13,14	Electrical	-4.7442	±654.6670	0.0072	104.1953
15,16	Electrical	-6.9730	±99.2611	0.0701	15.7979
17	Rotor Circuit	-33.4513	0	1	0
18	Rotor Circuit	-20.5376	0	1	0
19	Rotor Circuit	-4.4269	0	1	0
20	Rotor Circuit	-0.3972	0	1	0

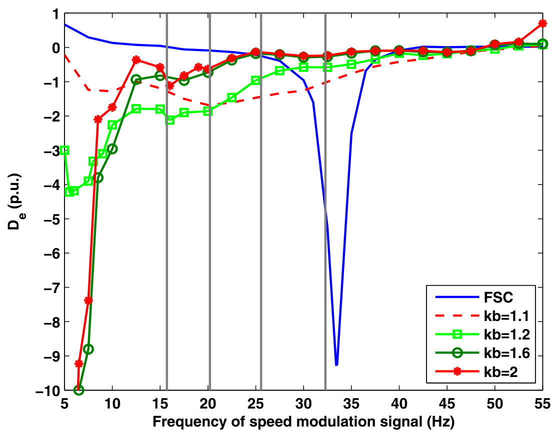

Fig. 3. Effect of boost factor on the damping torque coefficient (degree of compensation: 35%).

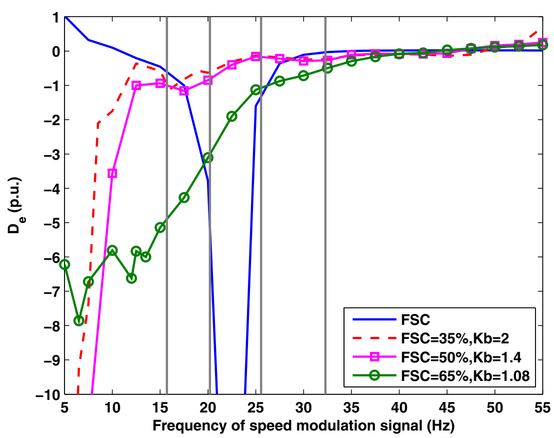

Fig. 4. Effect of boost factor on the damping torque coefficient in the existence of FSC (degree of compensation: 70%).

frequencies below 15 Hz.

A-3) Effect of TCSC to FSC rating ratio on sub-synchronous damping: To reduce the total cost of compensation, TCSC and FSC is used together [11]. The effect of TCSC to FSC rating ratio on sub-synchronous resonance damping is shown in Fig. 6. The TCSC parameters are K_b=1.2 and λ=2.5 and total compensation degree is 50%. Larger values of boost factor amplifies TCSC harmonic generation, hence K_b has not increased more than 1.2. Fig. 6 shows two phenomenon. First, a TCSC with even a small share of total compensation (i.e. 10%) can improve electrical damping considerably. Greater rating of TCSC to fixed capacitor leads to growth of damping. Second, as the rating of TCSC increase, resonance frequencies move toward higher frequencies. Considering these results a logical suggestion for TCSC to total compensation rating is 50%.

A-4) Effect of PLL parameters on sub-synchronous damping: A Phase Locked Loop (PLL) synchronizes TCSC and power system. Sub-synchronous oscillations produce low frequency currents which flow in the transmission lines. Distorted

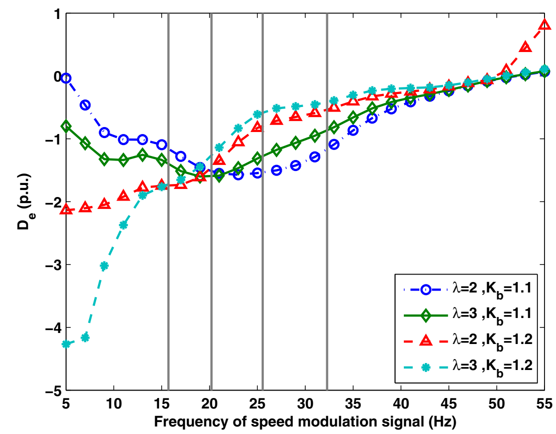

Fig. 5. Variations of D_e due to changing of K_b and λ.

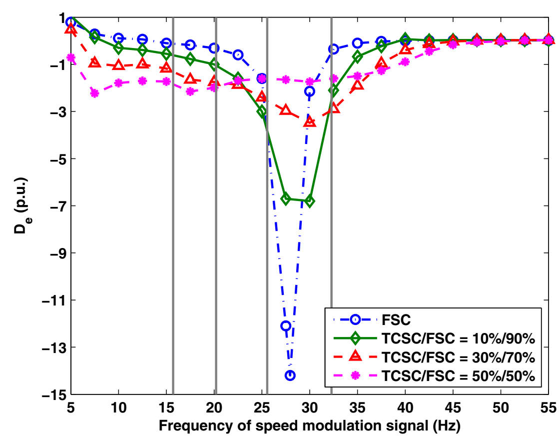

Fig. 6. Damping torque coefficient for simultaneous utilization of TCSC and FSC (K_b=1.2).

current shape leads to difficulties in PLL operation. PLL structure consist of: 1) phase comparator, 2) low pass filter and 3) voltage controlled oscillator. The low pass filter is implemented by a PI controller with two parameters, ie. K_p and K_I,

$$G(s)_{LPF} = K_p \frac{s + \frac{K_I}{K_p}}{s} \tag{16}$$

Effect of filter bandwidth on resonance damping is studied by changing K_I. It can be seen in Fig. 7 that increasing K_I (larger bandwidth) diminishes damping in frequencies below 10 Hz. On the other hand, reducing the bandwidth increases PLL response time. This causes greater stress on TCSC during system faults due to over currents. Increasing filter gain by considering greater value for K_p has reduced damping. In this case, higher frequency disturbances have greater effect on the system. When TCSC and FSC are used together, the parameters of the PLL can change damping of the system as can be seen in Fig. 8. In this case, 30% of total compensation is done by TCSC. Considering K_I =10, 100 and 1000, the bandwidth has altered. Damping at low frequencies is reduced due to larger bandwidth. The system response does not show significant changes at higher frequencies. Increasing filter gain

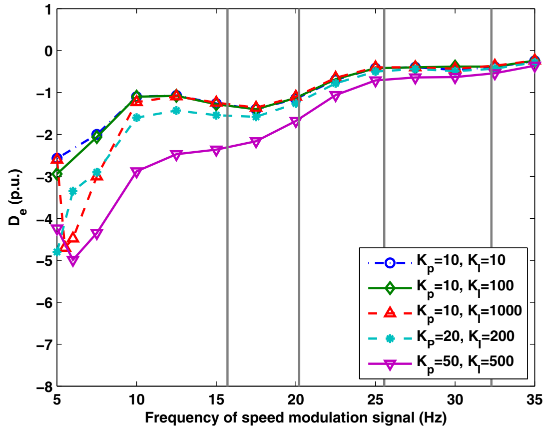

Fig. 7. Effect of PLL parameters on damping torque coefficient (TCSC).

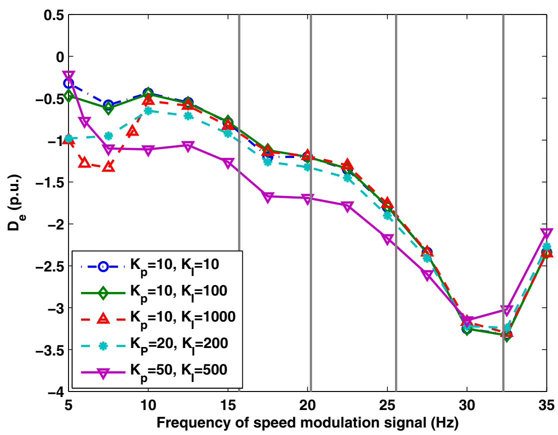

Fig. 8. Effect of PLL parameters on damping torque coefficient (TCSC + FSC).

reduces damping at frequencies above 7.5 Hz but increases it at lower frequencies. In all cases the damping has a big negative value around 32.28 Hz that is one of the mechanical resonance frequencies and SSR occurrence is possible in this frequency.

B. Constant current control case

In this section the constant current (CC) control method as shown in Fig. 9 is used to generate TCSC firing angle. The difference between line and reference current is fed into a PI controller. The output of the controller is reference impedance of TCSC. The reference impedance defines firing angle using a linearization block. TCSC capacitance is set to perform 50% compensation degree and λ is supposed 2.5.

B-1) Effect of reference current on sub-synchronous damping: Effect of reference current variations on damping torque coefficient is shown in Fig. 10. The damping is significantly dropped below zero at 27.5 Hz when reference current is 1.1 p.u., in spite of positive damping for other frequencies. For other reference values there is SSR possibility at 30 Hz where the damping coefficient is negative. As a general result, altering TCSC reference current can cause SSR

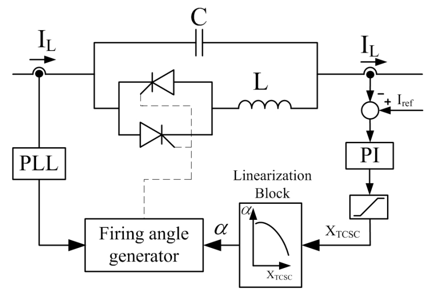

Fig. 9. TCSC constant current control structure.

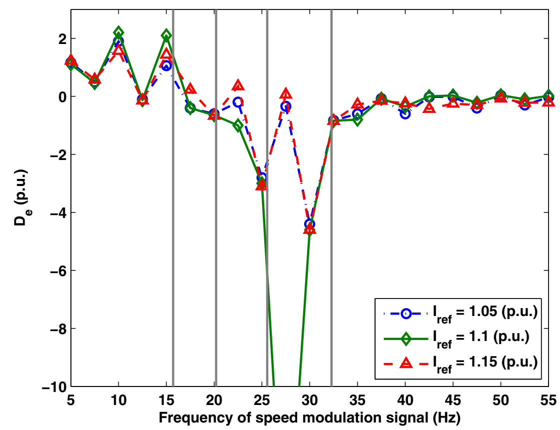

Fig. 10. Effect of reference current of constant current method on electrical damping.

at frequencies below 30 Hz depending on the system situation.

B-2) Effect of PI controller on sub-synchronous damping: As shown in Fig. 9 a PI controller is utilized in constant current control loop. Fig. 11 depicts damping variations in respect to controller parameters, supposing 1.1 p.u. for reference current. Considering the controller transfer function (16), the bode diagram of the controller is depicted in Fig. 12. Altering controller gain in higher frequencies by changing K_P can change damping between 25 and 30 Hz. By reducing the gain, damping is increased. But a low gain can not guarantee proper operation as shown for $K_p = 20$ and $K_I = 1000$. By reducing the controller gain the system response time will decrease and reference current tracking will diminish. So, there is a trade off between response time and SSR damping property of TCSC.

C. Constant power control case

A close loop constat power control structure is simulated as shown in Fig. 13. In this section the effect of reference power (P_{ref}), PI controller parameters (K_P, K_I) and power controller time constant (T_P) on damping coefficient is analyzed.

C-1) Effect of reference power on sub-synchronous damping: Reference power has significant effects on damping coefficient as shown in Fig. 14. For $P_{ref} = 1.05$ p.u. the damping is negative between 17.5 and 30 Hz and positive for higher frequencies. Increasing reference power to 1.1 and

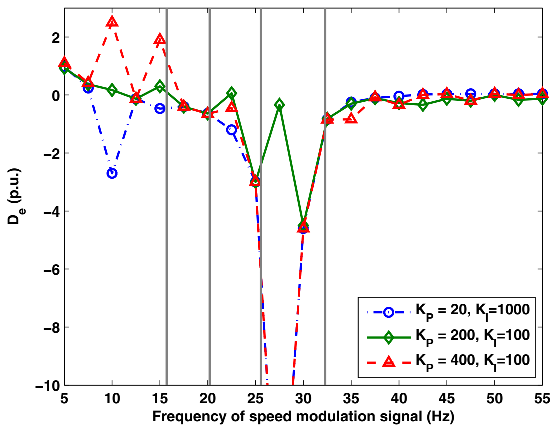

Fig. 11. Effect of constant current method PI controller parameters on damping.

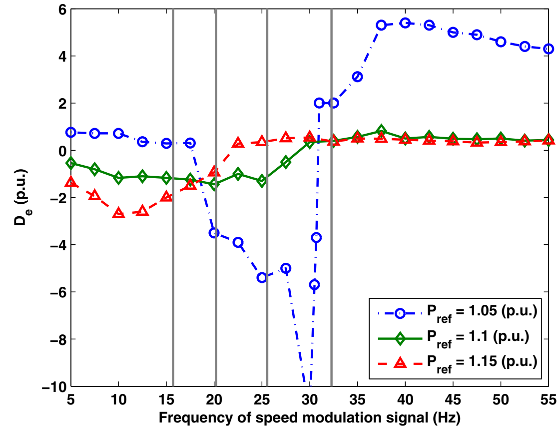

Fig. 14. Variation of damping coefficient in respect to reference power.

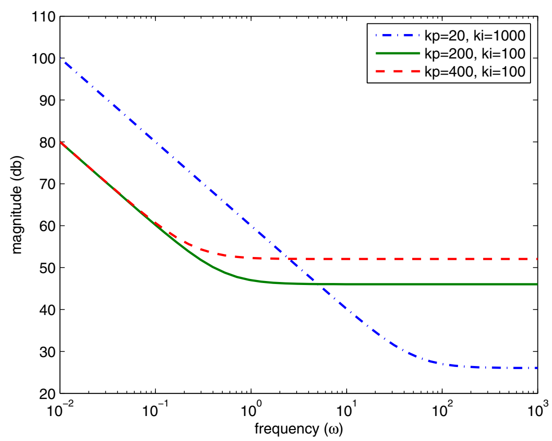

Fig. 12. PI controller bode diagram.

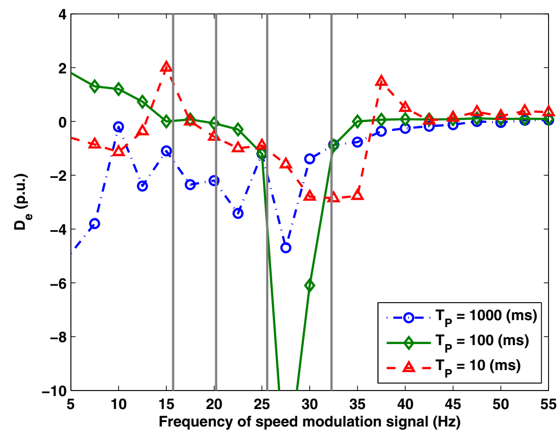

Fig. 15. Effect of power controller time constant on damping.

1.15 p.u. diminishes damping variations and leads to negative damping at frequencies below 20 Hz. For $P_{ref} = 1.15$ p.u. damping at lower frequencies is reduced compared to 1.1 p.u. So increasing the reference power decreases damping torque coefficient at frequencies below 15 Hz.

C-2) Effect of power controller time constant on sub-synchronous damping: Power controller is a simple low pass filter and increasing T_P decreases the bandwidth. Supposing $P_{ref} = 1.1$ p.u., Fig. 15 shows that improper choice of the filer bandwidth can cause large negative damping at [25-30] Hz frequency range. Two phenomenon is visible in Fig. 15, the damping is negative in lower frequencies for narrower bandwidth and a large bandwidth increases overall damping. However, there is a trade off between increasing damping and the system sensitivity to current noises, caused by supposing larger bandwidth.

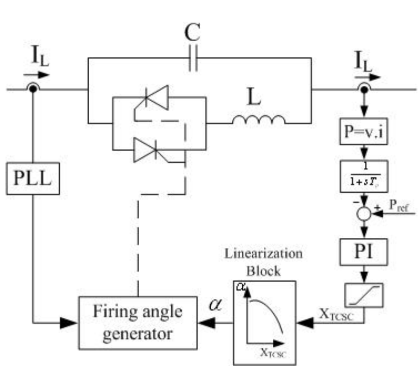

Fig. 13. TCSC constant power control structure.

C-3) Effect of PI controller parameters on sub-synchronous damping: Fig. 16 shows the effect of altering PI controller coefficients on the damping when P_{ref} is supposed 1.1 p.u. Increasing K_I causes negative damping at [25-30] Hz frequency range similar to constant current structure. Considering tracking error caused by lower values of K_I, a proper choice must be made to satisfy the SSR damping and reference power tracking of TCSC.

VI. Conclusion

In this paper effect of different parameters and control methods of TCSC on sub-synchronous resonance damping has been studied. Compared to fixed series capacitor, using TCSC reduces SSR possibility at [15-45] Hz frequency range. However, TCSC diminishes damping at frequencies below 5 Hz. Increasing boost factor K_b and λ can lead to less damping at low frequencies. When TCSC and FSC are used simultaneously to compensate a transmission line, larger share of TCSC in compensation causes better damping. Utilization

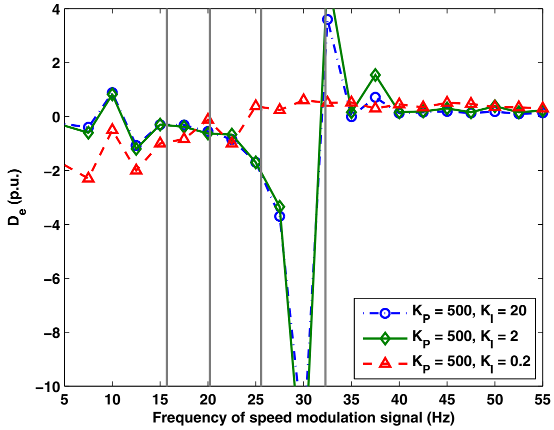

Fig. 16. Effect of PI controller parameters on damping coefficient (constant power case).

of faster PLL structures reduce damping torque coefficient at frequencies around 5 Hz and increases system sensibility to distortions.

When close loop control structures are utilized for TCSC, enough attention must be paid to selection of controller parameters. In both constant current and constant power methods, PI controller parameters have considerable effects on TCSC damping behavior. Decreasing system response time by choosing higher bandwidth for controllers can cause large negative damping at central frequencies ([15-30] Hz). On the other hand, higher bandwidth is essential to satisfy tracking characteristic. So, there is a trade off between SSR damping and reference signal tracking behavior of TCSC.

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