Performance Evaluation of Thyristor Controlled Series Capacitor Based Controller for Power System Damping

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***Abstract*— Power system damping through coordinated design of a power system stabilizer (PSS) and a thyristor controlled series capacitor (TCSC) –based controller is present in this paper. The design problem of the coordinated PSS and TCSC based controller is formulated as an optimization problem and optimization based linear control design technique isemployed to search for optimal controller parameters. The performance of different optimization techniques is compared in terms of finding quickly and enhance the stability by reducing the settling time. Optimization based tuning only changes the value of the controller parameters and not the controller structure itself. The coordinated design is tested in a single machine infinite bus system and the results are compared with conventional PSS and individually tuned PSS and TCSC. The time domain analysis and simulation results are presented to show the effectiveness of proposed technique in designing in a coordinated controller**

Keywords*— Power system stabilizer; FACTS devices; TCSC; Power oscillation damping.

I. INTRODUCTION

The development in the power electronics field introduced use of flexible ac transmission systems (FACTS) controller in power systems. FACTS controllers are used to control the network condition at a super lightening speed and this characteristic of FACTS is enhanced to improve the stability in entire power system. Thyristor restricted succession compensator is one of the essential members of FACTS family that has been exponentially come out with long transmission lines by the utility modules in today's power systems [1]. TCSC perform various roles in the operation and control of modern power systems, such as rescheduling of power flow, reducing unsymmetrical components, decreasing total power loss, providing voltage stability, limiting short-circuit currents, reduce sub-synchronous resonance (SSR), control damping the power oscillation and improve transient stability. The TCSC is an alternative to SSSC above and like an SSSC, it is a very important FACTS Controller [2]. It has been in use for many years to increase line power transfer as well as to enhance system stability. TCSC is a series FACTS device which allows rapid and continuous changes of the transmission line impedance.

The development in the power electronics field introduced use of flexible ac transmission systems (FACTS) controller in power systems. Some small signal stability studies the linear model of Phillips-Heffron is used a power system. In spite being of a linear model, it is quite accurate for the study of low frequency oscillations and stability of power systems [3]. The procedure of FACTS controller parameter tuning has always been a complex exercise. A number of techniques have been reported till now pertaining to design problems of conventional power system stabilizers namely: the Eigen value assignment, mathematical programming, gradient procedure for optimization and also the modern control theory. Unfortunately, these techniques are time consuming as they are performed by the iterative method and require heavy computation burden and slow convergence.

II. SMIB with TCSC Controller

The Single Machine Finite State system can qualitatively demonstrate the significant properties in the behavior of a multi-machine system and is convincingly simple to examine [4]. Henceforth it is conventionally accepted for describing the universal concepts of power system stability, influence of arbitrary factors upon stability and alternative concepts of controllers. We consider particular SMIB power system arrangement as portrayed in

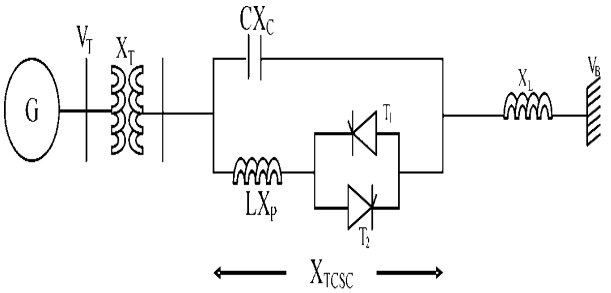

Fig.1: One Machine to Infinite Bus System

Figure (1) shows the basic diagram of TCSC controller encloses a series capacitor depository, shoved with a Thyristor Controlled Reactor (TCR) which provide variable series capacitive reactance. When the TCR firing angle is 180 degrees, the reactor becomes non conducting and the series capacitor has its normal impedance [5]. As the firing angle is advanced from 180 degrees to less than 180 degrees, the capacitive impedance increases. At the other end, when the TCR firing angle is 90 degrees, the reactor becomes fully conducting, and the total impedance becomes inductive, because the reactor impedance is designed to be much lower than the series capacitor impedance [6]. With 90 degrees firing angle, the TCSC helps in limiting fault current. The use of thyristor control to provide variable series compensation makes it attractive to employ series capacitors in long lines. A major advantage is that the SSR problem (Torsional Interaction) is significantly reduced [7]. The feasibility of fast control of thyristor valves enables the improvement of stability and damping of oscillations using appropriate control strategies. The steady-state impedance of the TCSC is that of a parallel LC circuit, consisting of a fixed capacitive reactance Xc, and a variable inductive reactance, $X_{L(\alpha)}$ that is

$$X_{tcsc(\alpha)} = \frac{X_c X_{L(\alpha)}}{X_{L(\alpha)} - X_c}$$

$X_L = \omega_L$, and α is the delay angle measured from the crest of the capacitor voltage (or, equivalently, the zero crossing of the line current) [8]. The steady state relationship between α and Xtcsc can be represented by the equations below:

$$X_{tcsc(\alpha)} = X_c - \frac{X_c^2}{(X_c - X_L)}\frac{\sigma + \sin\sigma}{\pi} + \frac{4X_c^2}{(X_c - X_L)} + \frac{\cos^2(\sigma/2)}{k^2 - 1}\frac{\left\{ k\tan\left(\frac{k\sigma}{2}\right) - \tan(\sigma/2) \right\}}{\pi}$$

Where

Xc = nominal impedance of fixed capacitor

XL= impedance of inductor connected in parallel of capacitor

α = firing angle

$$k = \sqrt{\frac{X_c}{X_L}} \qquad \beta = \pi - \alpha$$

Since the relationship between α and the equivalent fundamental frequency reactance offered by TCSC, X_{TCSC} (α) is a unique-valued function, the modeling of TCSC is performed here with a variable capacitive reactance within the operating region defined by the limits imposed by α. Thus X_{TCSC} min ≤ X_{TCSC} ≤ X_{TCSC} max, with X_{TCSC} max = X_{TCSC} (α_{min}) and X_{TCSC} min = X_{TCSC}(1800) = X_C. In this segment, the controller is assumed to operate only in the capacitive region, i.e., $\alpha_{min} > \alpha_r$ where α_r corresponds to the resonant point, as the inductive region of system is associated with $90^0 < \alpha < \alpha_r$ induces high harmonics that cannot be properly modelled in stability studies

$$Z_{eq} = \left(\frac{1}{\omega C}\right) \square (j\omega L) = -\mathrm{j}\frac{1}{\omega C - \frac{1}{\omega L}}$$

Overall effect of TCSC capacitive, when

$$\omega C - (1/\omega L) > 0$$

Resonance condition will occurs, when

$$\omega C - 1/\omega L = 0$$

Overall effect of TCSC inductive, when

$$\omega C - (1/\omega L) < 0$$

The steady-state model of the TCSC described below is based on the characteristics of the TCR established in an SVC environment as shown in figure (2), where the TCR is supplied from a constant voltage source.

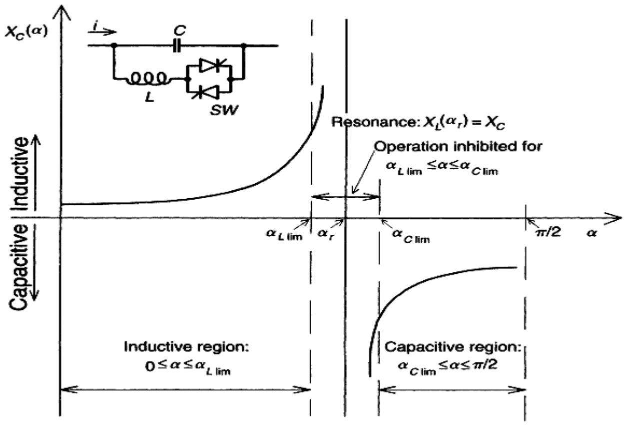

Fig. 2: The impedance vs. delay angles α characteristic of the TCSC.

This model is useful to attain a basic understanding of the functional behavior of the TCSC. However, in the TCSC scheme the TCR is connected in shunt with a capacitor, instead of a fixed voltage source. The dynamic interaction between the capacitor and reactor changes the operating voltage from that of the basic sine wave established by the constant line current [9]. A deeper insight into this interaction is essential to the understanding of the actual physical operation and dynamic behavior of the TCSC, particularly regarding its impedance characteristic at subsynchronous frequencies

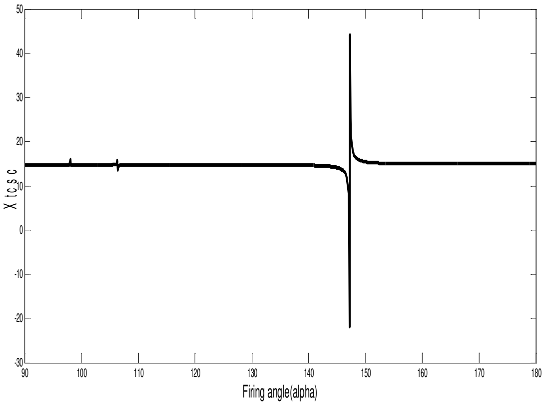

Fig. 3: Xtcsc Vs α for k=2

III. Power system modeling with TCSC

Here modeling of SMIB incorporated with TCSC is presented. Terminal voltage can be given a

$$V_t = V_d + jV_q$$

$$I_{tl} = I_{tld} + jI_{tlq}$$

$$V_t = jX_{tl}I_{tl} + jX_{lb}I_{lb} + jX_{tcsc}I_{tcsc} + jV\angle 0^\circ$$

Equations of state variables are as follows

$$\dot{\delta} = \omega_b \Delta\omega$$

$$\dot{\omega} = \frac{(P_m - P_e - D\Delta\omega)}{M}$$

$$\dot{E}'_q = \frac{\left(-E_q + E_{fd}\right)}{T'_{d0}}$$

$$\dot{E}'_{fd} = -\frac{1}{T_a}E_{fd} + \frac{k_a}{T_a}\left(V_{ref} - V_t\right)$$

$$\dot{X}_{tcsc} = \{k_s\left(X_{tcsc}^{ref} - U_{tcsc}\right) - X_{tcsc}\}/T_s$$

$$I_{tld} = \frac{E'_q - V_b\cos\delta}{\left(X_{tl} + X_{lb} + X'_d + X_{tcsc}\right)}$$

$$I_{tlq} = \frac{V_b\sin\delta}{\left(X_{tl} + X_{lb} + X_q + X_{tcsc}\right)}$$

After linearization the equation of state variable are as follows

$$\Delta\dot{X}_{tcsc} = k_1k_{11}\Delta\delta + Dk_{11}\Delta\omega + k_2k_{11}\Delta E'_q + \frac{\Delta X_{tcsc}}{T_s}\Delta X_{tcsc0}$$

With the help of linearised equations of the state variables, state space matrix for TCSC can be formulated as follows

$$\dot{X} = AX + BY$$

$$\begin{bmatrix} \Delta\dot{\delta} \\ \Delta\dot{\omega} \\ \Delta\dot{E}'_q \\ \Delta\dot{E}'_{fd} \\ \Delta\dot{X}_{tcsc} \end{bmatrix} = \begin{bmatrix} 0 & \omega_b & 0 & 0 & 0 \\ -\frac{k_1}{M} & -\frac{D}{M} & -\frac{k_2}{M} & 0 & 0 \\ -\frac{k_3}{T'_{do}} & 0 & -\frac{k_4}{T'_{do}} & \frac{1}{T'_{do}} & 0 \\ -\frac{k_ak_5}{T_a} & 0 & -\frac{k_ak_6}{T_a} & -\frac{1}{T_a} & -\frac{k_ak_{10}}{T_a} \\ k_1k_{11} & DK_{11} & k_2k_{11} & 0 & -\frac{1}{T_s} \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta\omega \\ \Delta E'_q \\ \Delta E'_{fd} \\ \Delta X_{tcsc} \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ \frac{k_a}{T_a} \end{bmatrix} * \Delta V_{ref}$$

IV. Calculation of Eigen values

The eigen value analysis have been carried out to ensure the stability of the system. Utilizing the state matrix A, the Eigen values are calculated at different loading.

Table 1: Eigen values of SMIB System with TCSC

Loading	80%	90%	100%

Eigen Values of SMIB with TCSC	-98.5200 -0.4973±5.1724i -12.4292 -1.8712	-98.5552 -0.5174±5.0566i -12.3126 -1.9124	-98.5952 -0.5514±4.8919i -12.1320 -1.9849

V. Simulation Results of SMIB System with TCSC

In this section simulation studies have been carried out on a SMIB system with TCSC at different loading [10]. The variation of different parameters at loading 80%, 90% & 100% during fault is shown in the below figures. The simulink diagram of SMIB system with TCSC is shown in the figure.4

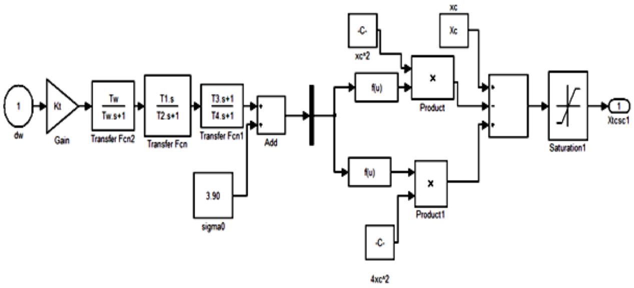

Fig. 4: Simulink Model of Sub-System for TCSC

Delta at different loadings of system

The following figures. 5 - 7 show the variation in delta at 80% , 90% & 100% loading

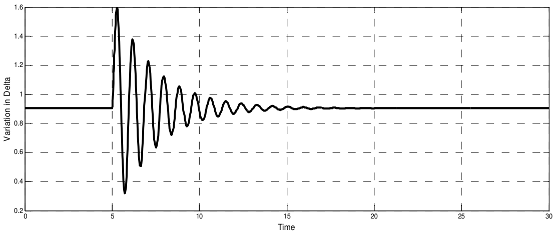

Fig. 5: Simulation results for delta at 80% loading with fault

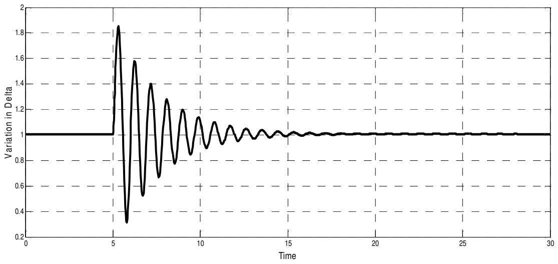

Fig. 6: Simulation results for delta at 90% loading with fault

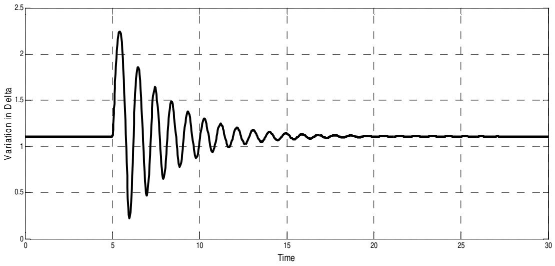

Fig. 7: Simulation results for delta at 100% loading with fault

Output power Pe at different loadings of system

The following figures 8 - 10 show the variation in Pe at 80%, 90% & 100% loading

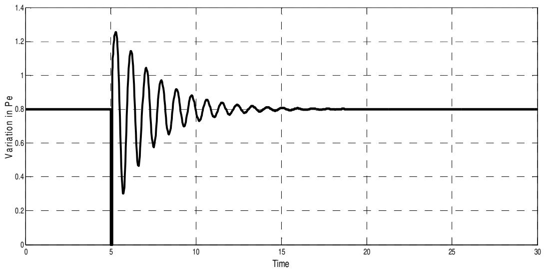

Fig. 8: Simulation results for generator real power output at 80% loading with fault

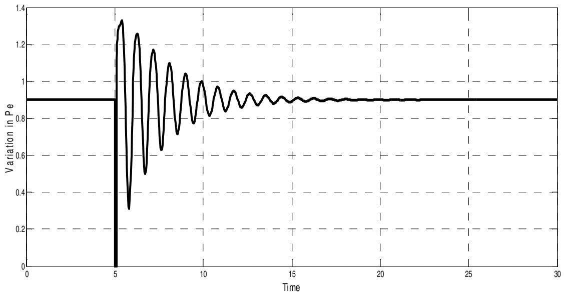

Fig. 9: Simulation results for generator real power output at 90% loading with fault

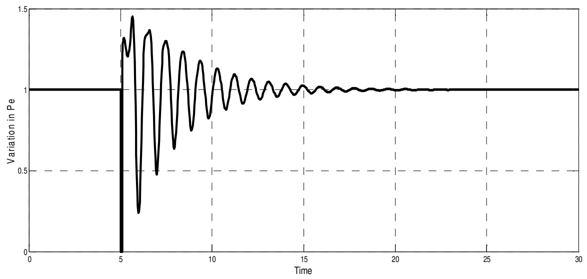

Fig.10: Simulation results for generator real power output at 100% loading with fault

Conclusion

Non linear simulation of SMIB system with TCSC has been carried out. Simulations for different loading conditions have been explored, and results validate the superior performance of the proposed system when tuned optimally. TCSC characteristic is explained mathematically hence it can be implemented in MATLAB OR SIMULINK and further can be extended for different applications. Simulation studies of SMIB system, load flow study results, Eigen value analysis have been discussed. The eigen values analysis and simulation results show that the controller has good performance on damping low frequency oscillations and improves the transient stability under different operating conditions. A power flow model of the TCSC is attempted and it is seen that the modified load flow equations help the system in better performance. Simulation studies shows that SMIB system becomes stable when we use TCSC individually with SMIB in faulty condition at different loadings but the performance of System is superior with the increased loading.

APPENDIX: System Parameters

All the quantities are in per unit, except as indicated.

H = 3.0s,D = 0.0,Td0’= 5.044s, Xd = 1.0, xq = 0.6,xd’= 0.3, Xtl = 0.3,xlb = 0.3,Ka =10,Ta =0.01s,Vt0 = 1.0,Vb0 = 1.0,

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