International Journal of Electrical, Electronics and Computer Engineering **1**(2): 105-110(2012) **ISSN No. (Online) : 2277-2626**
Special Edition for Best Papers of Michael Faraday IET India Summit-2012, MFIIS-12

Design of PI-Based TCSC Stabilizer for Power System Using Simulated Annealing Algorithm

P. Bera
Department of Electrical Engineering, Kalyani Govt. Engineering College, Kalyani, West Bengal, India

(Received 30 August, 2012 Accepted 02 October, 2012)

ABSTRACT: In this paper, the application of thyristor controlled series capacitor (TCSC) in damping power system oscillation is investigated. Analysis is carried out considering TCSC equipped with conventional lead-lag controller and with proportional-integral (P-I) controller. Parameter and gain settings of the TCSC controller are optimized using simulated annealing algorithm (SA). Dynamic performances considering TCSC equipped with conventional lead-lag controller and with proportional-integral (P-I) controller are compared. Analysis reveals that TCSC equipped with P-I controller improves the dynamic performances significantly as compared to that of TCSC equipped with lead-lag controller.

Keywords—TCSC, P-I Controller; Simulated Annealing Algorithm.

I. INTRODUCTION

Low frequency oscillations are very common phenomenon when large power systems are interconnected by relatively weak tie-lines. These oscillations may sustain and grow to cause system separation due to inadequate damping of electromechanical modes. Several approaches have been reported in the literature to provide the damping torque required for damping machine oscillations. DeMello and Concordia [1] proposed the concept of synchronous machine stability as effected by a lead-lag compensator usually called power system stabilizer (PSS), for damping the machine oscillations. Many researchers have made significant contribution in conventional lead-lag PSS design [2-7]. Although PSSs provide supplementary feedback stabilizing signals in the excitation systems and enhance the dynamic stability of power system by increasing the system damping of low frequency oscillations associated with the electromechanical mode but suffer a drawback of being liable to cause a great variations in the voltage profile and may even result in leading power factor operation under severe disturbance condition [2]. Recent advances in power electronics have led to the development of the flexible alternating current transmission system (FACTS). FACTS are designed to enhance power system stability by using reliable and high speed electronics devices. One of the promising FACTS devices is thyristor controlled series capacitor (TCSC) and has found application in improving power system dynamic stability. Chen et al [8] have used thyristor controlled series capacitor to increase the damping of dynamic oscillations of the power system. They have considered pole placement technique for computing the controller feedback gains of thyristor controlled series capacitor (TCSC). Thyristor controlled series capacitor (TCSC) with different control schemes have been suggested in [9-12]. Wang et al [13] have designed a TCSC based stabilizer which is not only avail to damp to target inter-area oscillation mode effectively but also imposes a positive interaction with a PSS in the power system to damp a local oscillation mode. In the present work, the TCSC control problems are investigated for single machine infinite bus (SMIB) power system. Controller design problem is formulated as an optimization problem. The simulated annealing algorithm (SA) is employed to solve this problem with the aim of getting the optimal or near optimal settings of the controller parameters. Different control schemes have been proposed and tested for single machine infinite bus (SMIB) power system.

II. SYSTEM INVESTIGATED

Fig. 1 shows a single machine infinite bus power system considering a TCSC located near the generator terminals. IEEE Type-I excitation model is considered for the analysis. A TCSC can extend the power transfer capability and provide additional damping for low frequency oscillations. Block diagram of small perturbation dynamic model of a single machine infinite bus system considering TCSC is shown in **Fig. 2.**

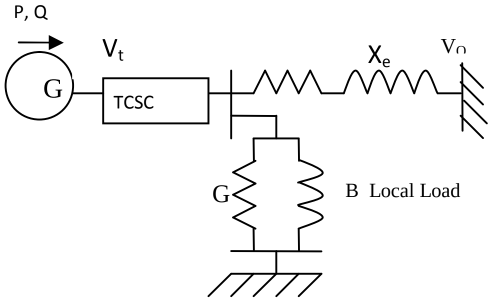

Fig. 1: Single machine infinite bus system considering a TCSC near generator terminal.

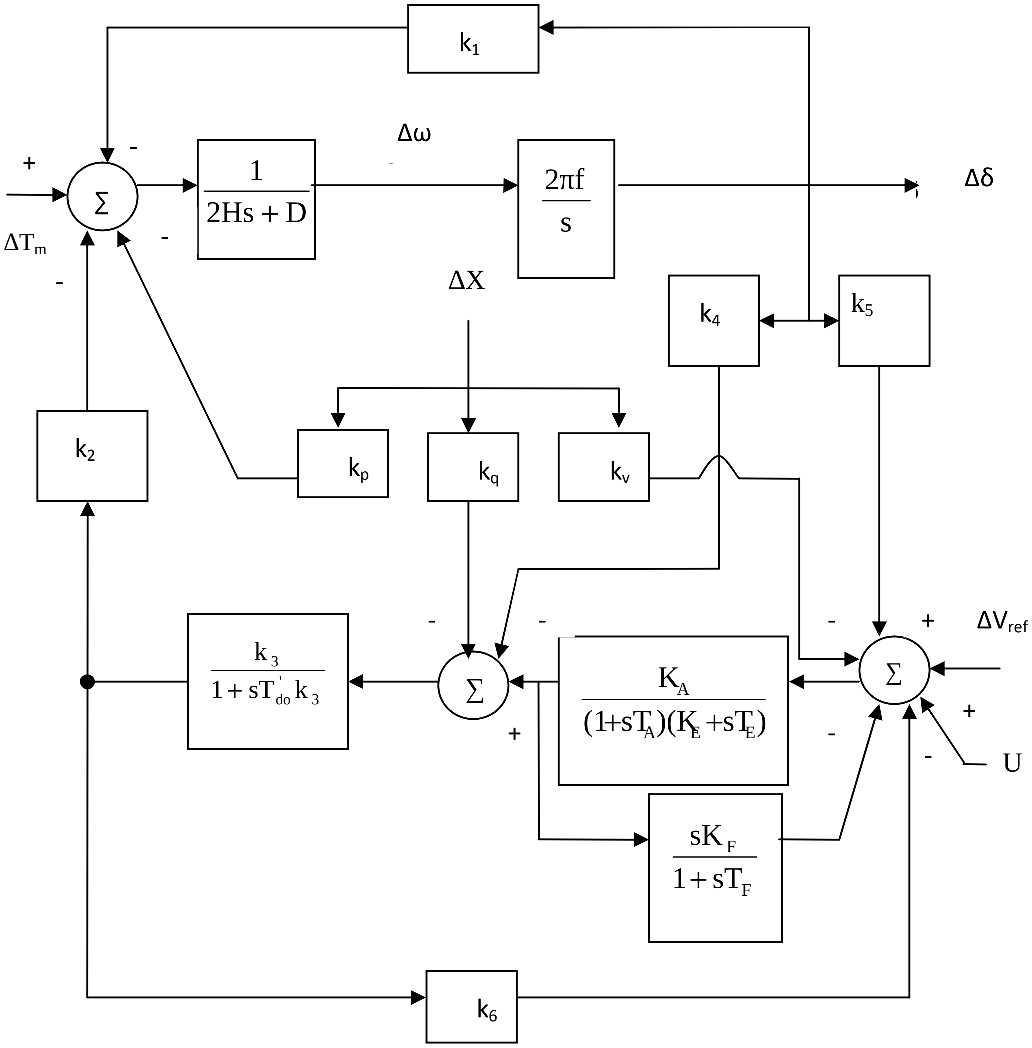

Fig . 2: Block diagram of small perturbation dynamic model of a single machine infinite bus system considering TCSC

The operating condition for SMIB system is completely defined by the values of the real power, P, the reactive power, Q, at the generator terminal and the transmission line impedance, X_c. P, Q and X_c are assumed to vary over the following ranges:

$$0.4 \le P \le 1.0 \;;\quad -0.2 \le Q \le 0.5 \;;\quad 0.2 \le X_c \le 0.7$$

It is assumed that

1. three phase thyristor networks are in a balanced condition,
2. the firing angle of the thyristors is continuous,
3. the effects of harmonics introduced into the system due to thyristor switching actions are neglected and
4. the filter network in the series capacitor has not been considered.

Each TCSC with its firing control system has been modeled with a first order model characterized by a gain and a time constant. To assess the effectiveness of the proposed control schemes, four different loading conditions as given in Table 1 are considered.

This encompasses almost all practical occurring operating conditions and very weak to very strong transmission networks.

III. STRUCTURE OF TCSC CONTROLLER

Fig.3 shows TCSC with conventional phase lead-lag controller. Fig. 4 shows the TCSC with P-I controller. The best location of the TCSC is at the generator terminal as it gives the greatest change of electrical distance between the generator and the disturbance point [11]. Hence the speed deviation $\Delta\omega$ is available and used as the input signal to TCSC controller. This makes the proposed controllers easy for implementation. In these figures $\Delta\Phi_{ref}$ is the reference angle and K_C and T_C are the gain and time constant of TCSC.

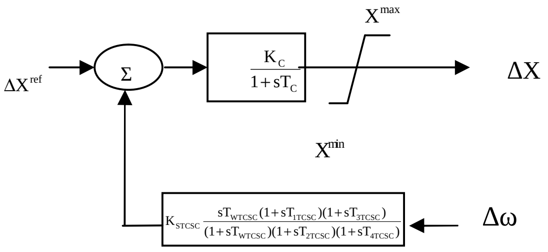

Fig. 3: Block diagram of TCSC equipped with Conventional Lead-Lag Controller.

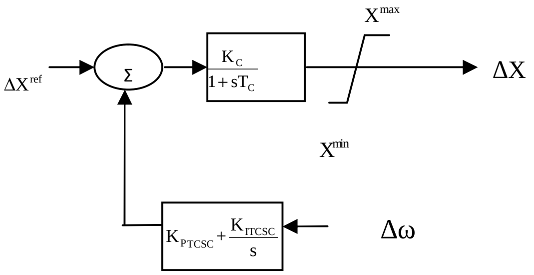

Fig. 4: Block diagram of TCSC equipped with P-I Controller

IV. CASE STUDIES

To investigate the ability of TCSC controller to damp out the low frequency oscillations associated with the electromechanical mode, two different control schemes are proposed as follows:

A TCSC with conventional lead-lag controller is considered: In this case tuning parameters are K_{STCSC}, T_{1TCSC}, T_{2TCSC}, T_{3TCSC}, T_{4TCSC} and $T_{WTCSC.}$

B TCSC with P-I controller is considered: In this case tuning parameters are $K_{PTCSC\text{ and }}$ K_{ITCS}.

V. DYNAMIC MODEL IN STATE SPACE FORM CONSIDERING TCSC EQUIPPED WITH LEAD–LAG CONTROLLER

In this case, the dynamic model in state space form can be given as:

$$\dot{X} = AX + \Gamma p \qquad \text{…(1)}$$

where X and p are the state and disturbance vectors, respectively, and are defined as:

$$X = [\Delta\delta\ \ \Delta\omega\ \ \Delta E_q'\ \ \Delta E_{fd}\ \ \Delta V_R\ \ \Delta V_E\ \ \Delta P_{TCSC1}\ \ \Delta P_{TCSC2}\ \ \Delta P_{TCSC3}\ \Delta X]^T \qquad \text{…(2)}$$

$$p = [\Delta T_m\ \ \Delta V_{ref}\ \ \Delta X_{ref}]^T \qquad \text{…(3)}$$

VI DYNAMIC MODEL IN STATE SPACE FORM CONSIDERING TCSC EQUIPPED WITH P-I CONTROLLER

In this case, the dynamic model in state space form can be given as:

$$\dot{X} = AX + \Gamma p \qquad \text{…(4)}$$

where X and p are the state and disturbance vectors, respectively, and are defined as:

$$X = [\Delta\delta\ \Delta\omega\ \Delta E_q'\ \Delta E_{fd}\ \Delta V_R\ \Delta V_E\ \Delta X]^T \qquad \text{…(5)}$$

$$p = [\Delta T_m\ \ \Delta V_{ref}\ \ \Delta X_{ref}]^T \qquad \text{…(6)}$$

VII OBJECTIVE FUNCTION

Scalar integral performance indices have proved to be the most meaningful and convenient measures of dynamic performances [14,15]. Penalizing only the speed excursions, an objective function based on the integral of time-multiplied square error (ITSE) criterion is considered in this study and is given by

$$J = \int_0^\infty t(\Delta\omega)^2 dt \qquad \text{…(7)}$$

This objective function has a characteristic in that a large initial error is weighted lightly, while errors occurring late in the transient response are penalized heavily. To compute the optimum parameter values, a step disturbance in mechanical torque (ΔT_m= 0.05 pu) was used to perturb the system from its operating point.

VIII. SIMULATED ANNEALING ALGORITHM

Simulated annealing (SA), based on the concept of modeling and simulation of a thermodynamic system, may be used to solve many combinatorial process optimization problems [16]. This technique starts with selection of an initial random process decision vector, and moves to new neighbourhood decision vector that improves objective function value. SA technique is a derivative-free optimization technique that simulates the physical annealing process in the field of combinatorial optimization. Annealing is the physical process of heating up a solid until it melts, followed by slow cooling it down by decreasing the temperature of the environment in steps. At each step, the temperature is maintained constant for a period of time sufficient for the solid to reach thermal equilibrium. At any temperature T, the thermal equilibrium state is characterized by the Boltzmann distribution. This distribution gives the probability of the solid being in a state i with energy E_i at temperature T as

$$P_i = k\exp(-E_i/K_BT) \qquad \ldots(8)$$

The generalized algorithm using metropolis simulated annealing algorithm can be written as[17]:

Step 1. Choose the Initial vector x to a random point in the set Φ and select an annealing schedule for the parameter T, and initialize T.

Step 2. Perturb X to obtain a neighboring Design Vector $X_p = X + \Delta X$
Step 3. Compute the change in the cool i.e. $\Delta f = f(X_p) - f(X)$.

Step 4: By using Metropolis Algorithm, decide if X_p should be used as the new state of the system or keep the current state X. Therefore, modified simulated annealing optimization algorithm is

$$p_r(x_p) = \begin{cases} 1 & \text{for } \Delta f < 0 \\ \exp^{-\Delta f/T} & \text{for } \Delta f \geq 0 \end{cases} \qquad \ldots.(9)$$

Where T replaces K_BT. Functionally, in cases when $\Delta f \geq 0$ a random number η is selected from a uniform distribution in the range [0,1]. If $p_r(X_p) > \eta$ then the perturbed state X_p is used as the new state (or search point) otherwise the state remains at X.

Step 5. Reduce T according to the cooling schedule.
Step 6. Terminate the algorithm.

IX ANALYSIS OF OPTIMUM PARAMETERS FOR DIFFERENT CONTROLLERS

In this case, six unknown parameters K_{STCSC}, T_{1TCSC}, T_{2TCSC}, T_{3TCSC}, T_{4TCSC} and T_{WTCSC} are optimized for several operating condition (eighty one combinations) by minimizing the objective function given by eqn. **(7)** for TCSC equipped with lead-lag controller. For TCSC equipped with P-I controller are K_{PTCSC} and K_{ITCSC}. Constraints are imposed on these gain and parameters. It was found that for each operating condition, numerical values of all the parameters for each case are different. Table 1 gives the optimum values of these parameters for some of the operating points.

X DYNAMIC RESPONSES

Figs. 5 & 6 show the comparison of dynamic responses considering TCSC equipped with lead-lag controller and TCSC equipped with P-I controller for two different loading conditions. From Figs. 5 & 6, it is observed that TCSC equipped with P-I controller gives better dynamic performances in terms of settling time as compared to that of TCSC equipped with lead-lag controller for both cases.
Similar findings were also observed for all other operating conditions within the range mentioned in Section-II. Therefore, it may be concluded that TCSC equipped with P-I controller can be an alternative of the TCSC equipped with lead-lag controller for providing much better dynamic responses.
However from the practical point of view, tuning of parameters at every operating point is a difficult task. Hence, an attempt was made to examine the dynamic responses at various operating conditions considering only one set of gain and parameters. After several computational experiments, it was found that, K_{PTCSC} = -40.25 and K_{ITCSC} -0.27 obtained for P = 0.8 and Q = 0.4 are also suitable within the range of operating conditions mentioned in section-II.

Fig. 7 shows the dynamic responses with t Secs) operating conditions corresponding to K_{PTCSC} = -40.25 and K_{ITCSC} -0.27 obtained for P = 0.8 and Q = 0.4. From Fig. 7, it is seen that the responses are quite satisfactory and settling time is about 3 seconds.
Dynamic responses were also examined for several other operating conditions for K_{PTCSC} = -40.25 and K_{ITCSC} -0.27 and it was found that responses were highly satisfactory. Therefore, it may be concluded that only one set of P-I gain settings is highly suitable for all other operating conditions. Hence, tuning of P-I gain settings at every operating point is not required.

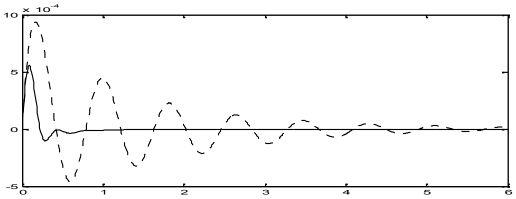

Fig. 5: Dynamic responses of SMIB system considering optimum parameters settings of TCSC equipped (i) P-I controller (ii) lead-lag controller for P = 1.1, Q = 0.5. (---- TCSC equipped with lead-lag controller, —— TCSC equipped with P-I controller).

XI. CONCLUSIONS

In this study, the effect of TCSC for the enhancement of power system stability has been investigated. Analysis were carried for TCSC equipped with conventional phase lead-lag controller and P-I controller. Parameters and gain settings of TCSC controller have been optimized using simulated annealing algorithm. Simulation results show that TCSC equipped with P-I controller gives better dynamic performances.

Numerical results on a single machine infinite bus system have shown that the regulating control actions on the TCSC can significantly enhance the small disturbance stability. The proposed control scheme have also been tested for different loading conditions and it was found that gain settings of P-I controllers of TCSC obtained for P = 0.8 & Q = 0.4 gives satisfactory dynamic performances to all other operating conditions over the prespecified range. Hence gain settings of P-I controller of TCSC at all other operating conditions over the prespecified range may be kept fixed and tuning of gain settings of P-I controller of TCSC are not required. It was also found that TCSC does not adversely affect the transient stability and damps out the oscillation following fault clearing.

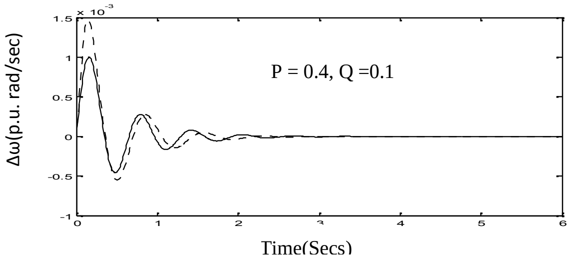

Fig. 6: Dynamic responses of SMIB system considering optimum parameters settings of TCSC equipped with (i) P-I controller (ii) lead-lag controller for P = 0.4, Q = 0.1 - - (TCSC equipped with lead-lag controller, . —— TCSC equipped with P-I controller)

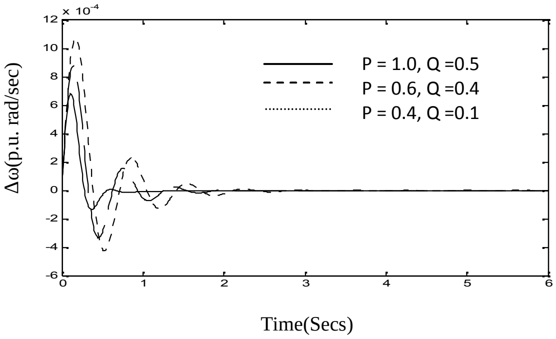

Fig. 7: Dynamic performances for three different loadings considering K_{PTCSC} = -40.25 and K_{ITCSC} = -0.27.

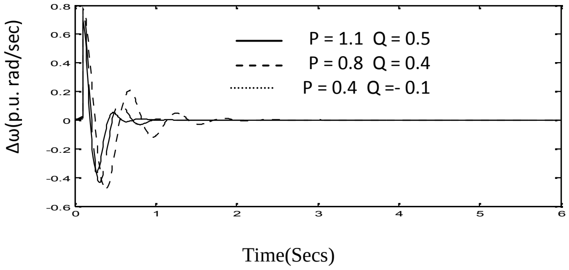

Fig. 8: System responses for a three phase six cycle fault at generator terminal considering K_{PTCSC} = -40.25 and K_{ITCSC} -0.25.

TABLE 1. OPTIMUM GAINS AND PARAMETERS OF THE DIFFERENT CONTROLLERS AT FIVE DIFFERENT OPERATING CONDITIONS.

Gains and Parameters	Operating Conditions			
	P=1.1 Q=0.5	P=0.8 Q=0.4	P=0.4 Q=0.1	P=0.4 Q=-0.2
K_{STCSC}	1.10	1.08	1.41	1.77
T_{WTCSC}	2.81	2.82	3.25	2.86
T_{1TCSC}	0.03	0.04	0.04	0.03
T_{2TCSC}	0.37	0.76	0.28	0.37
T_{3TCSC}	0.06	0.10	0.04	0.02
T_{4TCSC}	0.33	0.28	0.53	0.29
K_{PTCSC}	-45.23	-40.25	-32.38	-14.75
K_{ITCSC}	-0.41	-0.27	-0.75	-0.94

XII APPENDIX

The parameters of the system investigated are as given below: M = 4.74 pu, D = 0, $T'_{do} = 5.9$ Secs., K_A = 400, T_A = 0.05 Secs., K_E = -0.17, T_E = 0.95 Secs., K_F = 0.025, T_F = 1.0 Secs.; x_d = 1.70 pu, $x'_d = 0.245$ pu, x_q = 1.64 pu, R=0.02 pu, X = 0.4 pu, G = 0, B = 0, f = 50 Hz.

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