TUNING OF EXCITATION AND TCSC -BASED STABILIZERS FOR MULTIMACHINE POWER SYSTEM

P. Bera

Department of Electrical Engineering, Marine Engineering and Research Institute
W.B. 700088, Kolkata, India
partha_bera@rediffmail.com

D. Das* and T.K. Basu

Department of Electrical Engineering, Indian Institute of Technology Kharagpur
W.B. 721302, Kharagpur, India
ddas@ee.iitkgp.ernet.in - tkb@ee.iitkgp.ernet.in

*Corresponding Author

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Abstract In this paper, tuning of power system stabilizer (PSS) and thyristor controlled series capacitor (TCSC) is studied. The analysis of mode controllability is used to select the effective location for TCSC. The performances of TCSC equipped with a proportional-integral-derivative controller (P-I-D controller) and proportional-integral-derivative power system stabilizer (P-I-D PSS) are investigated. The dynamic responses considering TCSC equipped with a P-I-D controller and P-I-D PSS are compared with considering TCSC equipped with a phase lead-lag controller and conventional power system stabilizer (CPSS). The controllers design problem is formulated as an optimization problem. The genetic algorithm (GA) is used to search for optimal settings of controller parameters. Analysis reveals that the TCSC equipped with P-I-D controller and P-I-D PSS give better dynamic performances.

Keywords CPSS, P-I-D PSS, TCSC, Genetic Algorithm (GA)

چکیده در این مقاله تنظیم پایدار کننده سیستم برق (PSS) و خازن سری کنترل شده thyristor (TCSC) بررسی می‌شود. از تحلیل قابلیت کنترل روش برای انتخاب مکان مناسب برای TCSC استفاده می‌شود. عملکرد TCSC مجهز به یک کنترل کننده و پایدار کنند سیستم برق P-I-D مورد بررسی قرار می‌گیرد. پاسخ دینامیک با توجه به TCSC مجهز به یک کنترل کننده P-I-D و پایدار کننده سیستم P-I-D با در نظر گرفتن TCSC مجهز به یک کنترل کننده دارای یک جلو افتادگی فازی و پایدار کننده سیستم برق سنتی (CPSS) مقایسه می‌شود. مشکل طراحی کنترل کننده‌ها به‌عنوان یک مشکل بهینه‌سازی فرموله می‌شود. الگوریتم ژنتیک (GA) برای جستجوی تنظیمات بهینه پارامترهای کنترل کننده مورد بهره‌برداری قرار می‌گیرد. تحلیل‌ها نشان می‌دهد که TCSC مجهز به‌کنترل کننده و پایدار کننده سیستم برق P-I-D عملکرد دینامیک بهتری ارائه می‌دهد.

1. INTRODUCTION

Since the 1960s low frequency oscillations have been observed when large power systems are interconnected by relatively weak tie-lines. These oscillations may sustain and grow to cause system separation, if no adequate damping of electromechanical modes is provided.

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 affected by a lead-lag compensator usually called power system stabilizer (PSS), for damping the machine oscillations. Many researchers have made significant contribution to 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, they 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 [9-10]. Chang, et al [11] have used a time-optimal control to damp inter-area modes in multimachine systems. Rouco, et al [12] have presented tools and methods to study the application of TCSC for damping power system electromechanical oscillations based on eigenvalue sensitivity approach. Yang, et al [13] have used residue method together with modal sensitivities for TCSC to determine location, feedback signal and controller parameters. Tso, et al [14] have used a nonlinear design technique to deduce the control law for TCSC and SVC where SVC is treated as supplement of TCSC. Li, et al [15] have suggested a method to incorporate the analysis of the electromagnetic transient process of TCSC into the power system stability analysis. Son, et al [16] have used LQG (Linear Quadratic Gaussian) technique to the design of the robust TCSC controller for power system oscillation damping enhancement. They have also discussed the pitfalls in applying the LTR (Loop Transfer Recovery) technique to reserve the robustness of the LQG damping controller. Fan, et al [17] have proposed a method to identify an effective local signal for TCSC as a supplementary controller to dampen inter-area oscillations for power system. Ishimura, et al [18] have proposed a design method for the robust TCSC controllers for capacitive reactance in a power system. Del Rosso, et al [19] have proposed a novel hierarchical control designed for both dynamic and steady state stability enhancement for TCSC. Chen, et al [20] have studied the application of series compensator to improve the stability margin of power system. They have proposed state feedback controller using a linearized system model. Wang, et al [21] 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.

Design of various types of controllers for TCSC have been proposed in [22-24]. Chaturvedi, et al [25] have used generalized neuron based PSS to improved the stability and dynamic performance of a multi-machine power system.

In the present work, the effect of excitation and TCSC control problem are investigated for a multimachine power system. TCSC is very effective for the enhancement of both small disturbance and transient stability. In order to reach this goal, it is necessary to choose a suitable location of TCSC and to adopt an effective control strategy. This work deals with the series capacitor controller design and location of TCSC has been selected by modal controllability analysis [8]. Controller design problem is formulated as an optimization problem. Genetic algorithm is employed to solve this problem with the aim of getting the optimal or near optimal settings of the controller parameters.

2. SYSTEM INVESTIGATED

In the present work, a ten machine thirty nine bus system as given in Figure 1 is considered. Data for ten machine thirty nine bus system are taken from [26]. All the machines are equipped with IEEE Type-I exciter. Figure 2 shows the generalized model of multimachine system with TCSC. The model of TCSC as shown in Figure 1, is extensively discussed in [21] where a linearized model is also derived.

3. SELECTION OF PSS LOCATION FOR MULTIMACHINE SYSTEM

In the present work the concept of participation factor of each machine in various electromechanical mode [27] and the damping factor (ξ) have been

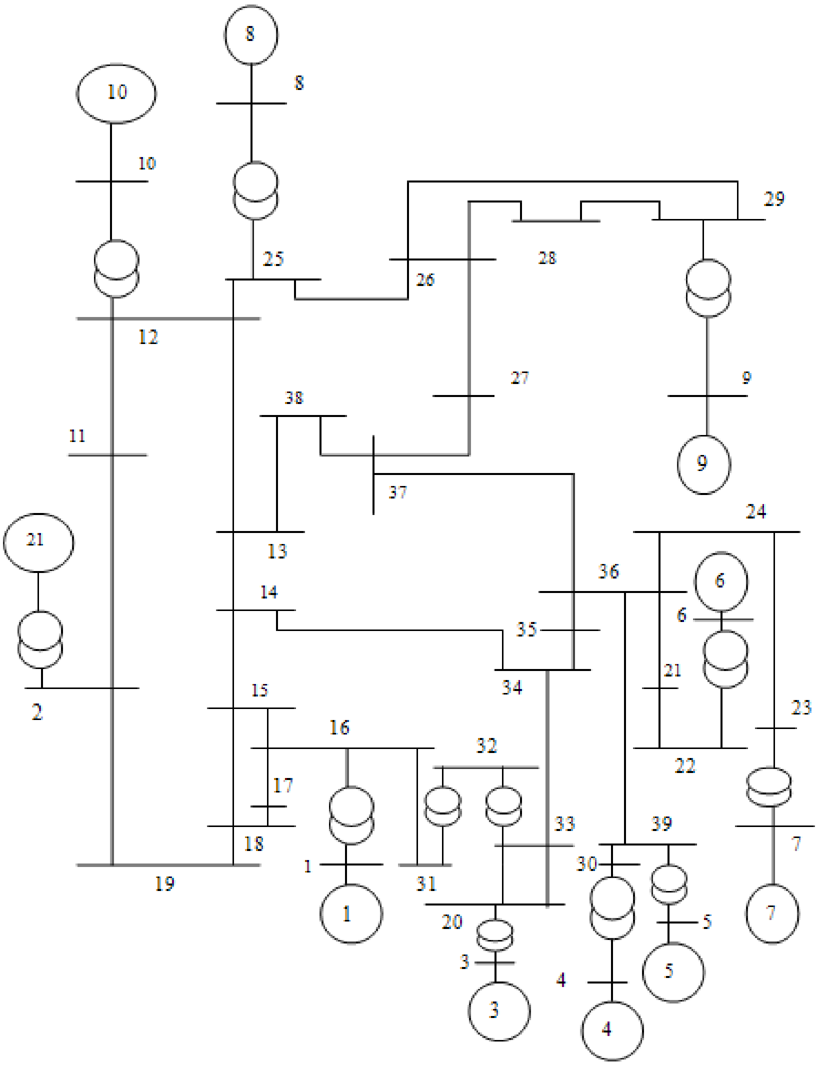

Figure 1. Ten machine thirty nine bus system.

used for the selection of PSS location. The participation factors are computed using right and left eigenvectors of the system matrix of the power system. The appropriate definition and determination as to which state variables significantly participate in the selected modes become very important. Verghese, et al [27] have suggested a related but dimensionless measure of state variable participation called participation factor. The participation factor q_{ki} is defined as [27]:

$$q_{ki} = \frac{|v_{ki}||w_{ki}|}{\sum_{k=1}^{n} |v_{ki}||w_{ki}|} \quad (1)$$

Where,

q_{ki} = participation factor relating to k^{th} state variable to the i^{th} eigenvalue.

v_{ki} = k^{th} entries in the right eigenvector associated with the i^{th} eigenvalue.

w_{ki} = k^{th} entries in the left eigenvector associated with the i^{th} eigenvalue.

Table 1 shows the electromechanical mode eigenvalues and the corresponding damping factor (ξ) without stabilizer. Table 2 gives the participation factors of the machines in each electromechanical mode. From Table 1, it is seen that mode 1 is the most critical mode and the damping factor for this mode is very less. So, in

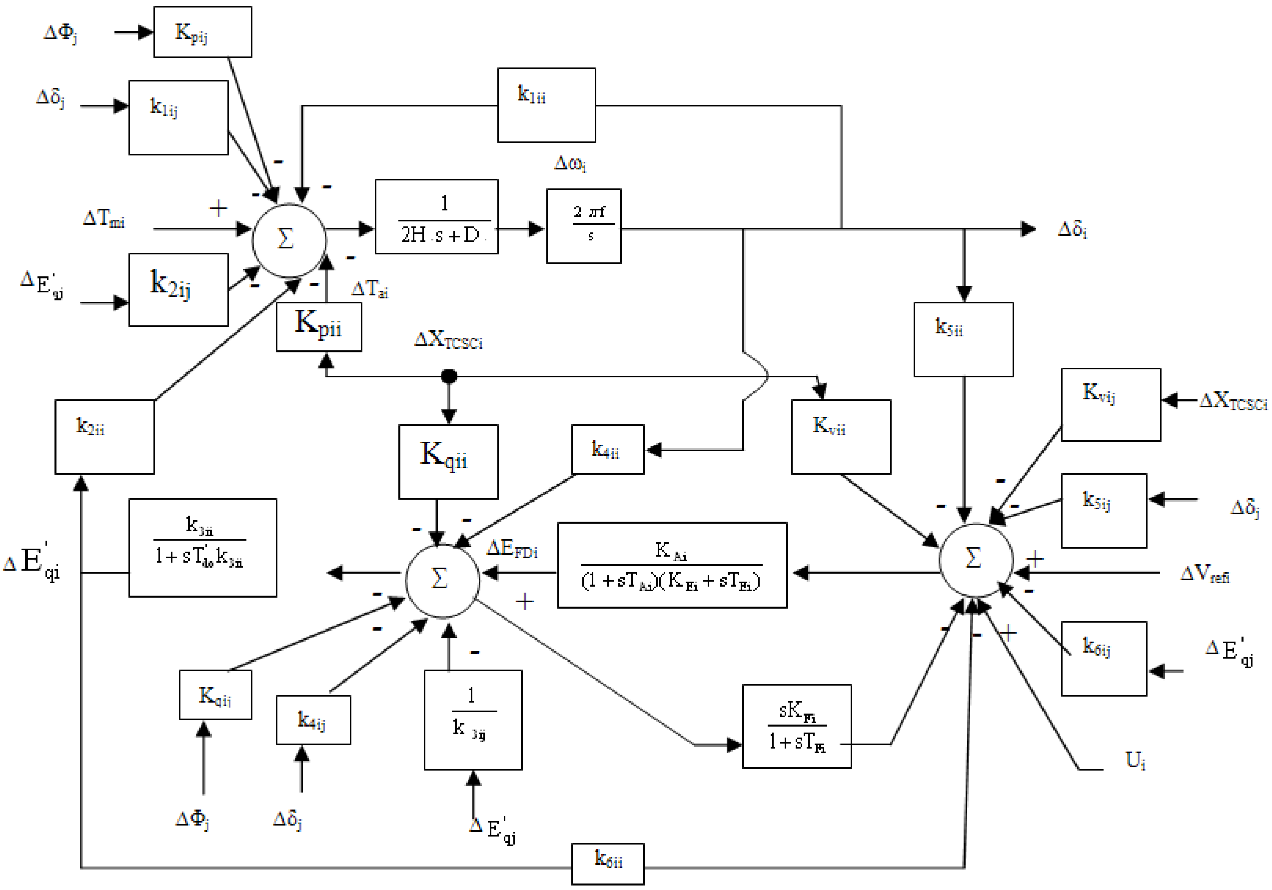

Figure 2. Generalized model of multimachine system with TCSC.

the present work only one machine has been selected for stabilizer placement based on the lowest damping factor and corresponding participation factor. From Table 2, it is seen that machine-4 has highest participation factor in mode 1 and from Table 1, it is seen that in mode 1, damping is the lowest and hence machine 4 is selected for stabilizer location.

4. SELECTION OF TCSC LOCATION FOR MULTIMACHINE SYSTEM

In the present work, the concept of mode controllability analysis [8] has been carried out to determine the most effective location for TCSC. If a single TCSC is considered in the power system, the natural modes present in the system can be seen in the response of any selected output variable in different proportion when the system is excited by an external stimulation via the control input. In general, for a system with n dynamic modes, the Laplace transform of any selected output variable Y(s) can be shown to be related to the Laplace transform of the input U(s) by

$$Y(s) = \left(\frac{R_1}{s-\lambda_1} + \ldots.. + \frac{R_n}{s-\lambda_n} \right) U(s) \quad (2)$$

Where $\lambda_1, \ldots., \lambda_n$ are the eigenvalues of the system and the $R_1, \ldots., R_n$ are the corresponding residues. The impulse response of the output y(t) is given by

$$y(t) = \sum_{i=1}^{n} R_i e^{-\lambda_i t} \quad (3)$$

TABLE 1. Electromechanical Mode Eigenvalues and Damping Factor.

Electromechanical Mode Eigenvalues		Damping Factor
Mode 1	-0.0039 ± j7.3248	0.0005328
Mode 2	-0.1944 ± j6.6865	0.0291
Mode 3	-0.2469 ± j7.1199	0.0347
Mode 4	-0.3492 ± j6.2590	0.0557
Mode 5	-0.4068 ± j8.4989	0.0478
Mode 6	-0.5682 ± j3.5178	0.1595
Mode 7	-0.7819 ± j7.4455	0.1044
Mode 8	-0.8870 ± j9.2709	0.0952
Mode 9	-1.1355 ± j6.7419	0.1661

TABLE 2. Participation Factors.

M/c-No.	Participation Factors				
	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5
	-0.0039 ± j7.32	-0.19 ± j6.69	-0.25 ± j7.1200	-0.35 ± j6.26	-0.41 ± j8.50
$\Delta\omega_1$	0.0006	0.1877	0.1702	0.0409	0.0005
$\Delta\omega_2$	0.0000	0.0005	0.0001	0.0017	0.0001
$\Delta\omega_3$	0.0008	0.0935	0.2836	0.0331	0.0010
$\Delta\omega_4$	0.2580	0.0591	0.0009	0.0363	0.0195
$\Delta\omega_5$	0.0140	0.0138	0.0002	0.0129	0.0215
$\Delta\omega_6$	0.1586	0.0734	0.0025	0.0561	0.0749
$\Delta\omega_7$	0.0100	0.0198	0.0003	0.0204	0.2950
$\Delta\omega_8$	0.0001	0.0033	0.0001	0.0518	0.0004
$\Delta\omega_9$	0.0006	0.0050	0.0005	0.0168	0.0025
$\Delta\omega_{10}$	0.0005	0.0020	0.0011	0.1381	0.0007
M/c-No.	Participation Factors				
	Mode 6	Mode 7	Mode 8	Mode 9	
	-0.57 ± j3.52	-0.78 ± j7.45	-0.89 ± j9.27	-1.14 ± j6.74	
$\Delta\omega_1$	0.0025	0.0006	0.0001	0.0012	
$\Delta\omega_2$	0.0388	0.0002	0.0000	0.0004	
$\Delta\omega_3$	0.0019	0.0006	0.0001	0.0022	
$\Delta\omega_4$	0.0015	0.0040	0.0269	0.0010	
$\Delta\omega_5$	0.0010	0.0022	0.3087	0.0016	
$\Delta\omega_6$	0.0010	0.0106	0.0012	0.0028	
$\Delta\omega_7$	0.0011	0.0013	0.0366	0.0011	
$\Delta\omega_8$	0.0011	0.0304	0.0002	0.1929	
$\Delta\omega_9$	0.0021	0.3138	0.0009	0.0117	
$\Delta\omega_{10}$	0.0086	0.0111	0.0007	0.0895	

The impulse response associated with any complex conjugate pair, a ± jb, can be further amplified to take the form

$$2e^{\alpha t}\sqrt{\left(p^2+q^2\right)}\sin(bt+\alpha) \quad (4)$$

Where,

p ± jq is the corresponding residue pair and

$$\alpha=\tan^{-1}\left(\frac{p}{q}\right)$$

The degree of controllability of a given oscillation mode in the output y(t) through the control input u(t) is indicated by the magnitude of the corresponding residue $(p^2+q^2)^{1/2}$.

The most effective location for a TCSC is that where the controller can exercise a sufficient degree of controllability over all the required oscillation modes through its control input. Therefore by analyzing the residues for different controller locations, the best location for the controller can be obtained. The method can also be used for the coordinated design of multiple controllers.

As the control objective is to provide additional damping to critical mode i.e. mode 1, only the controllability of this oscillatory mode has been considered. Initially, mode controllability analysis has been carried out considering a TCSC placed on line 8 -25, 14-34, 11-12, 12-13, 23-24, 36-39, 33-34, 16-31, 17-18, 36-37, 11-2, 19-2, 14-15, 26-29, 25-26, 28-29 and 26-28 respectively. Tables 3 and 4 show the residues for nine electro-mechanical modes. The mode controllability in Tables 3 and 4, shows that when a TCSC is installed in line 11-12, the controllability for mode 1 is better than other lines. So a TCSC is installed in line 11-12, which will improve damping mode 1.

5. CONVENTIONAL POWER SYSTEM STABILIZER (CPSS)

The typical structure of a conventional PSS is shown in Figure 3 [2]. To provide pure damping, the CPSS should have appropriate phase-lead characteristics to compensate the phase-lag between the generator exciter input and electrical output torque. Two lead-lag blocks are used in this paper although the number and characteristics of phase compensation units could be modified according to the design requirements.

The gain and time constants of the phase compensation units therefore need to be determined such that the system should give good dynamic performances. In this case also, limits are imposed on the output of CPSS and as mentioned in **Section 3** and positive and negative limits are considered as 0.2 pu and -0.1 pu respectively.

6. P-I-D POWER SYSTEM STABILIZER (P-I-D PSS)

Block diagram of the P-I-D power system stabilizer is shown in Figure 4. The input signal of the P-I-D stabilizer is the speed ($\Delta\omega$) of which the integral is the torque angle ($\Delta\delta$) and the derivative is acceleration ($\Delta\dot{\omega}=\Delta\alpha$). Therefore, the proposed P-I-D stabilizer may be called as $\Delta\omega-\Delta\delta-\Delta\dot{\omega}$ stabilizer. In order to restrict the level of the generator terminal voltage fluctuation during transient conditions, limits are imposed on power system stabilizer output. To ensure maximum contribution of the stabilizer, use of relatively large positive limits, i.e., 0.1 pu to 0.2 pu and negative limits of –0.05 pu to –0.1 pu is reported [2]. In the present work, positive and negative limits are considered as 0.2 pu and –0.1 pu respectively.

7. TCSC CONTROLLERS

Figure 5 shows the structure of TCSC equipped with lead-lag controller and Figure 6 shows the structure of TCSC equipped with P-I-D controller. The outputs of the both controllers are multiplied with a gain and compared with $\Delta X_{ref,i}$ of the TCSC and the error signal is an input to the TCSC. The speed deviation $\Delta\omega_i$ is used as an input to the both controllers. This makes the proposed controllers easy for implementation. In these figures, $\Delta X_{ref,i}$ is the reference angle and K_{Ci} and T_{Ci} are the gain and time constant of TCSC.

TABLE 3. Variation of Mode Controllability with TCSC Location.

Mode	Line 8-25	Line 14-34	Line 11-12	Line 12-13	Line 23-24
Mode 1	0.0038	0.0059	0.0078	0.0075	0.0071
Mode 2	1.0865	0.6437	2.4766	2.3307	2.4694
Mode 3	0.2169	0.4406	0.5001	0.4743	0.5011
Mode 4	0.3263	0.1743	0.7344	0.6887	0.7314
Mode 5	0.0040	0.0077	0.0089	0.0083	0.0088
Mode 6	0.1433	0.0013	0.1921	0.1716	0.1932
Mode 7	0.0032	0.0071	0.0093	0.0092	0.0086
Mode 8	0.0007	0.0013	0.0015	0.0014	0.0015
Mode 9	0.0114	0.0243	0.0286	0.0268	0.0281

TABLE 4. Variation of Mode Controllability with TCSC Location.

Mode	Line 36-39	Line 11-2	Line 19-2	Line 14-15	Line 26-29
Mode 1	0.0072	0.0076	0.0071	0.0062	0.0072
Mode 2	2.4370	2.4734	2.4748	2.0659	2.4893
Mode 3	0.4955	0.5006	0.5036	0.4180	0.5042
Mode 4	0.7206	0.7341	0.7332	0.6116	0.7374
Mode 5	0.0087	0.0088	0.0088	0.0074	0.0089
Mode 6	0.1902	0.1953	0.1950	0.1675	0.1938
Mode 7	0.0085	0.0092	0.0085	0.0071	0.0086
Mode 8	0.0015	0.0015	0.0015	0.0012	0.0015
Mode 9	0.0277	0.0284	0.0280	0.0233	0.0284

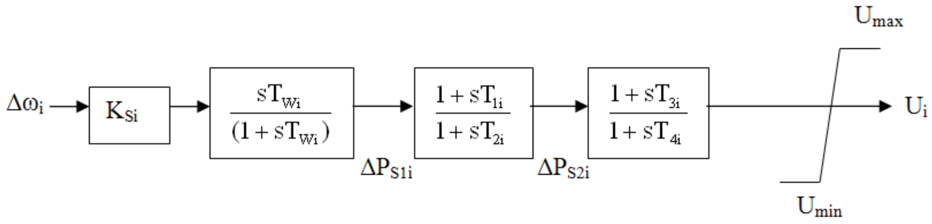

Figure 3. The structure of a conventional power system stabilizer (CPSS).

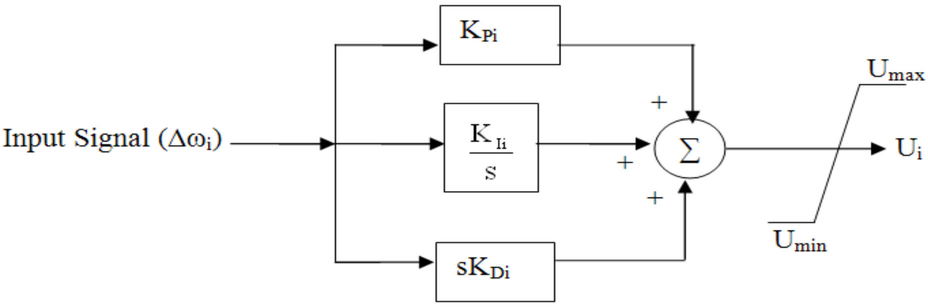

Figure 4. The structure of a P-I-D power system stabilizer.

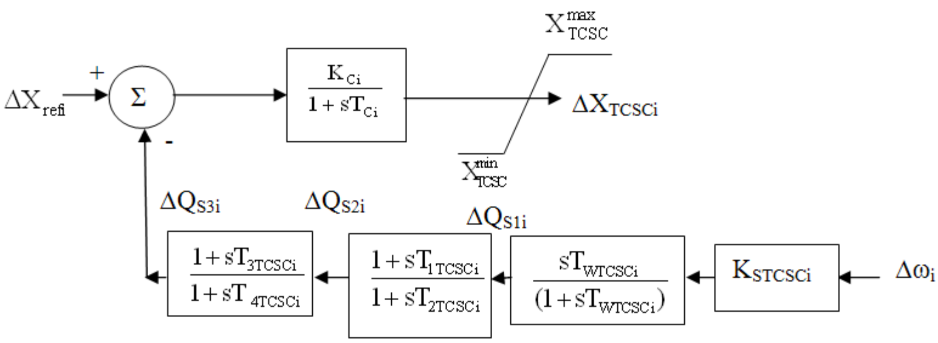

Figure 5. Structure of TCSC equipped with Lead-Lag controller.

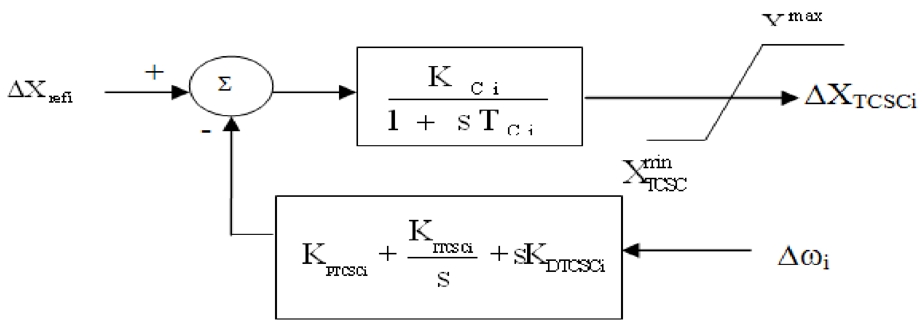

Figure 6. Structure of TCSC equipped with P-I-D controller.

In the both cases, TCSC is installed in line 11-12 as mentioned in Section 4 and input signal is taken from machine 10 for both controllers as machine 10 is nearer to this line.

8. DYNAMIC MODEL IN STATE SPACE FORM CONSIDERING CPSS P-I-D PSS AND TCSC CONTROLLERS

The dynamic model in state space form considering CPSS is written as [28,29]:

$$\dot{X} = AX + \Gamma p \quad (5)$$

Where X and p are the state and disturbance vectors and A and Γ are real constant matrices of appropriate dimensions. In this case ΔP_{S1i}, ΔP_{S2i} and U_i as shown in Figure 3, are considered as state variables.

In this case, state vector X and disturbance vector p for the i^{th} machine is defined as:

$$X_i = \left[\Delta\delta_i \ \Delta\omega_i \ \Delta E'_{qi} \ \Delta E_{FDi} \ \Delta V_{Ri} \ \Delta V_{Ei} \ \Delta P_{S1i} \ \Delta P_{S2i} \ U_i\right]^T \quad (6)$$

and

$$p_i = \left[\Delta T_{mi} \ \Delta V_{refi}\right]^T \quad (7)$$

The dynamic model in state space form considering P-I-D PSS is written as:

$$\dot{X} = AX + \Gamma p \quad (8)$$

Where X and p are the state and disturbance vectors and A and Γ are real constant matrices of appropriate dimensions.

In this case, state vector X and disturbance vector p for the i^{th} machine is defined as:

$$X_i = \left[\Delta\delta_i \ \Delta\omega_i \ \Delta E'_{qi} \ \Delta E_{FDi} \ \Delta V_{Ri} \ \Delta V_{Ei}\right]^T \quad (9)$$

and

$$p_i = \left[\Delta T_{mi} \ \Delta V_{refi}\right]^T \quad (10)$$

The dynamic model in state space form considering CPSS and TCSC equipped with lead-lag controller is written as:

$$\dot{X} = AX + \Gamma p \quad (11)$$

Where X and p are the state and disturbance vectors and A and Γ are real constant matrices of appropriate dimensions. In this case ΔP_{S1i}, ΔP_{S2i}, U_i, for CPSS and ΔQ_{S1i} ΔQ_{S2i} ΔQ_{S3i} and ΔX_{TCSCi} for TCSC equipped with lead-lag controller as shown in Figure 5, are considered as state variables.

In this case, state vector X and disturbance vector p for the i^{th} machine is defined as:

$$X_i = [\Delta\delta_i \ \Delta\omega_i \ \Delta E'_{qi} \ \Delta E_{FDi} \ \Delta V_{Ri} \ \Delta V_{Ei} \ \Delta P_{S1i} \ \Delta P_{S2i} \ U_i \ \Delta Q_{S1i} \ \Delta Q_{S2i} \ \Delta Q_{S3i} \ \Delta X_{TCSCi}]^T \quad (12)$$

and

$$p_i = \left[\Delta T_{mi} \ \Delta V_{refi} \ \Delta X_{refi}\right]^T \quad (13)$$

The dynamic model in state space form considering P-I-D PSS and TCSC equipped with P-I-D controller is written as:

$$\dot{X} = AX + \Gamma p \quad (14)$$

Where X and p are the state and disturbance vectors and A and Γ are real constant matrices of appropriate dimensions. In this case ΔX_{TCSCi} equipped with P-I-D controller as shown in Figure 6, is considered as state variable.

In this case, state vector X and disturbance vector p for the i^{th} machine is defined as:

$$X_i = \left[\Delta\delta_i \ \Delta\omega_i \ \Delta E'_{qi} \ \Delta E_{FDi} \ \Delta V_{Ri} \ \Delta V_{Ei} \ \Delta X_{TCSCi}\right]^T \quad (15)$$

and

$$p_i = \left[\Delta T_{mi} \ \Delta V_{refi} \ \Delta X_{refi}\right]^T \quad (16)$$

9. OBJECTIVE FUNCTION

Scalar integral performance indices have proved to be the most meaningful and convenient measures of dynamic performances [30,31]. Penalizing only the speed excursions, an objective function based on the integral square error (ISE) criterion is considered in this study and is given by

$$J = \int_{0}^{\infty} \sum_{i=1}^{n} (\Delta \omega_i)^2 dt \quad (17)$$

Where, n is the number of machines. For ten machine thirty nine bus system, n = 10.

This objective function has a characteristic that it penalizes large errors heavily and low errors lightly. To compute the optimum parameter values a step disturbance of mechanical torque at machine 4 (i.e. ΔT_{m4}=0.05 pu) was used to perturb the system from its operating point.

10. GENETIC ALGORITHMS

Genetic algorithms (GAs), a way to randomly search for the best answer to tough problems were first suggested by John Holland in his book in Natural and Artificial systems [32]. Over the last few years, it is becoming important to solve a wide range of search, optimization and machine learning problems.

A GA (multi path search scheme) is an iterative procedure which maintains a constant size population p(t) of candidate solutions. The initial population p(0) can be chosen heuristically or at random [32]. The structures of the population p(t+1) (i.e., for next iteration called generation) are chosen from p(t) by randomize selection procedure that ensures that the expected number of times a structure chosen is approximately proportional to that structure's performance relative to the rest of the population. In order to search other points in a search space, some variation is introduced into the new population by means of genetic operators (crossover and mutation).

Three processes, selection, mating and mutation are used to make the transition from one population generation to the next. These three steps are repeated to create new generation and it continues in this fashion until stopping condition is reached (such as maximum number of generations or resulting new population not improving enough).

10.1. Encoding The design variables are mapped onto a fixed–length binary digit string which is constructed over the binary alphabet (0,1), and is concatenated head-to-tail to form one long string referred to as a chromosome. That is, every string contains all design variables.

Each design variable is represented by a λ-bit string. We have to determine the value of λ. It is shown by Lin, et al [33] that

$$\lambda_i \geq \log_2\left(\frac{x_i^{max} - x_i^{min}}{\varepsilon}\right) \quad (18)$$

Where x_i^{max} = upper bound on x_i, x_i^{min} = lower bound on x_i and ε = the resolution. For example if ε = 0.01, x_i^{max} = 60, x_i^{min} = 20, then $\lambda_i \geq 11.9658$ but bit size must be an integer and hence, in this case $\lambda_i \geq 12$.

10.2. Decoding The physical value of i-th design variable x_i is computed from the following equations:

$$x_i = x_i^{min} + I_i \frac{(x_i^{max} - x_i^{min})}{2^{\lambda_i} - 1} \quad (19)$$

For example, if ε = 0.01; x_i^{max} = 60, x_i^{min} = 20.0 and λ_i = 12, then the bit string 100000000001 is decoded to I_i =2049 and thus x_i = 40.014652.

10.3. Fitness Function In GAs, the value of fitness represents the "performance" which is used to rank the string and the ranking is then used to determine how to allocate reproductive opportunities. This means that individuals with higher fitness value will have higher probability of being selected as a parent. Actually the 'fitness' is defined as nonnegative figure of merit to be maximized which is directly associated with the objective function.

In unconstrained maximization problem, the objective function can be adopted as the fitness function:

$$F = J \quad (20)$$

Where F is the fitness function and J is the objective function.

The unconstrained minimization problem is transformed to the fitness maximization problem according to the following equation:

$$F = \frac{K}{J} \quad (21)$$

Where K is a positive constant multiplier. To maximize the fitness function is same as minimize the objective function.

10.4. Control Parameters Selected First of all, effects of population were observed. Different population sizes (40-80) were considered and it has been observed that the population size of 60 was satisfactory. After selecting the population size, the effect of mutation and crossover probabilities were examined. Different combination of mutation (P_m) probabilities (0.0001, 0.001, 0.005 and 0.01) and the crossover (P_c) probabilities (0.6, 0.8, 0.9 and 1.0) were tested and it was found that $P_c = 1.0$ and $P_m = 0.005$ give the best performance for all the operating conditions. It is worth mentioning here that the bit size (gene length) of each variable is taken as 10 (i.e., λ=10).

11. OPTIMIZATION OF CONTROLLER PARAMETERS

11.1. Optimization of CPSS and P-I-D PSS Parameters The parameters of and CPSS and P-I-D PSS are optimized using GA. In the case of CPSS, gains and time constants i.e. K_{S4}, T_{14}, T_{24}, T_{34} and T_{44} are optimized by minimizing the objective function given by Equation 17. The washout time constant T_{W4} is considered as 10 Seconds. In the case of P-I-D PSS, gains i.e. K_{P4}, K_{I4} and K_{D4} are optimized by minimizing the objective function given by Equation 17. Constraints are also imposed on these parameters. The maximum and minimum limiting values of these parameters are given in Appendix. Optimum gains and different time constants of CPSS and optimum gains of P-I-D PSS are presented in Tables 5 and 6 respectively.

11.2. Optimization of Lead-Lag Controller Parameters The CPSS parameters for machine 4 presented in Table 5 is kept fixed and the problem is now to optimize the parameters of lead-lag controller of TCSC. As the input signals for TCSC controllers have been taken from machine 10, the speed deviations of machine-10 ($\Delta\omega_{10}$) is used as the input signal to the lead-lag controller of TCSC.

In the case of TCSC equipped with lead-lag controller, three parameters $K_{STCSC10}$, $T_{1TCSC10}$, $T_{2TCSC10}$, $T_{3TCSC10}$ and $T_{4TCSC10}$ are optimized by minimizing the objective function given by Equation 17 and $T_{WTCSC10}$ is taken as 10 seconds. Table 7 gives the optimum parameters of lead-lag controllers of TCSC.

11.3. Optimization of P-I-D Controller Parameters The P-I-D PSS parameters for machine 4 presented in Table 6 are kept fixed and the problem is now to optimize the parameters of P-I-D controller of TCSC. As the input signals for TCSC controllers have been taken from machine 10, the speed deviations of machine-10 ($\Delta\omega_{10}$) are used as the input signals to the P-I-D controller of TCSC.

In the case of TCSC equipped with P-I-D controller, three parameters $K_{PTCSC10}$, $K_{ITCSC10}$, and $K_{DTCSC10}$ are optimized by minimizing the objective function given by Equation 17. Table 8 gives the optimum parameters of P-I-D controllers of TCSC.

12. RESULTS AND DISCUSSIONS

Table 9 depicts the comparison of electromechanical mode eigenvalues and minimum values of J for TCSC equipped with lead-lag controller and CPSS and TCSC equipped with P-I-D controller and P-I-D PSS respectively. It is seen that considering TCSC for both the control systems, real parts of all electromechanical mode eigenvalues have shifted to the left half of s-plane than without controllers. From Table 9, it is seen that with the use of TCSC equipped with P-I-D controller and P-I-D PSS, the real parts of almost all electromechanical mode eigenvalues have moved (on the left half of the s-plane) far away from the origin as compared to that of TCSC equipped with lead-lag controller and CPSS. It is also seen from Table 9 that the value of J considering TCSC equipped with P-I-D controller and P-I-D PSS is much less as compared

TABLE 5. Optimum Values of the Gains and Parameters of CPSS for Machine 4.

Optimum Gains and Parameters of CPSS				
K_{S4} = 0.1817	T_{14} = 0.4272	T_{24} = 0.0805	T_{34} = 0.5143	T_{44} = 0.0959

TABLE 6. Optimum Values of the Gains of P-I-D Controller for Machine 4.

Optimum Gains of P-I-D PSS		
K_{P4} = 2.6598	K_{I4} = 0.0143.	K_{D4} = 4.4889

TABLE 7. Optimum Values of the Gains and Parameters of TCSC Equipped with Lead-Lag Controller for Machine 10.

Optimum gains and parameters of TCSC Equipped with Lead-Lag Controller			
$K_{STCSC10}$ = 2.7491	$T_{1TCSC10}$ = 0.7049	$T_{2TCSC10}$ = 0.0630	$T_{4TCSC10}$ = 0.1198

TABLE 8. Optimum Values of the Gains of P-I-D Controller for Machine 10.

Optimum Gains TCSC Equipped with P-I-D Controller		
$K_{PTCSC10}$ = 5.8806	$K_{ITCSC10}$ = 0.0246	$K_{DTCSC10}$ = 6.8347

TABLE 9. Comparison of the Electromechanical Mode Eigenvalues and Minimum Value of J Considering TCSC Equipped Lead-Lag Controller with CPSS and TCSC Equipped P-I-D Controller with P-I-D PSS.

TCSC Equipped Lead-Lag Controller with CPSS	TCSC Equipped P-I-D Controller with P-I-D PSS
-0.0048 ± j7.3247	-0.3140 ± j7.1390
-0.2872 ± j6.6818	-0.3919 ± j6.8006
-0.3467 ± j7.1210	-1.0214 ± j7.1005
-0.3564 ± j6.2433	-0.9198 ± j5.9391
-0.4153 ± j8.4992	-0.5703 ± j8.5396
-0.6854 ± j3.4634	-0.9198 ± j3.9391
-0.7819 ± j7.4389	-0.9627 ± j7.4371
-0.9061 ± j9.2699	-1.0944 ± j9.4938
-1.1415 ± j6.7300	-1.3032 ± j6.3334
J = 0.0143	J = 0.0083

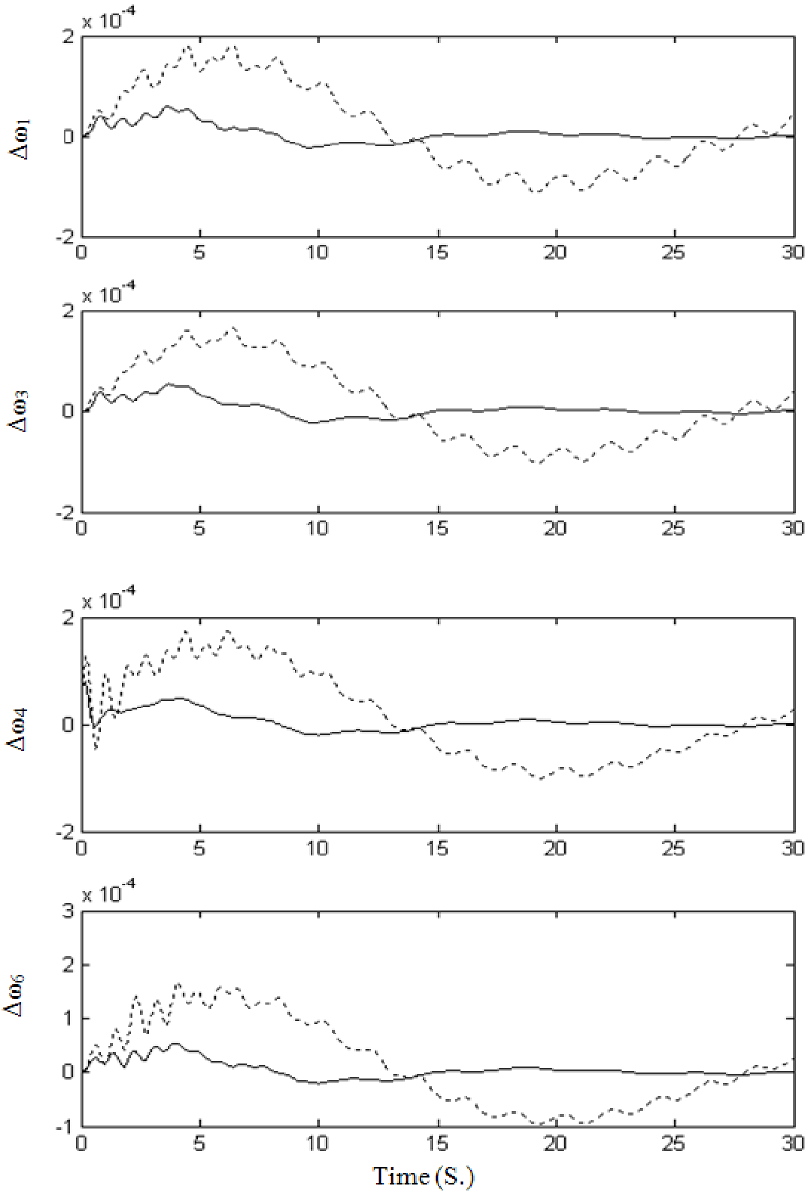

Figure 7. Dynamic responses for ten machine thirty nine bus system considering optimum parameters settings of TCSC equipped with P-I-D controller and P-I-D PSS and TCSC equipped with lead-lag controller and CPSS. (----TCSC equipped with P-I-D controller and P-I-D PSS, —TCSC equipped with lead-lag controller and CPSS).

to that of TCSC equipped with lead-lag controller and CPSS. From Table 9, it is clearly seen that TCSC equipped with P-I-D controller and P-I-D PSS is much better than that of TCSC equipped with lead-lag controller and CPSS. This is further compared by plotting the dynamic responses.

Figure 7 shows the speed deviation of some of the machines considering lead-lag controllers in machine 10 and CPSS in machine 4 and P-I-D controllers in machine 10 and P-I-D PSS in machine 4. It was found that settling time for these responses considering TCSC equipped with lead-lag controller and CPSS is more than 25 seconds. Whereas settling time for these responses considering TCSC equipped with P-I-D controller and P-I-D PSS is about 12 seconds and peak deviations are also very much less. Therefore, it may be concluded that TCSC equipped with P-I-D Controller and P-I-D PSS gives superior dynamic performances than that of TCSC equipped with lead-lag controller and CPSS.

For further illustration, a 6 cycle, 3-phase to ground fault at bus 14 on the line between buses 14 and 34 was simulated. Figure 8 shows the system response to a 3-phase to ground fault at bus 14. It is seen that TCSC equipped with P-I-D controller and P-I-D PSS do not adversely affect the transient stability and damp out the oscillations following the fault clearing.

13. CONCLUSIONS

In the present work, proportional-integral-derivative controller (P-I-D Controller) for TCSC and P-I-D PSS has been proposed for the enhancement of the dynamic stability of multi-machine power system. Gain settings of P-I-D controller of TCSC and P-I-D PSS and also the gains and time constants of conventional phase lead-lag controller of TCSC and CPSS have been optimized using genetic algorithm (GA). Analysis reveals that the TCSC equipped with P-I-D controller and P-I-D PSS give much better dynamic performances in terms of peak deviation and settling time as compared to that of TCSC equipped with phase lead-lag controller and CPSS. It was also found that the P-I-D controller for TCSC and P-I-D PSS do not adversely affect the transient stability and damp out oscillations following the fault clearing.

14. APPENDIX

The limiting values of gains and parameters of CPSS for multimachine system are given below:

$K_{Smin} = 0.01$, $K_{Smax} = 10.0$, $T_{1min} = 0.1$, $T_{1max} = 2.0$,

$T_{2min} = 0.01$, $T_{2max} = 0.5$, $T_{3min} = 0.1$, $T_{3max} = 2.0$, $T_{4min} = 0.01$, $T_{4max} = 0.5$.

The limiting values of gains of P-I-D PSS for multimachine system are given below:

$K_{Pmin} = -15$, $K_{Pmax} = 15$, $K_{Imin} = -0.1$, $K_{Imax} = 0.1$, $K_{Dmin} = -10$, $K_{Dmax} = 10$.

The limiting values of gains and parameters of TCSC Equipped with Lead-Lag Controller for multimachine system are given below:

$K_{STCSCmin} = 0.01$, $K_{STCSCmax} = 10.0$, $T_{1TCSCmin} = 0.1$, $T_{1TCSCmax} = 2.0$, $T_{2TCSCmin} = 0.01$, $T_{2TCSCmax} = 0.5$, $T_{3TCSCmin} = 0.1$, $T_{3TCSCmax} = 2.0$, $T_{4TCSCmin} = 0.01$, $T_{4TCSCmax} = 0.5$.

The limiting values of gains of TCSC Equipped with P-I-D Controller multimachine system are given below:

$K_{PTCSCmin} = -15$, $K_{PTCSCmax} = 15$, $K_{ITCSCmin} = -0.1$, $K_{ITCSCmax} = 0.1$, $K_{DTCSCmin} = -10$, $K_{DTCSCmax} = 10$.

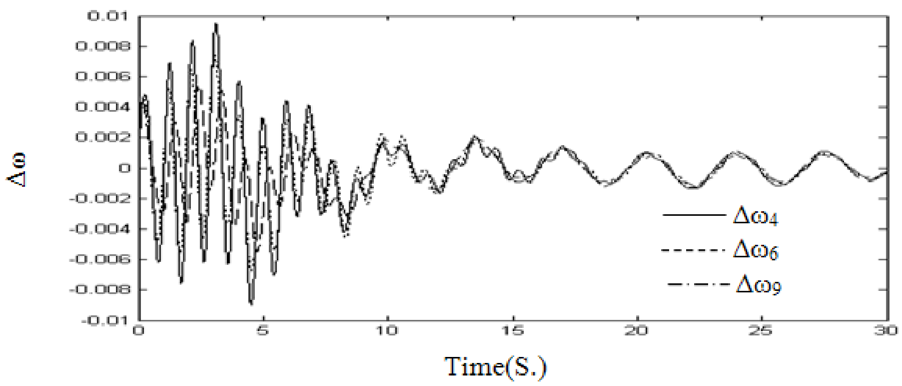

Figure 8. System responses to a six cycle three phase fault at bus 14 on the line between buses 14 and 34 considering TCSC equipped with P-I-D controller and P-I-D PSS.

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