ROBUST COORDINATED DESIGN OF PSS AND TCSC USING GENETIC ALGORITHMS

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ABSTRACT

Power system stability enhancement via robust coordinated design of a power system stabilizer (PSS) and a thyristor-controlled series capacitor (TCSC)-based stabilizer is thoroughly investigated in this paper. The coordinated design problem of robust excitation and TCSC-based controllers over a wide range of loading conditions and system configurations is formulated as an optimization problem with an eigenvalue-based objective function. The real-coded genetic algorithm (RCGA) is employed to search for optimal controller parameters. This study also presents a singular value decomposition (SVD) based approach to assess and measure the controllability of the poorly damped electromechanical modes by different control inputs. The damping characteristics of the proposed control schemes are also evaluated in terms of the damping torque coefficient over a wide range of loading conditions. The proposed stabilizers were tested on a weakly connected power system. The damping torque coefficient analysis, nonlinear simulation results, and eigenvalue analysis show the effectiveness and robustness of the proposed approach over a wide range of loading conditions.

1. INTRODUCTION

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 is available [1,2]. Nowadays, the conventional power system stabilizer (CPSS) is widely used by power utilities.

Generally, it is important to recognize that machine parameters change with loading making the machine behavior quite different at different operating conditions. Hence, PSSs should provide some degree of robustness to the variations in system parameters, loading conditions, and configurations.

H_∞ optimization techniques [3] have been applied to robust PSS design problem. However, the order of the H_∞ based stabilizer is as high as that of the plant. This gives rise to complex structure of such stabilizers and reduces their applicability.

A comprehensive analysis of the effects of the different CPSS parameters on the dynamic performance of the power system was presented in [4]. It is shown that the CPSS provide satisfactory damping over a wide range of system loading conditions [5].

Although PSSs provide supplementary feedback stabilizing signals, they suffer a drawback of being liable to cause great variations in the voltage profile. The recent advances in power electronics have led to the development of the flexible alternating current transmission systems (FACTS). Along with primary function of the FACTS devices, the real power flow can be regulated to mitigate the low frequency oscillations and enhance system stability.

Recently, several FACTS devices have been implemented and installed in practical power systems [6]. In the literature, a little work has been done on the coordination problem. Noorozian and Anderson [7] presented a comprehensive analysis of damping of power system electromechanical oscillations using FACTS. Wang and Swift [8] have discussed the damping torque contributed by FACTS devices. However, all controllers were assumed proportional and no efforts have been done towards the controller design. A comprehensive study of the coordination problem requirements among PSSs and different FACTS devices has been presented in [9]. However, no efforts have been done towards the coordinated design problem.

In this paper, a comprehensive assessment of the effects of the excitation and TCSC control when applied independently and also through coordinated application has been carried out. The design problem is transformed into an optimization problem where the real-coded genetic algorithm (RCGA) is employed to search for the optimal settings of stabilizer parameters. A controllability measure based on singular value decomposition (SVD) is used to identify the effectiveness of each control input. In addition, the damping torque coefficient is evaluated with the proposed stabilizers over a wide range of loading conditions. For completeness, the eigenvalue analysis and nonlinear simulation results are carried out to demonstrate the effectiveness and robustness of the proposed stabilizers to enhance system stability.

2. POWER SYSTEM MODEL

2.1. Generator

In this study, a single machine infinite bus system as shown in Fig. 1 is considered. The generator is equipped with PSS and the system has an TCSC as shown in Fig. 1. The generator is represented by the third-order model as follows.

$$\dot{\delta} = \omega_b(\omega - 1) \tag{1}$$

$$\dot{\omega} = (P_m - P_e - D(\omega - 1)) / M \tag{2}$$

$$\dot{E}_q' = (E_{fd} - (x_d - x_d')i_d - E_q') / T_{do}' \tag{3}$$

where, P_m and P_e are the input and output powers of the generator respectively; M and D are the inertia constant and damping coefficient respectively; δ and ω are the rotor angle and speed respectively; ω_b is the synchronous speed, E_q' is the internal voltage. Also, E_{fd} is the field voltage; T_{do}' is the open circuit field time constant; x_d and $x_d^{'}$ are d-axis reactance and d-axis transient reactance of the generator respectively.

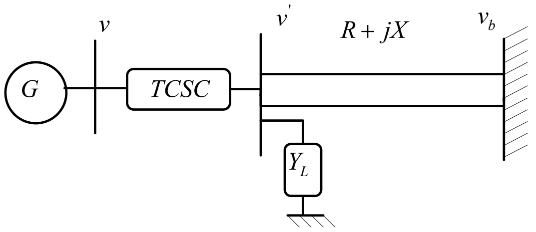

Fig. 1: Single machine infinite bus system

2.2. Exciter and PSS

The IEEE Type-ST1 excitation system shown in Fig. 2 is considered. It can be described as

$$\dot{E}_{fd} = (K_A(V_{ref} - v + u_{PSS}) - E_{fd})/T_A \quad (5)$$

where, K_A and T_A are the gain and time constant of the excitation system respectively; V_{ref} is the reference voltage. As shown in Fig. 2, a conventional lead-lag PSS is installed in the feedback loop to generate a stabilizing signal u_{PSS}.

2.3. TCSC-Based Stabilizer

Fig. 3 illustrates the block diagram of a TCSC with a lead-lag compensator. The reactance of the TCSC, X_{TCSC}, can be expressed as

$$\dot{X}_{TCSC} = (K_s(X_{TCSC}^{ref} - u_{TCSC}) - X_{TCSC})/T_s \quad (6)$$

where, X_{TCSC}^{ref} is the reference reactance of TCSC; K_s and T_s are the gain and time constant of the TCSC. A conventional lead-lag controller is installed in the feedback loop to generate the TCSC stabilizing signal u_{TCSC} as shown in Fig. 3

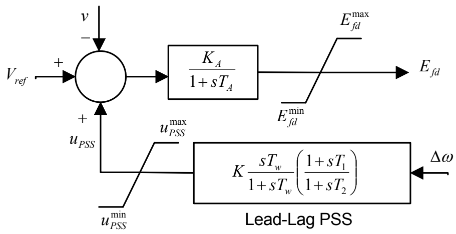

Fig. 2: IEEE Type-ST1 excitation system with PSS

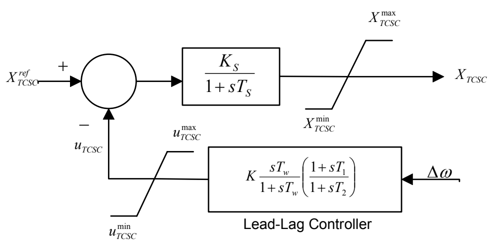

Fig. 3: TCSC with lead-lag controller

2.4. Linearized Model

In the design of electromechanical mode damping controllers, the linearized incremental model around a nominal operating point is usually employed [1-2]. Linearizing the system model yield the following state equation

$$\dot{X} = AX + HU \quad (7)$$

Here, the state vector X is $[\Delta\delta, \Delta\omega, \Delta E_q^{'}, \Delta E_{fd}]^T$ and the control vector U is $[u_{PSS}, \Delta X_{TCSC}]^T$. K_1-K_6, K_p, K_q, and K_v are linearization constants.

3. THE PROPOSED APPROACH

3.1. Electromechanical Mode Identification

The state equations of the linearized model can be used to determine the eigenvalues of the system matrix A. Out of these eigenvalues, there is a mode of oscillations related to machine inertia. For the stabilizers to be effective, it is extremely important to identify the eigenvalue associated with the electromechanical mode. In this study, the participation factors method [10] is used.

3.2. Controllability Measure

To measure the controllability of the electromechanical mode by a given input, the singular value decomposition (SVD) is employed in this study. Mathematically, if G is an $m \times n$ complex matrix then there exist unitary matrices W and V with dimensions of $m \times m$ and $n \times n$ respectively such that G can be written as

$$G = W \Sigma V^H \quad (8)$$

where

$$\Sigma = \begin{bmatrix} \Sigma_1 & 0 \\ 0 & 0 \end{bmatrix}, \quad \begin{matrix} \Sigma_1 = diag(\sigma_1, \ldots.., \sigma_r) \\ \text{with } \sigma_1 \geq \ldots \geq \sigma_r \geq 0 \end{matrix} \quad (9)$$

where $r = min\{m,n\}$ and $\sigma_1,\ldots,\sigma_r$ are the singular values of G.

The minimum singular value σ_r represents the distance of the matrix G from the all matrices with a rank of r–1. This property can be utilized to quantify modal controllability [11]. The minimum singular value, σ_{min}, of the matrix $[\lambda I - A \; h_i]$ indicates the capability of the i-th input to control the mode associated with the eigenvalue λ. Having been identified, the controllability of the electromechanical mode can be examined with both inputs in order to identify the most effective one to control that mode.

3.3. Stabilizer Design

A widely used conventional lead-lag structure for both excitation and TCSC-based stabilizers, shown in Figs. 2 and 3, is considered. In this structure, the washout time constant T_w is usually prespecified. The controller gain K and time constants T_1 and T_2 are to be determined.

In this study, several loading conditions represent nominal, light, high, and leading power factor without and with system parameter uncertainties are considered to ensure the robustness of the proposed stabilizers. In the stabilizer design process, it is aimed to enhance the system damping of the poorly damped electromechanical mode eigenvalues at the entire range of the specified loading conditions. Therefore, the following objective function J is used.

$J = max\{Real(\lambda_i)$: λ_i is the electromechanical mode eigenvalue of the ith loading condition$\}$ (10)

In the optimization process, it is aimed to *Minimize J* while satisfying the problem constraints that are the optimized parameter bounds. Therefore, the design problem can be formulated as the following optimization problem.

Minimize J (11)

Subject to

$K^{\min} \le K \le K^{\max}$ (12)

$T_1^{\min} \le T_1 \le T_1^{\max}$ (13)

$T_3^{\min} \le T_3 \le T_3^{\max}$ (14)

The proposed approach employs RCGA to solve this optimization problem and search for optimal or near optimal set of the optimized parameters. To investigate the capability of PSS and TCSC controller when applied individually and also through coordinated application, both are designed independently first and then in a coordinated manner.

3.4. Damping Torque Coefficient Calculation

To assess the effectiveness of the designed stabilizers, the damping torque coefficient is evaluated and analyzed. The torque can be decomposed into synchronizing and damping components as follows

$$\Delta T_e(t) = K_{syn}\,\Delta\delta(t) + K_d\,\Delta\omega(t) \tag{15}$$

where K_{syn} and K_d are the synchronizing and damping torque coefficients respectively. It is worth mentioning that K_d is a damping measure to the electromechanical mode of oscillations [12].

4. IMPLEMENTATION

Genetic algorithms (GA) are search algorithms based on the mechanics of natural selection and survival-of-the-fittest. One of the most important features of the GA as a method of control system design is the fact that minimal knowledge of the plant under investigation is required. Since the GA optimize a performance index based on input/output relationships only, far less information than other design techniques is needed. Further, because the GA search is directed towards increasing a specified performance, the net result is a controller which ultimately meets the performance criteria.

Linearizing the system model at each loading condition of the specified range, the electromechanical mode is identified and its damping ratio is calculated. Then, the objective function is evaluated and RCGA is applied to search for optimal settings of the optimized parameters of the proposed control schemes. In our implementation, the crossover and mutation probabilities of 0.9 and 0.01 respectively are found to be quite satisfactory. The number of individuals in each generation is selected to be 100. In addition, the search will terminate if the best solution does not change for more than 50 generations or the number of generations reaches 500.

5. RESULTS AND DISCUSSIONS

5.1. Loading Conditions and Proposed Stabilizers

In this study, the PSS and TCSC-based controller parameters are optimized over a wide range of operating conditions and system parameter uncertainties. Four loading conditions represent nominal, light, heavy, and leading power factor are considered. Each loading condition is considered without and with parameter uncertainties as given in Table 1. Hence, the total number of points considered for the design process is 16.

Table 1: Loading conditions and parameter uncertainties

Loading condition (P,Q) in pu	***Parameter uncertainties***
Nominal (1.0,0.015)	No parameter uncertainty
Light (0.3,0.100)	30% increase of line reactance *X*
Heavy (1.1,0.100)	30% decrease of T'_{do}
Leading pf (0.7,-0.300)	25% decrease of machine inertia *M*

The proposed approach has been implemented on a weakly connected power system. The detailed data of the power system used in this study is given in [1]. The final settings of the optimized parameters for the proposed stabilizers are given in Table 2.

Table 2: Optimal parameter settings of the proposed stabilizers

	Individual Design		***Coordinated Design***	
	PSS	***TCSC***	***PSS***	***TCSC***
K	35.889	87.359	70.702	100.00
T_1	0.2624	0.0402	0.1059	0.2026
T_2	0.1000	0.1000	0.1000	0.1000

5.2. Mode Controllability Measure

With each input signal, the minimum singular value σ_{min} has been estimated to measure the controllability of the electromechanical mode from that input. Fig. 4 shows σ_{min} with loading conditions over the range of P_e = [0.05 – 1.4] pu and Q = 0.4 pu. It can be seen that the electromechanical mode controllability through TCSC is much more effective than the case of PSS.

5.3. Damping Torque Coefficient

The damping torque coefficient has been estimated with PSS and TCSC-based stabilizer when designed individually and in a coordinated manner. Fig. 5 shows K_d versus the loading variations. It was observed that the TCSC provides negative damping at low loading conditions in particular with leading power factor loading. It is also evident that the coordinated design of PSS and TCSC-based stabilizer provides great damping characteristics and enhance significantly the system stability compared to individual design of these stabilizers.

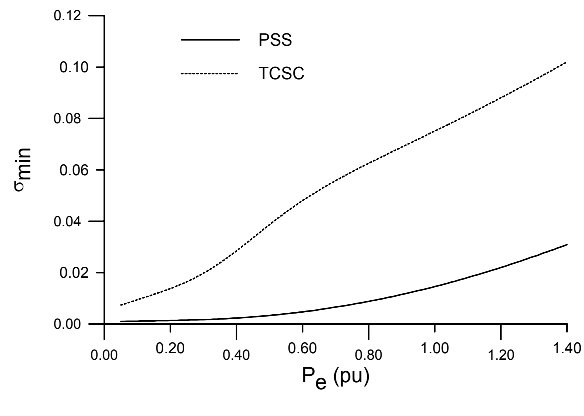

Fig. 4: σ_{min} with loading variations and Q = 0.4 pu

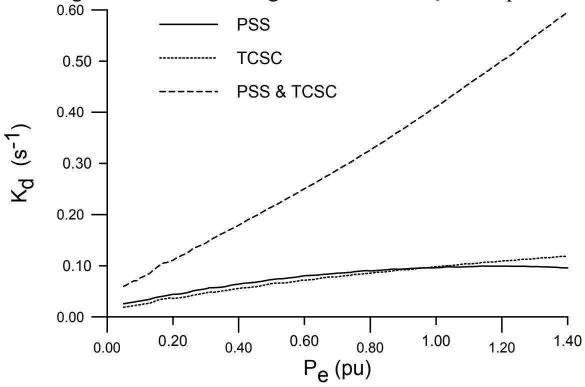

Fig. 5: K_d with the loading variations and Q = 0.4 pu

5.4. Eigenvalue Analysis and Nonlinear Simulations

For completeness and verification, all the proposed stabilizers were tested at nominal Loading (P,Q)=(1.0,0.015) pu with 6-cycle fault. The system eigenvalues are given in Table 3. It is clear that the system stability is greatly enhanced with the proposed stabilizers. It can be also seen that the coordinated design outperforms the individual design in the sense that the damping factors of the electromechanical modes are greatly shifted to the left on the *s*-plane.

Table 3: Eigenvalues at nominal loading

No Control	*PSS Only*	*TCSC Only*	*Coord. Design*
+0.30 ±*j* 4.96	**-2.23 ±*j* 9.62**	**-2.64 ±*j* 7.88**	**-7.85 ±*j* 7.03**
-10.39 ±*j* 3.287	-2.60 ±*j* 2.70	-4.30 ±*j* 2.84	-10.5 ±*j* 12.6
------	-20.53, -0.209	-23.03, -13.28	-12.15, -10.00
------	------	-0.209	-1.387, -0.234
------	------	------	-0.200

The nonlinear time domain simulations have been carried out to assess the effectiveness of the proposed control schemes. Fig. 6 shows the system response with the specified disturbance at nominal loading condition. It can be seen that the coordinated design approach provides the best damping characteristics and enhance greatly the first swing stability.

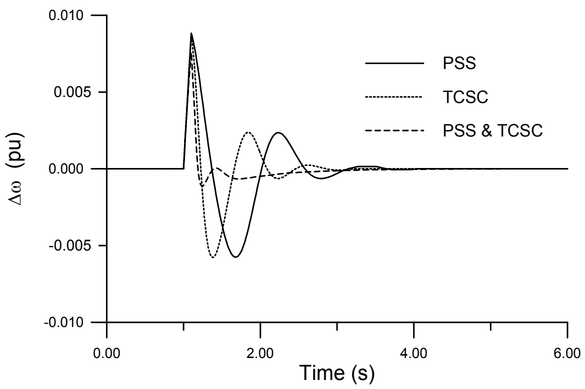

Fig. 6: Rotor speed response at nominal loading

6. CONCLUSION

In this study, the power system stability enhancement via robust design of PSS and TCSC-based stabilizer when applied independently and also through coordinated application was discussed and investigated. A controllability measure for the poorly damped electromechanical modes using a singular value decomposition approach was employed to assess the effectiveness of the proposed stabilizers. The damping characteristics of the proposed schemes were also evaluated in terms of the damping torque coefficient. The proposed stabilizers have been tested on a weakly connected power system with different loading conditions. The eigenvalue analysis and nonlinear simulation results show the effectiveness and robustness of the proposed stabilizers to enhance the system stability.

7. ACKNOWLEDGMENT

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