POWER SYSTEM STABILITY ENHANCEMENT VIA COORDINATED DESIGN OF A PSS AND AN SVC-BASED CONTROLLER

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ABSTRACT

Power system stability enhancement via robust coordinated design of a power system stabilizer (PSS) and a static VAR compensator (SVC)-based stabilizer is thoroughly investigated in this paper. The coordinated design problem of robust excitation and SVC-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 schemes are also evaluated in terms of the damping torque coefficient over a wide range of loading conditions. The proposed stabilizers are tested on a weakly-connected power system. The nonlinear simulation results and eigenvalue analysis show the effectiveness and robustness of the proposed approach.

1. INTRODUCTION

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

H_∞ optimization techniques [3] have been applied to robust PSS design problem. However, the importance and difficulties in the selection of weighting functions of H_∞ optimization problem have been reported. On the other hand, 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 overall dynamic performance of the power system was presented in [4]. Robust design of CPSSs in multimachine power systems using genetic algorithm is presented in [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 AC transmission systems (FACTS). Generally, a potential motivation for the accelerated use of FACTS devices is the deregulation environment in contemporary utility business. Along with FACTS devices primary function, the real power flow can be regulated to mitigate the low frequency oscillations and enhance power system stability.

In the literature, a little work has been done on the coordination problem of excitation and FACTS-based stabilizers. Mahran et al [6] presented a coordinated PSS and SVC control for a synchronous generator. Rahim and Nassimi [7] presented optimum feedback strategies for both SVC and exciter controls. Noorozian and Anderson [8] presented a comprehensive analysis of damping of power system electromechanical oscillations using FACTS. Wang and Swift [9] have discussed the damping torque contributed by FACTS devices. A comprehensive study of the coordination problem requirements has been presented in [10]. However, no efforts have been done towards the coordinated design problem.

In this paper, a comprehensive assessment of the effectiveness of the excitation and SVC control when applied independently and also through coordinated application has been carried out.

2. POWER SYSTEM MODEL

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

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

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

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

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; i_d is d-axis current; 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.

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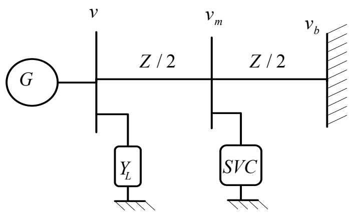

Figure 1: Single machine infinite bus system

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

$$\dot{E}_{fd} = (K_A(V_{ref} - v + u_{PSS}) - E_{fd}) / T_A \tag{4}$$

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}.

Fig. 3 illustrates the block diagram of an SVC with a lead-lag compensator. The susceptance of the SVC, B, can be expressed as

$$\dot{B} = (K_s(B_{ref} - u_{SVC}) - B) / T_s \tag{5}$$

where, B_{ref} is the reference susceptance of SVC; K_s and T_s are the gain and time constant of the SVC.

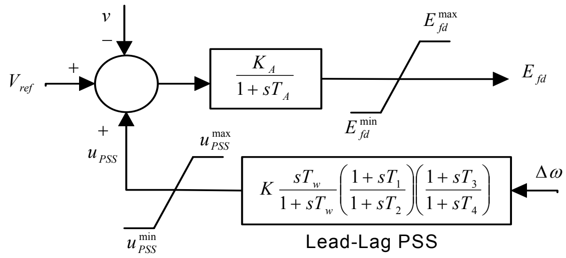

Figure 2: IEEE Type-ST1 excitation system with PSS

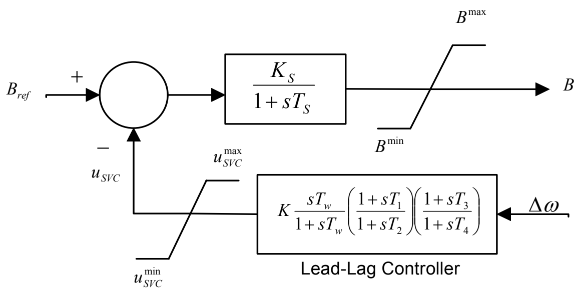

Figure 3: SVC with lead-lag controller

2.4. Linearized Model

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

$$\dot{X} = AX + HU \tag{6}$$

Here, the state vector X is $[\Delta\delta, \Delta\omega, \Delta E_q^{'}, \Delta E_{fd}]^T$ and the control vector U is $[u_{PSS}, \Delta B]^T$. 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 [5] 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

$$G = W \Sigma V^H \tag{7}$$

where

$$\Sigma = \begin{bmatrix} \Sigma_1 & 0 \\ 0 & 0 \end{bmatrix}, \quad \begin{matrix} \Sigma_1 = diag(\sigma_1, ..., \sigma_r) \\ \text{with } \sigma_1 \geq ... \geq \sigma_r \geq 0 \end{matrix} \tag{8}$$

where $r = min\{m,n\}$ and σ's 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 [10]. 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 SVC-based stabilizers, shown in Figs. 2 and 3, is considered. 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.

$J = min\{\zeta_i$: ζ_i is the electromechanical mode damping ratio of the ith loading condition$\}$ (9)

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

Maximize J (10)

Subject to

$$K^{min} \leq K \leq K^{max} \tag{11}$$

$$T_1^{min} \leq T_1 \leq T_1^{max} \tag{12}$$

$$T_3^{min} \leq T_3 \leq T_3^{max} \quad (13)$$

The proposed approach employs RCGA [10] to solve this optimization problem and search for optimal set of the optimized parameters. To investigate the capability of PSS and SVC 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

$$\Delta T_e(t) = K_{syn}\, \Delta\delta(t) + K_d\, \Delta\omega(t) \quad (14)$$

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 of the electromechanical mode of oscillations [10].

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 SVC-based controller parameters are optimized over a wide range of operating conditions and system parameter uncertainties. Four loading conditions 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.

The detailed data of the system used in this study is given in [1]. The final settings of the proposed stabilizers are given in Table 2.

Table 1: Loading conditions and parameter uncertainties

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

Table 2: Optimal settings of the proposed stabilizers

	Individual Design		***Coordinated Design***	
	PSS	***SVC***	***PSS***	***SVC***
K	17.849	300.00	43.457	99.737
T_1	0.4334	0.2143	0.1647	0.7650
T_2	0.1000	0.3000	0.1000	0.3000
T_3	------	0.0100	------	0.3789
T_4	------	0.3000	------	0.3000

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 is almost the same with both PSS and SVC.

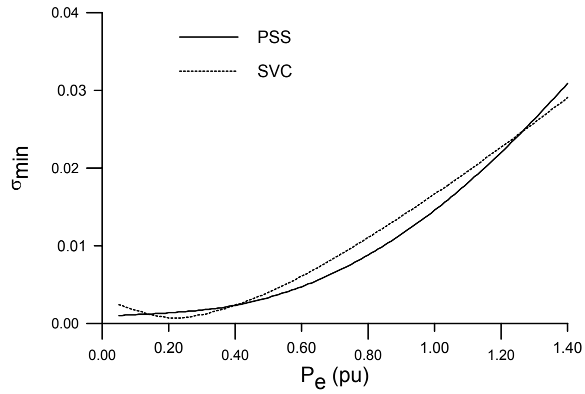

Figure 4: σ_{min} with loading variations and Q = 0.4 pu

5.3. Damping Torque Coefficient

In order to evaluate the effectiveness of the proposed stabilizers, the damping torque coefficient has been estimated with PSS and SVC-based stabilizer when designed individually and in coordinated manner. Fig. 5 shows K_d versus the loading variations. It is clear that the SVC provides negative damping at low loading conditions. This problem is alleviated with the coordinated design approach. It can be also seen that PSS outperforms SVC and does not suffer from such a prblem. It is also evident that the coordinated design of PSS and SVC-based stabilizer provides great damping characteristics and enhance significantly the system stability compared to individual design.

5.4. Eigenvalue and Nonlinear Simulations

For completeness, 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 coordinated design of the proposed stabilizers.

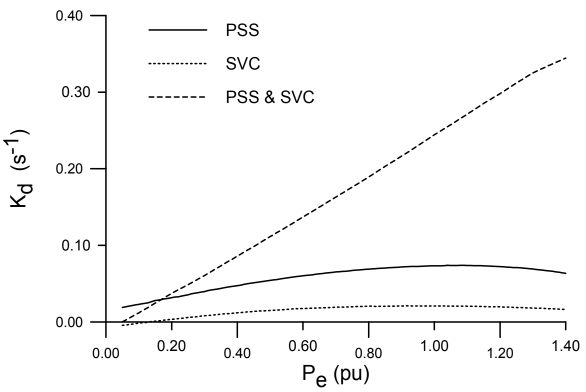

Figure 5: K_d with the loading variations and Q = 0.4 pu

Table 3: System eigenvalues with the proposed stabilizers

No Control	*PSS Only*	*SVC Only*	*Coord. Design*
+0.3 ±*j* 5.0	-1.8 ±*j* 3.5	-0.6 ±*j* 6.0	-2.2 ±*j* 3.1
-10.4 ±*j* 3.3	-3.2 ±*j* 9.0	-3.0 ±*j* 1.1	-7.0 ±*j* 12.2
------	-20; -0.2	-20; -12.6	-2.9 ±*j* 0.3
------	------	-7.0; -0.2	-17.9; -14.8
------	------	------	-0.210; -0.200

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

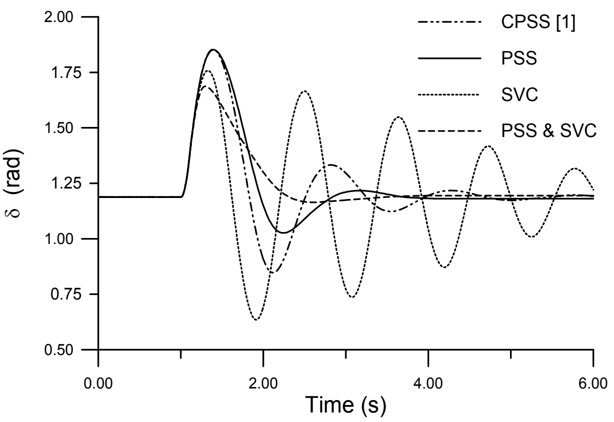

Figure 6: System response with a 6-cycle fault

6. CONCLUSION

In this study, the power system stability enhancement via PSS and SVC-based stabilizer when applied independently and also through coordinated application was discussed and investigated. For the proposed stabilizer design problem, an eigenvalue-based objective function to increase the system damping was developed. Then, the real-coded genetic algorithm was implemented to search for the optimal stabilizer parameters. In addition, a controllability measure for the poorly damped modes using a singular value decomposition approach was used 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

The authors acknowledge the support of King Fahd University of Petroleum & Minerals.

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