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Coordinated Design of TCSC and PSS by Using PSO Algorithm for Enhancement of SMIB Power System Stability

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ABSTRACT

The main aim of this study is to investigate the enhancement of power system stability via individual and coordinated design of Thyristor Controlled Series Compensation (TCSC) and Power System Stabilizer (PSS) in single machine infinite bus (SMIB) power system. The coordinated design problem of PSS and TCSC-based controllers is formulated as an optimization problem with an eigenvalue-based objective function. Then, particle swarm optimization (PSO) algorithm is applied to search for optimal controller parameters. To compare the performance of PSS and TCSC-based controllers, both of them are designed independently at first and then in a coordinated manner for individual and coordinated applications. The proposed stabilizers are tested on a weakly connected power system subjected to various disturbances. The eigenvalue analysis and nonlinear simulation results show the robustness and the effectiveness of the proposed controllers and their ability to provide efficient damping of low frequency oscillations. Matlab/SIMULINK software package is used for the simulations.

Keywords: Particle swarm optimization, power system stability, PSS, simultaneous stabilization, TCSC.

TMSB Güç Sistemi Kararlılığının Artırılması için PSO Algoritması Kullanarak TKSK ve GSKK'nin Koordineli Tasarımı

ÖZ

Bu çalışmanın temel amacı, tek makinalı sonsuz baralı (TMSB) güç sisteminde tristör kontrollü seri kompanzatör (TKSK) ve güç sistemi kararlı kılıcısının (GSKK) bireysel ve koordineli tasarım yoluyla güç sistemi kararlılığının iyileştirilmesini araştırmaktır. GSKK ve TKSK tabanlı kontrolörlerin koordineli tasarım problemi özdeğer tabanlı bir amaç fonksiyonu ile bir optimizasyon problemi olarak formüle edildi. Daha sonra parçacık sürü optimizasyonu (PSO) algoritması uygun kontrolör parametrelerini bulması için uygulandı. GSKK ve TKSK tabanlı kontrolörlerin performansını karşılaştırmak amacıyla, bireysel ve koordineli uygulamalar için bunların her ikisi ilkin bağımsız ve daha sonra koordineli bir şekilde tasarlandı. Önerilen stabilizatörler çeşitli arızalara maruz kalan zayıf bağlı bir güç sistemi üzerinde test edildi. Özdeğer analizi ve lineer olmayan simülasyon sonuçları önerilen kontrolörlerin dayanıklılığı ile etkinliğini ve düşük frekanslı salınımların etkin bir şekilde sönümlenmelerini sağlama becerilerini göstermektedir. Simülasyonlar için Matlab/SIMULINK yazılım paketi kullanılmıştır.

Anahtar Kelimeler: Parçacık sürü optimizasyonu, güç sistemi kararlılığı, PSS, eşzamanlı stabilizasyon, TKSK.

1. INTRODUCTION

The problem of poorly damped low frequency oscillations associated with the generator rotor swings has been a matter of concern to power engineers for a long time. Plentiful work has been dedicated in power engineering to achieve stable and reliable operation of synchronous generators. Power system stabilizers (PSSs) are widely used to suppress the generator electromechanical oscillations and improve the overall stability of power system. PSSs have been extensively studied and used in power systems in the last few decades. Early years, DeMello and Concordia (1969) presented the concept of synchronous machine stability as affected by excitation control. Presently, the conventional lead-lag power system stabilizer (CPSS) widely used in power systems to damp out small oscillations.

Kundur et al. (1989) have presented a detailed analytical work to determine the parameters of conventional lead-lag PSSs so as to improve the transient stability of both local and inter-area modes. These parameters consist of the stabilizer gain, stabilizer output limits, and signal washout. In addition, Gibbard (1991) demonstrated that the CPSS provide satisfactory damping performance over a wide range of system loading conditions. The robustness nature of the CPSS is due to the fact that the torque-reference voltage transfer function remains more or less invariant over a wide range of operating conditions.

Recently appeared FACTS (Flexible AC Transmission System)-based stabilizers offer an alternative method to improve the damping of power system. Thyristor-controlled FACTS devices, such as static var compensator (SVC) and thyristor-controlled series compensator (TCSC), have successfully been used in power systems for dynamic reactive power compensation. Thyristor controlled series compensation (TCSC) is a kind of new power system equipment developed from the conventional fixed series capacitor. Its effective fundamental equivalent reactance can be controlled continuously by tuning the thyristor in a relatively large range, either capacitive or inductive. It can have various roles in the operation and control of power systems, such as the utilization of the transmission capability, transient stability improvement, efficient power flow control, power oscillation damping, subsynchronous resonance (SSR) mitigation, and short-circuit currents limitation. Thus, research on the TCSC has attracted much attention. The applications of TCSC for power oscillation damping and stability enhancement can be found in several references (Del Rosso et al., 2003; Li et al., 2000; Mattavelli et al., 1997).

Uncoordinated FACTS-based stabilizers and PSS may cause destabilizing interaction. To improve overall system performance, many researches were made on the coordination between FACTS Power Oscillation Damping (POD) and PSS controllers (Pourbeik and Gibbard, 1998; Abdel-Magid and Abido, 2004; Abido and Abdel-Magid, 2003; Cai and Erlich, 2005). Pourbeik and Gibbard (1998) proposed a technique for the simultaneous coordination of PSS and FACTS-based lead-lag controller in multi-machine power systems by using the concept of induced damping and synchronizing torque coefficients. Abido and Abdel-Magid (2003) represented a coordinated design of robust excitation and TCSC-based damping controllers using real-coded genetic algorithms in SMIB power system. Some of these methods are based on the linearized power system models and the others on complex nonlinear simulations.

The Phillips-Heffron model is a well-known model for synchronous generators (Yu, 1983). Traditionally, for the small signal stability studies of a SMIB power system, the linear model of Phillips-Heffron has been used for years, providing reliable results (Heffron and Phillips, 1952). Although the model is a linear model, it is quite accurate for studying low frequency oscillations and stability of power systems. It has also been successfully used for designing and tuning of the conventional PSS.

Heuristic optimization techniques such as particle swarm optimization, genetic algorithm (GA), tabu search algorithm, and simulated annealing are the most fast growing optimization method in the past decades. Recently, PSO technique is a promising heuristic algorithm for handling the optimization problem. It is a population-based search algorithm and searches in parallel using a group of particles similar to other artificial intelligent based on heuristic optimization techniques. The original PSO suggested by Kennedy and Ebenhart is based on the analogy of swarm of bird and schooling of fish (Kennedy and Ebenhart, 1995). In PSO system, particles change their positions by flying around in a multi-dimensional search space. During flight, each particle adjusts its position according to its own experience and the experience of neighboring particles, making use of the best position encountered by itself and its neighbors. Generally, PSO algorithms are summarized as: a simple concept, easy to implement, robustness to control parameters, and computationally efficient. Unlike the other heuristic techniques, PSO has a flexible and well-balanced mechanism to improve the local and global exploration abilities (Ekinci, 2016; Ekinci, 2015).

In this paper, a comprehensive assessment of the effects of the PSS and TCSC based control when applied independently and also through coordinated application has been carried out. The design problem of PSS and TCSC based controller to improve power system stability is transformed into an optimization problem. The design objective is to improve the stability of SMIB power system, subjected to different disturbances. PSO technique is employed to search for the optimal PSS and TCSC controller parameters. For completeness, the eigenvalue analysis and nonlinear simulation results are presented to demonstrate the effectiveness of the proposed controllers to improve the power system stability.

2. POWER SYSTEM MODELING

In this study, the SMIB power system shown in Fig. 1 is considered. The generator is equipped with a PSS and the system has a TCSC installed in transmission line. The synchronous generator is delivering power to the infinite bus through a double circuit transmission line. In the figure, X_T, X_L and X_{TH} represent the reactance of the transformer, the transmission line per circuit and the Thevenin's impedance of receiving end of the system, respectively. V_T and V_∞ are the generator terminal and infinite bus voltage, respectively.

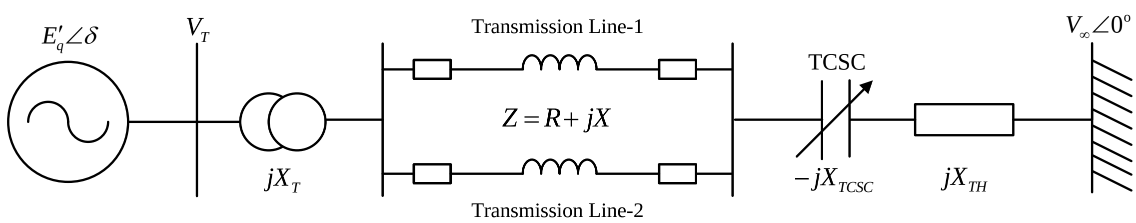

Fig. 1. Single machine infinite bus power system

2.1. Modeling of the SMIB Power System

The non-linear differential and algebraic equations of the single-machine infinite-bus power system with PSS and TCSC are (Yu, 1983):

$$\frac{d\delta}{dt} = \omega_s(\omega - 1) \tag{1}$$

$$\frac{d\omega}{dt} = \frac{1}{2H}\left[P_m - P_e - D(\omega - 1)\right] \tag{2}$$

$$\frac{dE_q'}{dt} = -\frac{1}{T_{do}'}(E_q' + (X_d - X_d')I_d - E_{fd}) \tag{3}$$

$$P_e = E_q' I_q + (X_q - X_d')I_d I_q \tag{4}$$

$$V_d = X_q I_q \tag{5}$$

$$V_q = E_q' - X_d' I_d \tag{6}$$

$$V_T = (V_d^2 + V_q^2)^{1/2} \tag{7}$$

$$I = (I_d + jI_q)e^{j(\delta - \pi/2)} \tag{8}$$

where, P_m and P_e are the input and output powers of the generator respectively; E_q' is the internal voltage; H and D are the inertia constant and damping coefficient, respectively; ω_s is the synchronous speed; δ and ω are the rotor angle and speed, respectively; V_T is the terminal voltage; E_{fd} is the field voltage; T_{do}' is the open circuit field time constant; X_q is the q-axis reactance of the generator; X_d and X_d' are the d-axis reactance and the d-axis transient reactance of the generator, respectively.

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

$$\frac{dE_{fd}}{dt} = \frac{1}{T_A}(K_A(V_{ref} - V_T + V_{PSS}) - E_{fd}) \tag{9}$$

$$E_{fd}^{\min} \le E_{fd} \le E_{fd}^{\max} \tag{10}$$

Here, K_A and T_A are the gain and time constant of the excitation system; V_{ref} is the reference voltage; V_T is the terminal voltage; V_{PSS} is signal from the PSS output. As shown in Fig. 2, a conventional lead-lag PSS is installed in the feedback loop to generate a stabilizing signal. The input to the PSS is the speed deviation $\Delta\omega$.

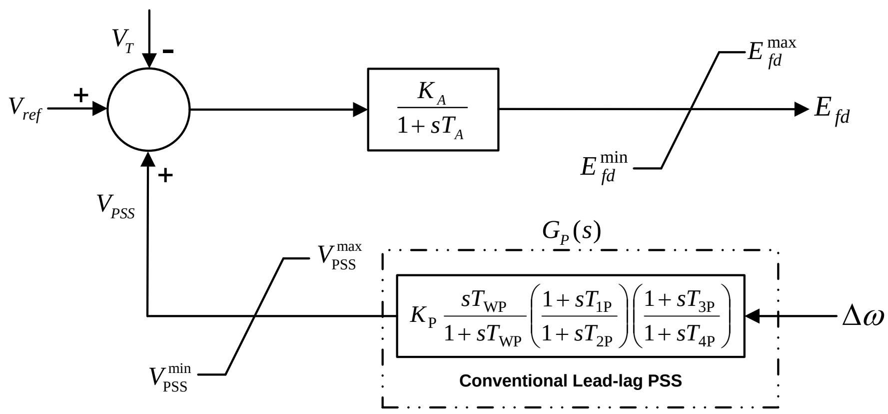

Fig. 2. IEEE type ST1A excitation system with PSS

2.2. Modeling of TCSC-Based Stabilizer

Thyristor controlled series compensation (TCSC) is an important member of FACTS family. It has been in use for many years to increase line power transfer as well as to improve power system stability. The main circuit of a TCSC is shown in Fig 3. It consists of three components, capacitor banks C, bypass inductor L, and bi-directional thyristors SCR. The firing angles of the thyristors α are controlled to adjust the TCSC reactance X_{TCSC} in accordance with a system control algorithm.

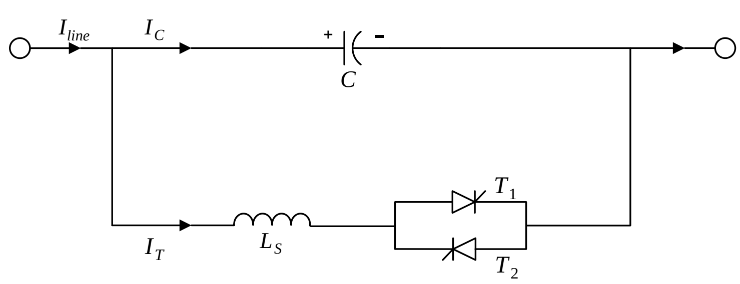

Fig. 3. The main circuit of TCSC

According to the variation of the thyristor firing angle α or conduction angle σ, this process can be modeled as a fast switch between corresponding reactance offered to the power system. Assuming that the total current passing through the TCSC is sinusoidal; the equivalent reactance at the fundamental frequency can be represented as a variable reactance X_{TCSC}. There exists a steady-state relationship between α and X_{TCSC}. This relationship can be described by the following equation (Mathur and Varma, 2002).

$$\begin{aligned} X_{TCSC} &= X_C - \frac{X_C^2}{(X_C - X_P)}\frac{\sigma + \sin\sigma}{\pi} \\ &+ \frac{4X_C^2}{(X_C - X_P)}\frac{\cos^2(\sigma/2)}{(k^2-1)}\frac{[k\tan(k\sigma/2) - \tan(\sigma/2)]}{\pi} \end{aligned} \tag{11}$$

where $\sigma = 2(\pi - \alpha)$ is the conduction angle of TCSC controller; $k = \sqrt{X_C / X_P}$ is the compensation ratio; X_C is the capacitor nominal reactance and X_P is the inductor reactance.

2.3. The Linearized Model of Power System

In the design of electromechanical mode damping controllers, the linearized incremental model around a nominal operating point is usually employed (Yu, 1983; Sauer and Pai, 1998). Linearizing of the system model yields the following state equation.

$$\begin{bmatrix} \Delta\dot{\delta} \\ \Delta\dot{\omega} \\ \Delta\dot{E}'_q \\ \Delta\dot{E}_{fd} \end{bmatrix} = \begin{bmatrix} 0 & \omega_s & 0 & 0 \\ \frac{-K_1}{2H} & -\frac{D}{2H} & \frac{-K_2}{2H} & 0 \\ \frac{-K_4}{T'_{do}} & 0 & \frac{-1}{K_3 T'_{do}} & \frac{1}{T'_{do}} \\ \frac{-K_A K_5}{T_A} & 0 & \frac{-K_A K_6}{T_A} & \frac{-1}{T_A} \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta\omega \\ \Delta E'_q \\ \Delta E_{fd} \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ 0 & \frac{-K_{px}}{2H} \\ 0 & \frac{-K_{qx}}{T'_{do}} \\ \frac{K_A}{T_A} & \frac{-K_A K_{vx}}{T_A} \end{bmatrix} \begin{bmatrix} \Delta V_{PSS} \\ \Delta X_{TCSC} \end{bmatrix} \quad (12)$$

In short;

$$\Delta\dot{x} = A\Delta x + B\Delta u \quad (13)$$

Here, the state vector Δx is $\begin{bmatrix} \Delta\delta & \Delta\omega & \Delta E'_q & \Delta E_{fd} \end{bmatrix}^T$ and the control vector Δu is $\begin{bmatrix} \Delta V_{PSS} & \Delta X_{TCSC} \end{bmatrix}^T$. The block diagram of the modified Phillips-Heffron model of the single machine infinite bus (SMIB) power system with PSS and TCSC is shown in Fig. 4. This model is very close to the traditional Phillips-Heffron model, differing by the inclusion of three new constants (K_{px}, K_{qx}, K_{vx}) related to the TCSC. The K coefficients are listed by Equations (B-2, B-11) in Appendix B.

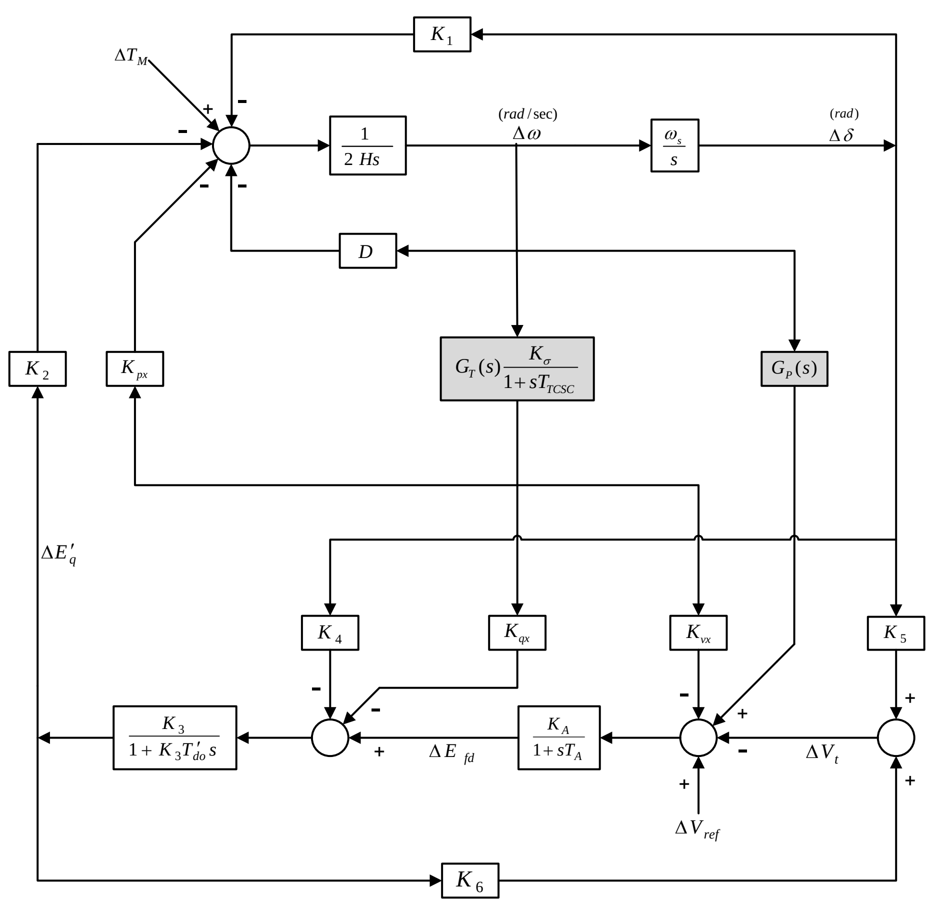

Fig. 4. The modified Phillips-Heffron model of SMIB with PSS and TCSC

3. PARTICLE SWARM OPTIMIZATION

Particle Swarm Optimization (PSO) is population based stochastic optimization method developed by Kennedy and Ebenhart in 1995 and hereafter PSO has been extended to numerous field applications. PSO was inspired by social behavior of organisms such as fish schooling, bird flocking or even human social behavior being influenced by other individuals (Ekinci, 2015). It has been used to solve a wide range of optimization problems such as power system and fuzzy system control problems that are complicated and difficult to solve by conventional optimization methods. PSO is a swarm intelligence algorithm that mimics the movement of individuals (fishes, birds, or insects) within a group (flock, swarm, and school).

More recently, Maurice Clerc has introduced a constriction factor K that improves PSO's ability to constrain and control velocities (Clerc, 1999). Ebenhart and Shi experimented the performance of PSO using an inertia weight as compared with PSO performance using a constriction factor (Eberhart and Shi, 2000). They concluded that the best approach is to use a constriction factor while limiting the maximum velocity $v_{\max}$ to the dynamic range of the variable $x_{\max}$ on each dimension. They showed that this approach provides performance superior to any other published results.

The advantages of PSO over other evolutionary and genetic algorithms are that PSO has comparable or even superior search performance for many hard optimization problems with faster and more stable convergence rates. Also it is easy to implement and can be coded in few lines. The PSO technique requires less computation time and less memory because of its storage requirement is minimal. The major drawbacks of PSO are lack of solid mathematical background and failure to assure an optimal solution.

PSO starts with a population of random solutions particles in d-dimensional space. The i^{th} particle is represented by a d-dimensional vector $X_{\text{i}} = (x_{\text{i1}}, x_{\text{i2}}, \ldots, x_{\text{id}})$ and the velocity of i particle is represented by another *d*-dimensional vector $V_{\text{i}} = (v_{\text{i1}}, v_{\text{i2}}, \ldots, v_{\text{id}})$. PSO consist of, at each step, changing the velocity of each particle toward its p_{best} and g_{best} according to (14). The position of i^{th} particle is updated according to (17) (Ekinci, 2015). In a d-dimensional search space, the best particle updates its velocity and positions with following equations:

$$v_{\text{id}}^{(\text{t}+1)} = K \cdot [v_{\text{id}}^{(\text{t})} + \varphi_1 \cdot rand(\ldots) \cdot (pbest_{\text{id}} - x_{\text{id}}^{(\text{t})}) + \varphi_2 \cdot rand(\ldots) \cdot (gbest_{\text{d}} - x_{\text{id}}^{(\text{t})})] \tag{14}$$

$$-v_{\max} \le v_{\text{id}}^{(\text{t}+1)} \le v_{\max} \tag{15}$$

$$K = \frac{2}{\left|2 - \varphi - \sqrt{\varphi^2 - 4\varphi}\right|}, \qquad \text{where } \varphi = \varphi_1 + \varphi_2 \text{ and } \varphi > 4 \tag{16}$$

$$x_{\text{id}}^{(\text{t}+1)} = x_{\text{id}}^{(\text{t})} + v_{\text{id}}^{(\text{t}+1)} \tag{17}$$

$$x_{\min} \le x_{\text{id}}^{(\text{t}+1)} \le x_{\max} \tag{18}$$

with $i = 1,\ 2,\ \ldots,\ n$ and $d = 1,\ 2,\ \ldots,\ m$

where

$n =$ number of particles in the swarm;

$m =$ number of elements in a particle;

$t =$ number of generations (iterations);

$\varphi_1,\ \varphi_2 =$ cognitive and social acceleration constant;

$rand(\ldots) =$ uniform random value in the range (0, 1);

$v_{\text{id}}^{(\text{t})} =$ *d*-th element of velocity of particle *i* at iteration *t*;

$x_{\text{id}}^{(\text{t})} =$ *d*-th element of position of particle *i* at iteration *t*;

$K =$ constriction factor introduced by Maurice Clerc

$pbest_i =$ best position of particle *i* so far;

$gbest_d =$ global best position of the group;

$x_{\min}, x_{\max} =$ minimum and maximum values of the particle position

$v_{\max} =$ represents the maximum particle moving velocity allowed

4. FORMULATION OF THE PROBLEM

4.1. Structure of the TCSC Controller

A widely used conventional lead-lag structure is selected in this study as a TCSC controller. The structure of the TCSC-based damping controller, to modulate the reactance offered by the TCSC $(X_{TCSC}(\alpha))$ is shown in Fig. 5. The input signal of the proposed controllers is the speed deviation $(\Delta\omega)$, and the output signal is the reactance offered by TCSC $\left(X_{TCSC}(\alpha)\right)$.

The structure consists of a gain block with gain K_T, a signal wash-out block and two-stage phase compensation block. The phase compensation block provides the appropriate phase-lead characteristics to compensate for the phase lag between input and the output signals. The signal wash-out block serves as high-pass filter, with the time constant T_{WT}, high enough to allow signals associated with oscillations in input signal to pass unchanged. Without it steady changes in input would modify the output. From the viewpoint of the wash-out function, the value of T_{WT} is not critical and may be in the range of 1 to 20 s (Kundur, 1994).

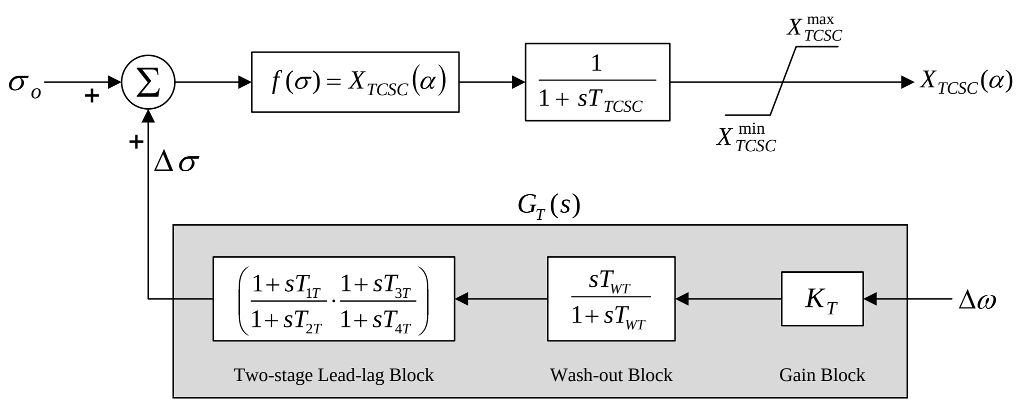

Fig. 5. TCSC Controller Structure

4.2. Structure of the PSS

The commonly used lead-lag structure is considered in the present study and its structure is shown in Fig. 2. The transfer function of the stabilizer is

$$V_{PSS} = K_P \left(\frac{sT_{WP}}{1+sT_{WP}}\right) \cdot \left(\frac{1+sT_{1P}}{1+sT_{2P}}\right) \cdot \left(\frac{1+sT_{3P}}{1+sT_{4P}}\right) \cdot \Delta\omega \tag{19}$$

The input signal is the speed deviation $\Delta\omega$, and the output signal is the stabilizing signal V_{PSS}, which is added to the excitation system reference voltage V_{ref}. K_P is the stabilizer gain, T_{WP} is the washout time constant, and T_{1P}, T_{2P}, T_{3P} and T_{4P} are the stabilizer time constants.

4.3. Problem Formulation and the Objective Function

In this study, a wash-out time constant of $T_{\mathrm{WT}} = T_{\mathrm{WP}} = 5$ s. is used. The controller gains K_{T}, K_{P}, and time constants $T_{1\mathrm{T}}$, $T_{2\mathrm{T}}$, $T_{3\mathrm{T}}$, $T_{4\mathrm{T}}$ and $T_{1\mathrm{P}}$, $T_{2\mathrm{P}}$, $T_{3\mathrm{P}}$, $T_{4\mathrm{P}}$ are to be determined.

In the stabilizer design process, it is aimed to enhance the system damping of the poorly damped electromechanical modes, the objective function J defined below is proposed.

$$J = \max\left\{\begin{array}{l}\sigma : \text{the real part of the} \\ \text{electromechanical mode eigenvalue}\end{array}\right\} \tag{20}$$

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 subject to

$$K_{\mathrm{T}}^{\min} \le K_{\mathrm{T}} \le K_{\mathrm{T}}^{\max} \tag{21}$$

$$T_{\mathrm{iT}}^{\min} \le T_{\mathrm{iT}} \le T_{\mathrm{iT}}^{\max} \qquad i = 1,\ldots,4 \tag{22}$$

$$K_{\mathrm{P}}^{\min} \le K_{\mathrm{P}} \le K_{\mathrm{P}}^{\max} \tag{23}$$

$$T_{\mathrm{iP}}^{\min} \le T_{\mathrm{iP}} \le T_{\mathrm{iP}}^{\max} \qquad i = 1,\ldots,4 \tag{24}$$

The minimum and maximum values of the controller gains are set as 1 and 100, respectively and the minimum and maximum values of the controller time constants are set as 0.01 and 1 s, respectively. The proposed approach employs PSO algorithm to solve this optimization problem and search for optimal set of the stabilizer parameters. To investigate the capabilities of PSS and TCSC controllers when applied individually and also through coordinated application, both of them are designed independently at first and then in a coordinated manner.

5. THE SIMULATION RESULTS

In order to optimally tune the parameters of the PSS and TCSC-based controller, as well as to assess their performance and robustness under various fault disturbances, the test system shown in Fig. 1 is considered for analysis.

5.1. Application of PSO to the Proposed Controllers

PSO algorithm was implemented in MATLAB software so as to resolve the optimization problem and to examine the optimal set of stabilizers parameters. The final values of the optimized parameters for the proposed stabilizers are given in Table 1. The convergence rate of the objective function J when PSS and TCSC-based controllers designed individually and through coordinated design is depicted in Fig. 6. It can be seen that the damping characteristics of the coordinated design approach are much better than those of the individual design ones.

Table 1. Optimal parameter settings of PSS and TCSC

Parameters	Individual Design		Coordinated Design	
	PSS	**TCSC**	**PSS**	**TCSC**
K	1.0000	30.3213	5.1564	19.7211
T_1	0.0481	0.1464	0.1513	0.9673
T_2	0.0100	0.1402	0.0100	0.6030
T_3	0.5205	0.1235	0.1513	1.0000
T_4	0.0138	0.1524	0.5372	0.5032

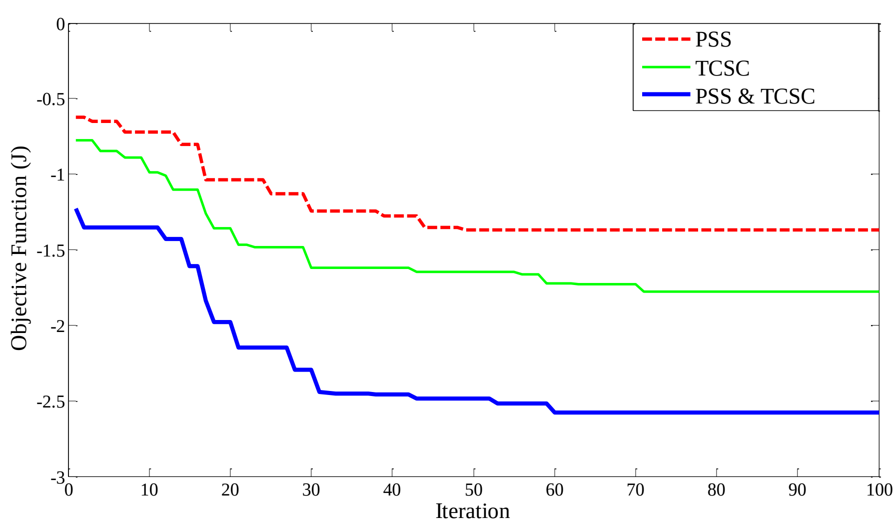

Fig. 6. Convergence rate of the objective function J

5.2. Eigenvalue Analysis

The system eigenvalues without and with the proposed stabilizers are given in Table 2, where the first row represents the electromechanical mode eigenvalues. It is evident that the open loop system is unstable because of the negative damping of electromechanical mode. It is also clear that both individual design of PSS and TCSC shift substantially the electromechanical mode eigenvalues to the left of the line in the *s*-plane ($s = -1.3686$ for PSS and $s = -1.7795$ for TCSC). With the coordinated design approach, maximum shift occurs in the electromechanical mode eigenvalue to the left of the line ($s = -2.5756$) in the *s*-plane. Hence the system stability and damping characteristics greatly enhance with the coordinated design approach.

Table 2. System Eigenvalues without and with Control

Without Control	PSS	TCSC	PSS & TCSC
0.1052 ± 8.4408i	**-1.3686 ± 6.3452i**	**-1.7795 ± 8.4255i**	**-2.5756 ± 8.5362i**
–2.8251 ± 7.4146i	–1.6384 ± 10.267i	–3.2521 ± 7.594i	–5.5545 ± 3.4681i
-------	–102.13	–62.497	–54.427
-------	–69.76	–7.0108	–100.07
-------	–0.20035	–6.2264	–3.5019
-------	-------	–0.20276	–1.4987
-------	-------	-------	–1.8486
-------	-------	-------	–0.2037
-------	-------	-------	–0.2

5.3. Nonlinear Time Domain Simulation

The nonlinear simulations have been carried out to assess the potential of the proposed controllers. The following cases are considered.

Case-1: *Large Disturbance*

A three phase fault is applied at the middle of the one transmission line at $t = 1$ sec. and cleared without tripping after 6 cycles (100 ms). The original system is restored upon the fault clearance. The system response to this disturbance is shown in Fig. 7-10. It can be seen from the figures that, the system is unstable without control under this severe disturbance. The individual application of PSS and TCSC controller significantly suppresses the oscillations in the power angle and provides good damping characteristics to low frequency oscillations by stabilizing the system quickly. The coordinated design of PSS and TCSC-based stabilizer improves greatly the system damping compared to their individual applications. In the first swing, at δ, $\Delta\omega$, X_{TCSC} and V_{PSS} is also slightly suppressed and the setting time is reduced with the coordinated design.

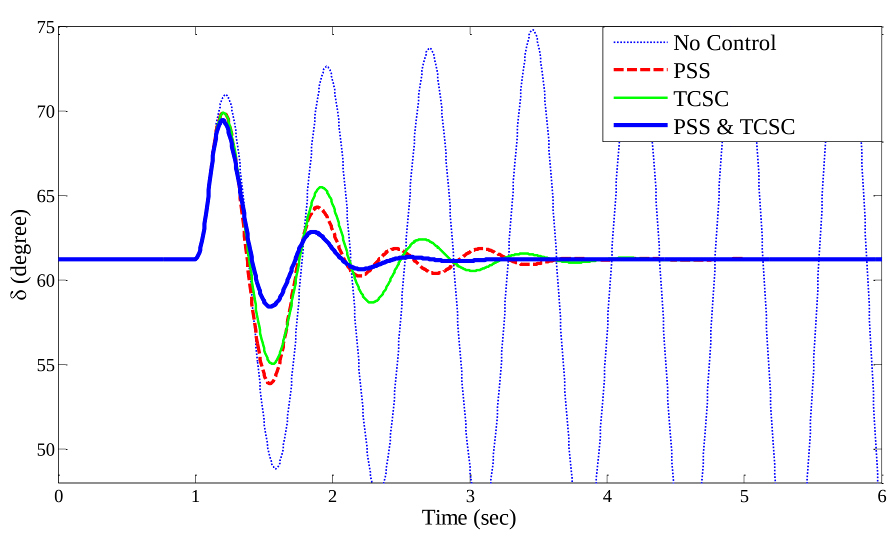

Fig. 7. Variation of power angle δ : Case-1

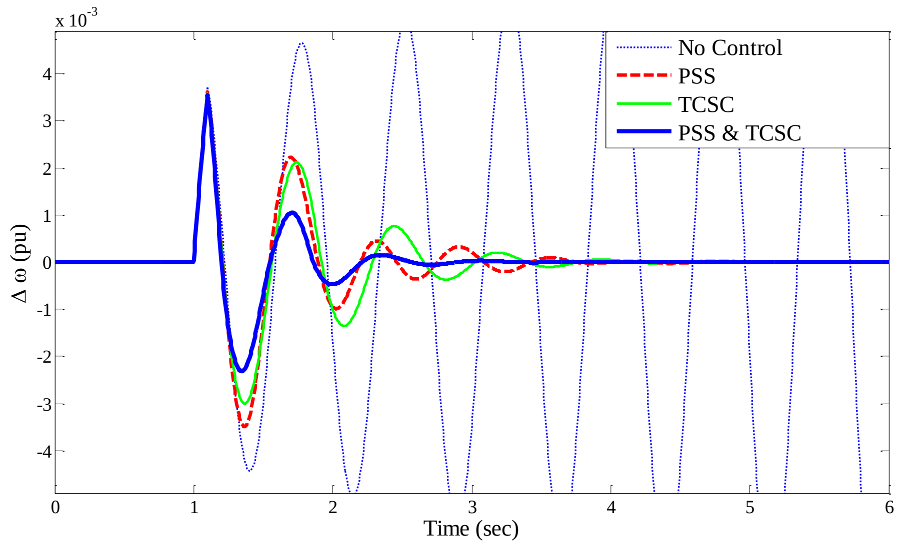

Fig. 8. Variation of speed deviation $\Delta\omega$: Case-1

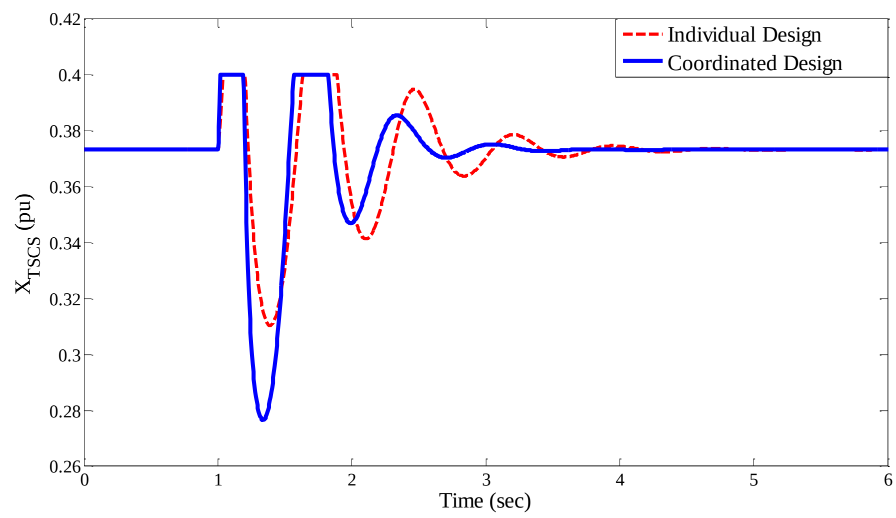

Fig. 9. Variation of X_{TCSC} : Case-1

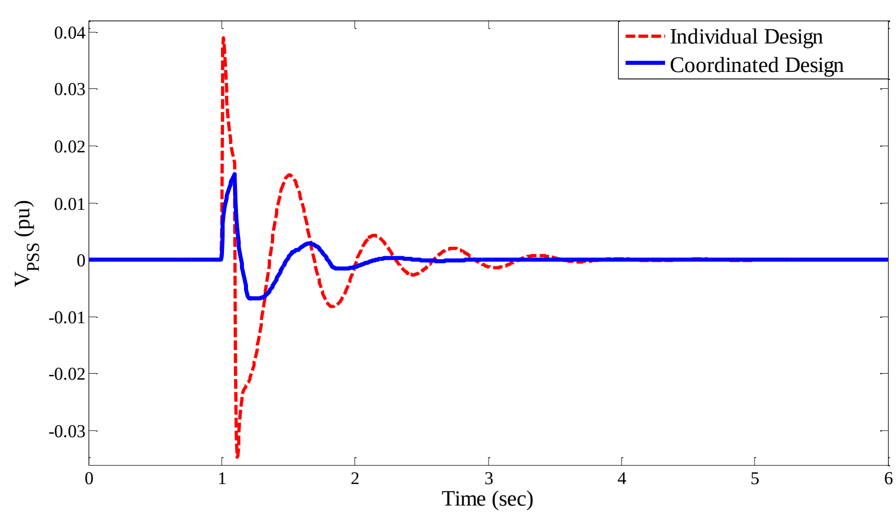

Fig. 10. Variation in stabilizing signal of PSS V_{PSS} : Case-1

Case-2: *A Small Disturbance in Mechanical Power Input*

Another disturbance is considered in the input mechanical power and it is increased by a step of 5% at $t=1$ sec. Figs. 11–13 show the system response of power angle, speed deviation and electrical power output. The deviation in the stabilizing signal of PSS (V_{PSS}) and the reactance offered by TCSC, X_{TCSC} when designed individually and in coordinated manner are also compared and shown in Figs. 14 and 15 respectively.

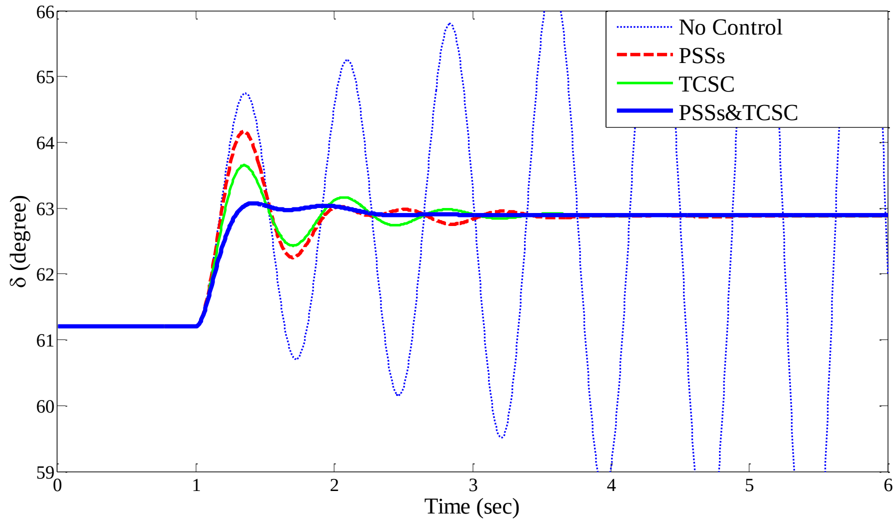

Fig. 11. Variation of power angle δ : Case-2

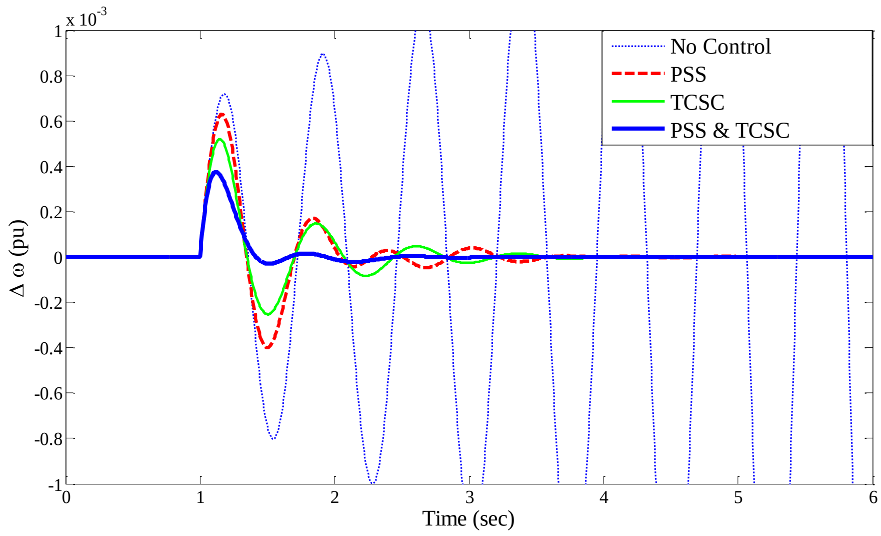

Fig. 12. Variation of speed deviation $\Delta\omega$: Case-2

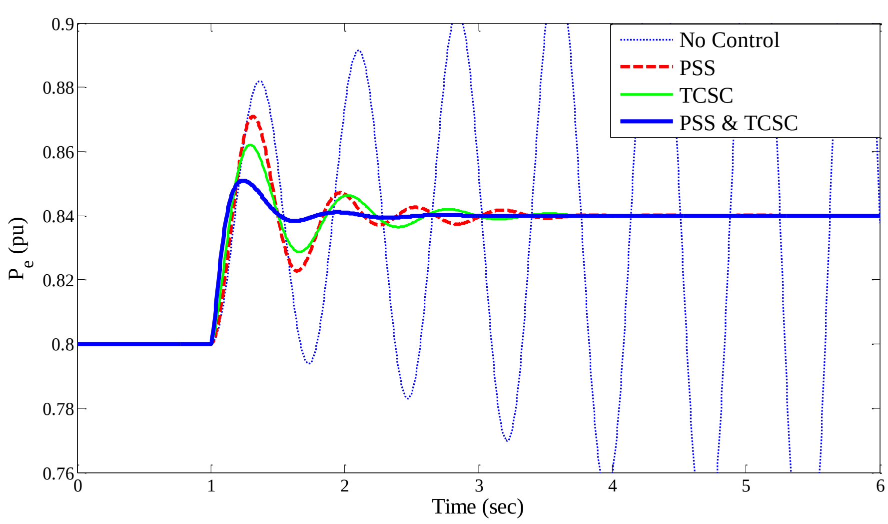

Fig. 13. Variation of electrical power P_e : Case-2

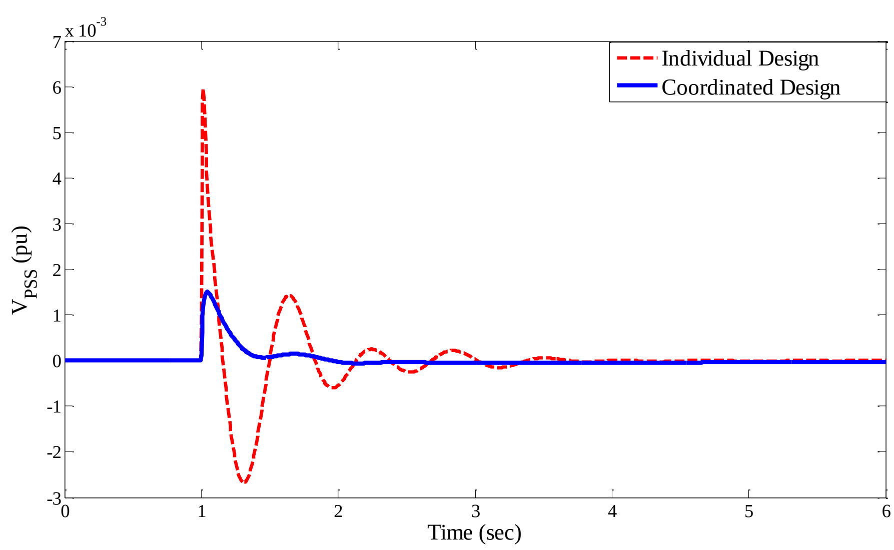

Fig. 14. Variation in stabilizing signal of PSS V_{PSS} : Case-2

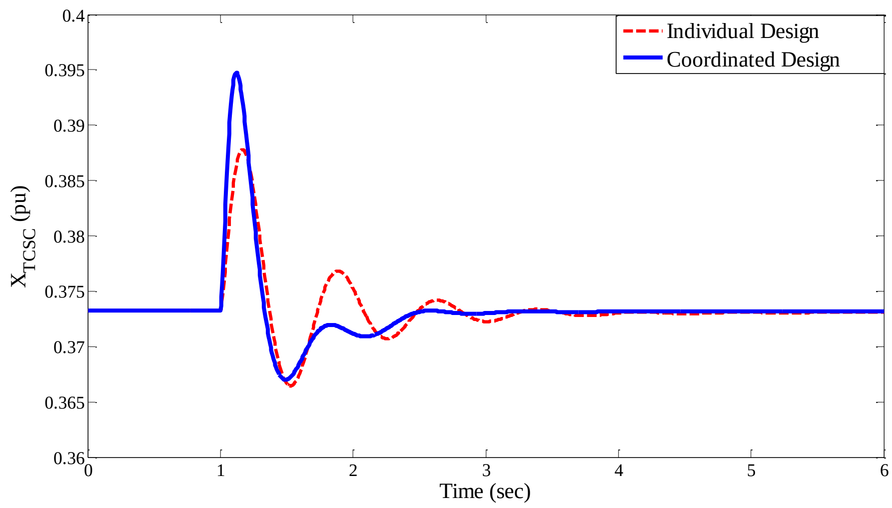

Fig. 15. Variation of X_{TCSC} : Case-2

It can be seen from the figures that the system is unstable without control and the simultaneous design of PSS and TCSC-based controllers by the proposed approach significantly improves the stability performance of the example power system and power system oscillations are well damped out.

6. CONCLUSION

In this study, the power system stability enhancement via design of PSS and TCSC-based stabilizers 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 PSO algorithm was implemented to search for the optimal stabilizer parameters. The proposed stabilizers have been applied and tested on a weakly connected single machine infinite bus power system subjected to large and small disturbances. The eigenvalue analysis and the nonlinear time-domain simulation results show the effectiveness and the robustness of the proposed stabilizers to improve the system stability and their ability to provide good damping of low frequency oscillations. Also, the advantages of the coordinated design compared to individual design of various stabilizers have been demonstrated.

APPENDIX A

System data: All data are in p.u. unless specified otherwise.

Generator: $H = 3.2$ s., $D = 0$, $X_d = 2.5$, $X'_d = 0.39$, $X_q = 2.1$, $T'_{do} = 9.6$ s, $f = 60$, $R_s = 0$, $P_m = 0.8$, $\delta_o = 61.2^o$.

Exciter (IEEE Type ST1): $K_A = 400$, $T_A = 0.2$ s.

Transmission Line and Transformer: $R_e = 0$, $X_L = 0.8$, $X_T = 0.1$, $X_{TH} = 0.1383$.

TCSC Controller: $T_{TCSC} = 0.015$, $X^o_{TCSC} = 0.3733$, $\alpha_o = 144^o$, $\alpha_r = 135^o$, $X_C = 0.18$, $k = 2$.

APPENDIX B

X_e : The equivalent reactance between generator terminal and infinite bus voltage.

$$\Delta = R_e^2 + (X_q + X_e)\cdot(X'_d + X_e) \tag{B.1}$$

$$K_1 = -\frac{1}{\Delta}\Big[I_q^o V_\infty (X'_d - X_q)\big\{(X_q + X_e)\sin\delta_o - R_e\cos\delta_o\big\} + V_\infty\big\{(X'_d - X_q)I_d^o - E_q'^o\big\}\big\{(X'_d + X_e)\cos\delta_o + R_e\sin\delta_o\big\}\Big] \tag{B.2}$$

$$K_2 = \frac{1}{\Delta}\Big[I_q^o\Delta - I_q^o(X'_d - X_q)(X_q + X_e) - R_e(X'_d - X_q)I_d^o + R_e E_q'^o \Big] \tag{B.3}$$

$$\frac{1}{K_3}=1+\frac{(X_d-X'_d)(X_q+X_e)}{\Delta} \quad \text{(B.4)}$$

$$K_4=\frac{V_\infty(X_d-X'_d)}{\Delta}\left[(X_q+X_e)\sin\delta^{\circ}-R_e\cos\delta^{\circ}\right] \quad \text{(B.5)}$$

$$K_5=\frac{1}{\Delta}\left\{\frac{V_d^{\circ}}{\mathrm{V_t}}X_q\left[R_eV_\infty\sin\delta^{\circ}+(X'_d+X_e)V_\infty\cos\delta^{\circ}\right]\right. \\ \left.+\frac{V_q^{\circ}}{\mathrm{V_t}}X'_d\left[R_eV_\infty\cos\delta^{\circ}-(X_q+X_e)V_\infty\sin\delta^{\circ}\right]\right\} \quad \text{(B.6)}$$

$$K_6=\frac{1}{\Delta}\left\{\frac{V_d^{\circ}}{\mathrm{V_t}}X_qR_e-\frac{V_q^{\circ}}{\mathrm{V_t}}X'_d(X_q+X_e)\right\}+\frac{V_q^{\circ}}{\mathrm{V_t}} \quad \text{(B.7)}$$

$$K_{qx}=\frac{(X_d-X'_d)}{\Delta}\left[-R_eI_q^{\circ}+(X_q+X_e)I_d^{\circ}\right] \quad \text{(B.8)}$$

$$K_{px}=-\frac{1}{\Delta}\left[I_q^{\circ}(X'_d-X_q)\left\{-R_eI_q^{\circ}+(X_q+X_e)I_d^{\circ}\right\}\right. \\ \left.+\left\{I_d^{\circ}(X'_d-X_q)-E_q'^{\circ}\right\}\left\{R_eI_d^{\circ}+(X'_d+X_e)I_q^{\circ}\right\}\right] \quad \text{(B.9)}$$

$$K_{vx}=\frac{1}{\Delta}\left\{\frac{V_d^{\circ}}{\mathrm{V_t}}X_q\left[R_eI_d^{\circ}+(X'_d+X_e)I_q^{\circ}\right]+\frac{V_q^{\circ}}{\mathrm{V_t}}X'_d\left[R_eI_q^{\circ}-(X_q+X_e)I_d^{\circ}\right]\right\} \quad \text{(B.10)}$$

$$K_\sigma=\frac{\partial f(\sigma)}{\partial\sigma}\Big|_{\sigma=\sigma_\circ} \quad \text{(B.11)}$$

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