

## Power Oscillation Damping Control using Robust Coordinated Smart Devices

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### Abstrak

Sistem interkoneksi tenaga listrik dengan daya damping yang rendah dapat menjadi penyebab terjadinya masalah osilasi frekuensi rendah pada sistem tenaga listrik. Pada kondisi kerja yang ekstrim, stabilitas sistem daya (PSS) bisa mengalami kegagalan dalam meredam osilasi tersebut. Makalah ini menyajikan desain kendali robust pada PSS dan kapasitor seri terkontrol thyristor (TCSC) secara simultan untuk meredam osilasi pada sistem interkoneksi tenaga listrik. Untuk menggaransi kendali yang kokoh, teknik perturbasi aditif invers digunakan untuk merepresentasikan ketidakpastian sistem pada sistem tenaga listrik seperti perubahan parameter sistem, pembangkitan sistem dan kondisi pembebanan yang sulit diprediksi secara pasti. Pada studi ini, algoritma genetika digunakan untuk menala parameter kendali pada PSS dan TCSC secara simultan. Studi simulasi telah dilakukan pada sistem bus tak berhingga mesin tunggal (SMIB) untuk membuktikan bahwa kendali yang telah didesain mempunyai unjuk kerja dan kekokohan yang lebih bagus dibandingkan dengan kendali konvensional.

**Kata kunci:** algoritma genetika, kendali kokoh, perturbasi aditif invers, PSS, TCSC

### Abstract

The lack of damping of the electromechanical oscillation modes usually causes severe problems of low frequency oscillations in interconnected power systems. In the extreme operating conditions, PSS may fail to damp power oscillation. This paper presents a robust coordinated design of power system stabilizer (PSS) and thyristor controlled series capacitor (TCSC) to damp power oscillation in an interconnected power system. The inverse additive perturbation is applied to represent unstructured uncertainties in the power system such as variations of system parameters, system generating and loading conditions. In addition, genetic algorithm is employed to search a robust tuning to the controller parameters of both PSS and TCSC simultaneously. Simulation studies have been done in a single machine infinite bus system to confirm that the performance and robustness of the proposed controller are superior to that of the conventional controller.

**Keywords:** genetic algorithm, inverse additive perturbation, PSS, robust control, TCSC

### 1. Introduction

Power system black out due to low frequency oscillation becomes serious problem in the power system. To prevent this problem, the application of smart technology such as PSS and flexible alternating current transmission systems (FACTS) device to provide an additional damping of power system is highly needed. At present, power system stabilizer (PSS) has been selected as a cost effective device to damp power oscillation via the excitation system [1]. Several approaches based on modern control theories have been successfully applied to design PSSs, such as eigenvalue assignment [2, 3], and linear quadratic regulator [4]. These works have confirmed the significant performance of PSS. However, PSS may suffer a drawback of being liable to cause great variations in the voltage profile and they may even result in leading power factor operation and losing system stability under severe disturbances [5].

The application of FACTS devices such as thyristor controlled series capacitor (TCSC), unified power flow controller (UPFC), and static var compensator (SVC), which using reliable and high-speed electronic devices to damp electromechanical oscillations in power systems has

been observed [6]. In this study, TCSC is installed in the power system to tackle the limitation of PSS. Several previous works has paid attentions to tuning conventional lead/lag PSS and TCSC parameters simultaneously by heuristic methods such as simulated simulated annealing [7] and genetic algorithm [8]. In these studies, however, the uncertainty model is not embedded in the mathematical model of the power system. Therefore, the robust stability margin of the system in these works may not be guaranteed in the face of several uncertainties.

To get the robust controller,  $H_\infty$  control has been applied to design of a robust PSS configuration [9]. In this work, the designed  $H_\infty$  PSS via mixed sensitivity approach have confirmed the significant performance and high robustness. In this approach, however, due to the trade-off relation between sensitivity function and complementary sensitivity function, the weighting functions in  $H_\infty$  control design cannot be selected easily. Moreover, the structure of conventional  $H_\infty$  controller is high order and complex which is different from the conventional PI or lead/lag controller. Despite the significant potential of control techniques mentioned above, power system utilities still prefer the conventional low order PI or lead/lag controller. This is due to the ease of implementation, the long-term reliability, etc.

This paper proposes the robust coordinated PSS and TCSC to damp low frequency oscillation in an interconnected power system. To take system uncertainties into account in the control design, an inverse additive perturbation [10] is applied to represent all unstructured uncertainties in the system modeling. Moreover, the performance conditions in the damping ratio and the real part of the dominant mode is applied to formulate the optimization problem. In this work, the structure of the both proposed controller of PSS and TCSC are the first-order lead/lag compensator. It is easy to implement in the real system. To achieve the controller parameters, the genetic algorithm (GA) is used to solve the optimization problem. Simulation studies explicitly show that the proposed robust PSS and TCSC are very robust to various system uncertainties in comparison to that of conventional controller [3,7].

This paper is organized as follows. First, power system modeling is explained in section 2. Section 3 presents the proposed design method for optimization of coordinated robust PSS and TCSC parameters using GA. Subsequently, section 4 shows the results and analysis. Finally, the conclusion is given.

**2. A Robust Tuning to the Controller Parameters**

**2.1 Power System Modeling**

A single machine infinite bus (SMIB) system shown in Figure 1 is used to explain the design of proposed robust coordinated PSS and TCSC. The linearized forth-order model of SMIB system [1] for robust PSS and TCSC design is depicted in Figure 2. System parameters and notations are given in [7]. The initial condition used as the design condition of the proposed PSS is  $P_e = 1.0$  p.u.,  $Q_e = 0.015$  p.u.

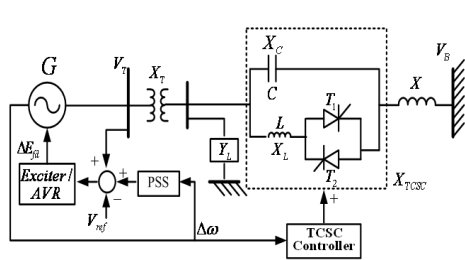


Figure 1. Single line of SMIB system.

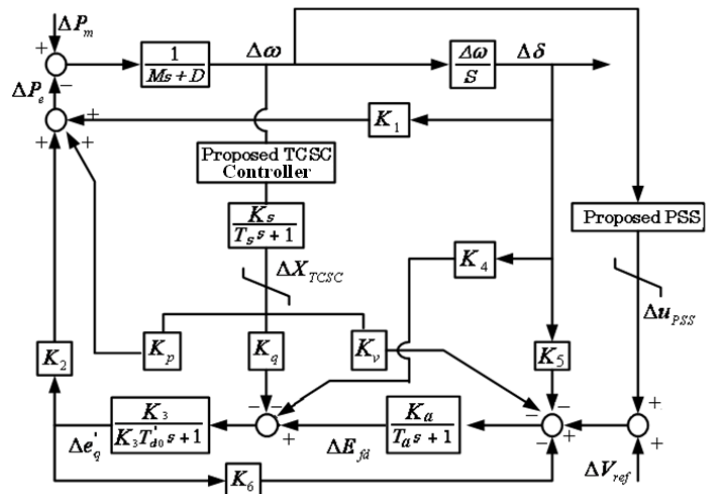


Figure 2. Linearized of SMIB system with PSS and TCSC

The linearized system in Figure 2 can be written as

$$\begin{bmatrix} \Delta\delta' \\ \Delta\omega' \\ \Delta E'_q \\ \Delta E'_{fd} \end{bmatrix} = \begin{bmatrix} 0 & 377 & 0 & 0 \\ -\frac{K_1}{M} & -\frac{D}{M} & -\frac{K_2}{M} & 0 \\ -\frac{K_4}{T'_{d0}} & 0 & -\frac{K_3}{T'_{d0}} & 1 \\ -\frac{K_A K_5}{T_A} & 0 & -\frac{K_A K_6}{T_A} & -\frac{1}{T_A} \end{bmatrix} X + \begin{bmatrix} 0 & 0 \\ 0 & -\frac{K_p}{K_q} \\ 0 & -\frac{M}{T'_{d0}} \\ \frac{K_A}{T_A} & -\frac{K_A K_V}{T_A} \end{bmatrix} \begin{bmatrix} \Delta u_{PSS} \\ \Delta u_{TCSC} \end{bmatrix} \quad (1)$$

In short, the state equation of system can be expressed as

$$\dot{\Delta X} = A\Delta X + B\Delta u \quad (2)$$

$$\Delta Y = C\Delta X + D\Delta u \quad (3)$$

$$\Delta u = K(s)\Delta\omega \quad (4)$$

Where the state vector  $\Delta X = [\Delta\delta \ \Delta\omega \ \Delta e'_q \ \Delta E'_{fd}]^T$ , the output vector  $\Delta Y = [\Delta\omega]$ ,  $\Delta u = [\Delta u_{PSS} \ \Delta u_{TCSC}]$  are the control output signal of the PSS and TCSC, which uses only the angular velocity deviation ( $\Delta\omega$ ) as a feedback input signal.

**2.2 Configuration of PSS and TCSC Controller**

As shown in Figure 3, the PSS controller ( $K_{PSS}$ ) is represented by a simple 1<sup>st</sup> order lead/lag controller and wash out which uses system frequency deviation ( $\Delta\omega$ ) as a feedback input signal. The power system stabilizer (PSS) is used to provide the additional damping via the excitation system. Moreover, the TCSC block diagram is depicted in Figure 4. The TCSC diagram consists of two transfer functions, i.e. the TCSC model and the lead/lag based power oscillation controller. Based on [7], the TCSC can be modeled by the first-order transfer function with time constant  $T_C = 0.05$  sec. In this work, TCSC controller is presented by practically a 1<sup>st</sup> order lead/lag controller and wash out with single feedback input signal, system frequency deviation ( $\Delta\omega$ ). Note that the system in equation (2) is a multi-input single-output (MISO) system. Here, the proposed design approach is applied to design a robust coordinated PSS controller ( $K_{PSS}$ ) and TCSC controller ( $K_{TCSC}$ ) simultaneously.

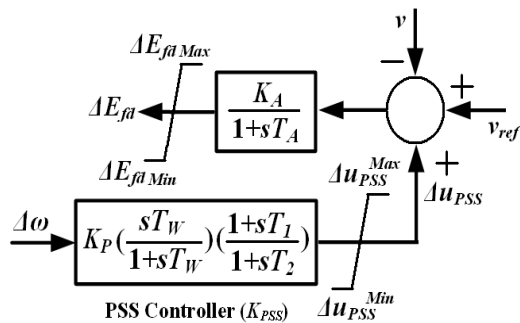


Figure 3. Block diagram of PSS controller ( $K_{PSS}$ )

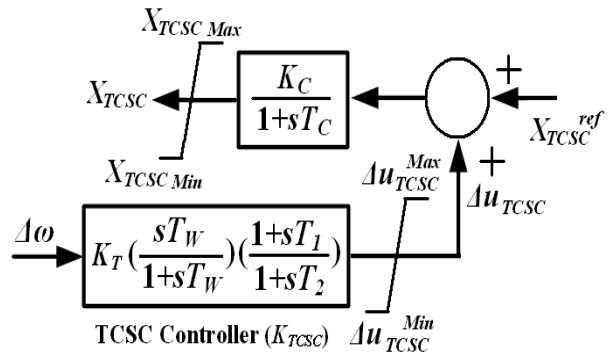


Figure 4. Block diagram of TCSC controller ( $K_{TCSC}$ )

**3. Research Method**

In this section, GA is applied to search the controller parameters with off line tuning. The flow chart of proposed control design is shown in Figure 5. Each step proposed method is explained as follows.

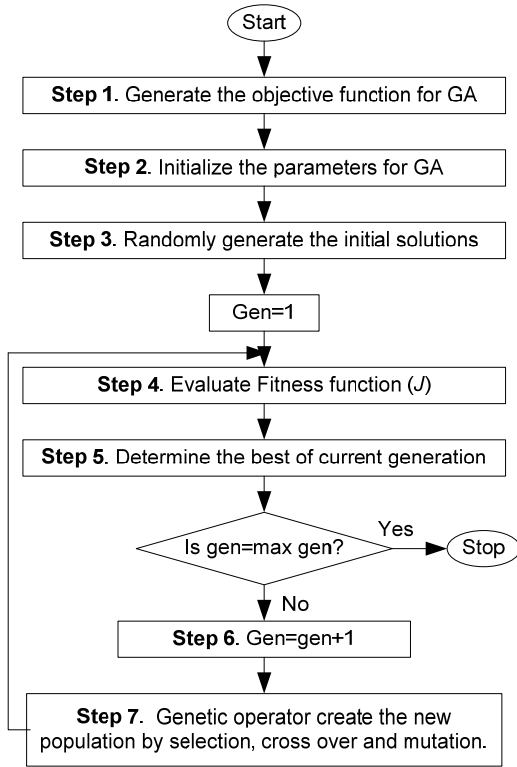


Figure 5. Flow chart of the proposed design

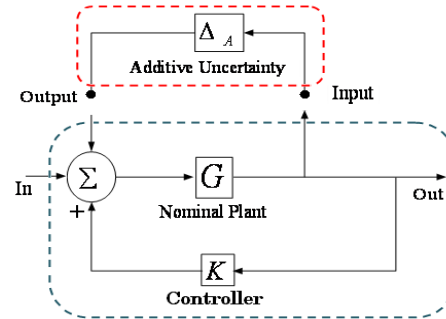


Figure 6. Feedback system with inverse additive perturbation

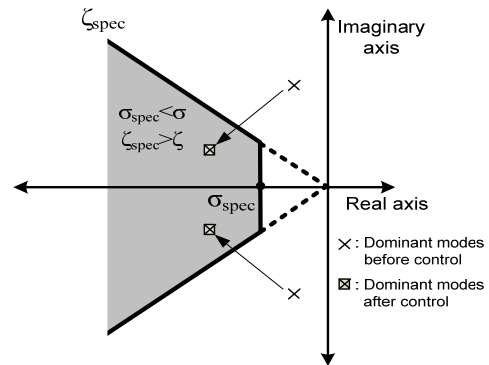


Figure 7. D-shape region in the s-plane

**Step 1** Generate the objective function for GA optimization.

In this study, the performance and robust stability conditions in the inverse additive perturbation design approach is adopted to design a both robust PSS and TCSC. The conventional PSS and TCSC controller with a 1<sup>st</sup>-order lead/lag controller are represented by

$$\Delta u_{PSS} = K_p \left( \frac{sT_w}{sT_w + 1} \right) \left( \frac{sT_1 + 1}{sT_2 + 1} \right) \Delta \omega \tag{5}$$

$$\Delta u_{TCSC} = K_T \left( \frac{sT_w}{sT_w + 1} \right) \left( \frac{sT_1 + 1}{sT_2 + 1} \right) \Delta \omega \tag{6}$$

where,  $\Delta u_{PSS}$ ,  $\Delta u_{TCSC}$  and  $\Delta \omega$  are the control output signal and the rotor speed deviation at both of PSS and TCSC, respectively;  $K_p$  and  $K_T$  are a controller gain of PSS and TCSC, respectively;  $T_w$  is a wash-out time constant (s): and  $T_1$  and  $T_2$  are time constants (s).

In this paper, the control parameters  $K$ ,  $T_1$  and  $T_2$  are optimized by GA based on the following concept. As shown in Figure 6, the system with inverse additive perturbation [10] is applied to take the robust stability against uncertainties into account. For a stable additive uncertainty  $\Delta_A$ , the closed loop system is robust if the controller  $K$  stabilizes the nominal plant  $G$ . Based on the small gain theorem, the system is stable if

$$\|\Delta_A G / (1 - GK)\|_\infty < 1 \tag{7}$$

Then

$$\|\Delta_A\|_\infty \|G/(1-GK)\|_\infty < 1 \quad (8)$$

This yield

$$\|\Delta_A\|_\infty < 1/\|G/(1-GK)\|_\infty \quad (9)$$

The right hand side of equation (9) implies the maximum robust stability margin against inverse additive perturbation. Then, the robust stability margin of the closed loop system can be guaranteed in terms of the additive stability margin (ASM) as,

$$ASM < \frac{1}{\|G(s)/(1-G(s)K(s))\|_\infty} \quad (10)$$

By minimizing  $\|G/(1-GK)\|_\infty$ , the robust stability margin of the closed-loop system is a near optimum. In this study, the problem constraints are the controller parameters bounds. In addition to enhance the robust stability, another objective is to increase the damping ratio and place the closed-loop eigenvalues of hybrid wind-diesel power system in a D-shape region [11]. The conditions will place the system closed-loop eigenvalues in the D-shape region characterized by  $\zeta \geq \zeta_{spec}$  and  $\sigma \leq \sigma_{spec}$  as shown in Figure 7.

Therefore, the design problem can be formulated as the following optimization problem.

$$\begin{aligned} \text{Minimize} \quad & \|G/(1-GK)\|_\infty \quad (11) \\ \text{Subject to} \quad & \zeta \geq \zeta_{spec}, \quad \sigma \geq \sigma_{spec} \\ & K_{c,i,\min} \leq K_{c,i} \leq K_{c,i,\max}, \quad T_{i,\min} \leq T_i \leq T_{i,\max}, \quad i = 1,2 \end{aligned}$$

Where  $\zeta$  and  $\zeta_{spec}$  are actual and desired damping ratio, respectively,  $\sigma$  and  $\sigma_{spec}$  are actual and desired real part of the electromechanical mode,  $K_{c,\min}$  and  $K_{c,\max}$  are minimum and maximum gains of both PSS and TCSC,  $T_{i,\min}$  and  $T_{i,\max}$  are minimum and maximum time constants of PSS and TCSC. The optimization problem is solved by GA.

**Step 2** Initialize the search parameters for GA. Define genetic parameters such as population size, crossover, mutation rate, and maximum generation.

**Step 3** Randomly generate the initial solution.

**Step 4** Evaluate objective function of each individual in equation (11).

**Step 5** Select the best individual in the current generation. Check the maximum generation.

**Step 6** Increase the generation.

**Step 7** While the current generation is less than the maximum generation, create new population using genetic operators and go to step 4. If the current generation is the maximum generation, then stop

#### 4. Simulation Results and Analysis

In this section, simulation studies in a single machine connected to infinite bus are carried out. System parameters are given in [7]. In the optimization, the ranges of search parameters are set as follows:  $\zeta_{spec}$  is desired damping ratio is set as 0.5,  $\sigma_{spec}$  is desired real part is set as -0.2,  $K_{\min}$  and  $K_{\max}$  are minimum and maximum gains of both PSS and TCSC are set as 1 and 60,  $T_{\min}$  and  $T_{\max}$  are minimum and maximum time constants of both PSS and TCSC controllers are set as 0.01 and 1. Moreover, the ranges of GA parameters are set as follows: crossover probability is 0.9, mutation probability is 0.05, population size is 100 and

maximum generation is 100. The optimization problem is solved by genetic algorithm [12]. As a result, the designed controllers which are referred as "RPSS and RTCSC" are given simultaneously as shown as follows

$$RPSS = 38.58 \left( \frac{5s}{5s+1} \right) \left( \frac{0.7437s+1}{0.4478s+1} \right) \quad (12)$$

$$RTCSC = 44.28 \left( \frac{5s}{5s+1} \right) \left( \frac{0.4576s+1}{0.1336s+1} \right) \quad (13)$$

In simulation studies, the performance and robustness of the proposed controllers are compared with PSS [3] and PSS and TCSC [7], that is PSS[3] :

$$PSS = 7.091 \left( \frac{5s}{5s+1} \right) \left( \frac{0.685s+1}{0.1000s+1} \right) \quad (14)$$

PSS and TCSC [7]:

$$PSS = 22.523 \left( \frac{5s}{5s+1} \right) \left( \frac{0.1212s+1}{0.1000s+1} \right) \left( \frac{0.2156s+1}{0.1000s+1} \right) \quad (15)$$

$$TCSC = 74.726 \left( \frac{5s}{5s+1} \right) \left( \frac{0.0115s+1}{0.1000s+1} \right) \left( \frac{0.1249s+1}{0.1000s+1} \right) \quad (16)$$

Next, the performance and robustness of the RPSS and RTCSC is compared with PSS and TCSC [7]. To evaluate the robustness of controllers, the value of ASM of PSS and TCSC [7] and RPSS and RTCSC are shown in Table 1. As shown in Table 1, the value of ASM in the case of RPSS and RTCSC is greater than that in the case of PSS and TCSC [7]. It is indicated that the better robust stability margin of the closed loop system can be achieved by the proposed method

In addition, the eigenvalues corresponding to the electromechanical mode without controllers, PSS and RTCSC [7] and RPSS and RTCSC are listed in Table 2. Clearly, the damping ratio and real part of the oscillation mode are greatly enhanced with the proposed controller. On the other hand, system without controller has negative damping or unstable. The limit on each PSS output ( $\Delta u_{PSS}$ ) and TCSC output ( $\Delta u_{TCSC}$ ) is  $\pm 0.05$  p.u. The system responses with controller are examined under three case studies as in Table 3.

Table 1. Comparison of ASM

Controller	ASM
PSS and TCSC [7]	0.6445
RPSS and RTCSC	8.0319

Table 3. Operating condition

System parameter	Case 1	Case 2	Case 3
	Normal condition	Light Loading	Heavy Loading
P (pu)	1.000	0.800	1.20
Q (pu)	0.015	0.15	0.15
Xcsc (pu)	0.000	0.000	-0.2

Table 2. Comparison of oscillation mode

System	Eigen value and Damping ratio
Without Controller	$+0.30 \pm j 4.96$ , $\zeta = -0.06$
	$-10.39 \pm j 3.28$ , $\zeta = 0.954$
PSS and TCSC [7]	$-5.074 \pm j 7.308$ , $\zeta = 0.57$
	$-0.729 \pm j 3.179$ , $\zeta = 0.224$
RPSS and RTCSC	$-14.35 \pm j 1.01$ , $\zeta = 0.98$
	$-8.87 \pm j 8.62$ , $\zeta = 0.717$
	$-9.61 \pm j 7.50$ , $\zeta = 0.788$
	$-1.54 \pm j 1.31$ , $\zeta = 0.762$

#### Case 1: Normal condition

First, a disturbance of 10 % (0.1 p.u.) step response of  $\Delta V_{ref}$  is applied to the system at  $t = 1$  s. Figure 8 shows the responses of system frequency deviation. System without controller can't

stabilize the power oscillation, the oscillation become higher and unstable. On other hand, PSS [3], PSS and TCSC [7] and proposed RPSSandRTCSC are able to damp power oscillations. However, the overshoot and setting time of power oscillation in case of RPSS and RTCSC is much lower than those of both PSS [3] and PSS and TCSC [7]. Next, to evaluate power capacities of both PSS and TCSC controller required for power oscillation stabilization. Figure 9 shows the controller output power deviation in case 1. Both controller power output of PSS and TCSC [7] and RPSS and RTCSC can properly remain within the allowable limits. However, the stabilizing effect of frequency oscillation by RPSS and RTCSC is superior to that of PSSandTCSC [7].

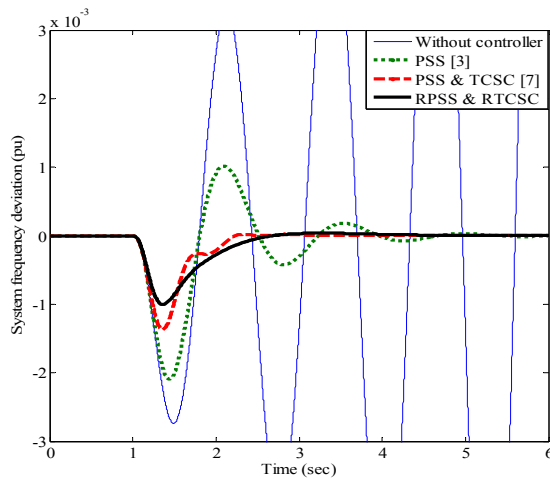


Figure 8. Simulation result of case 1

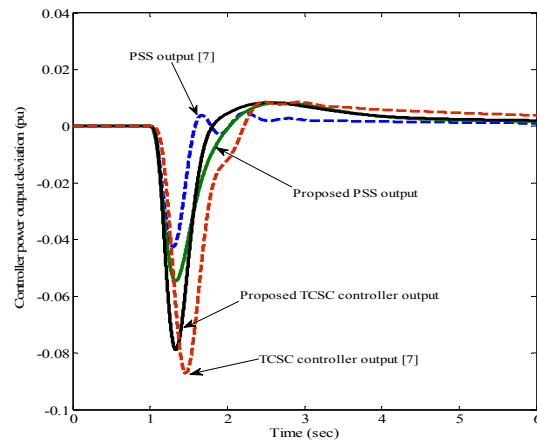


Figure 9. Controller power output deviation

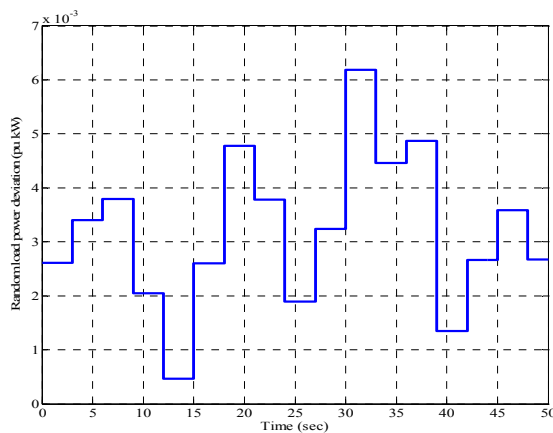


Figure 10. Random load power deviation

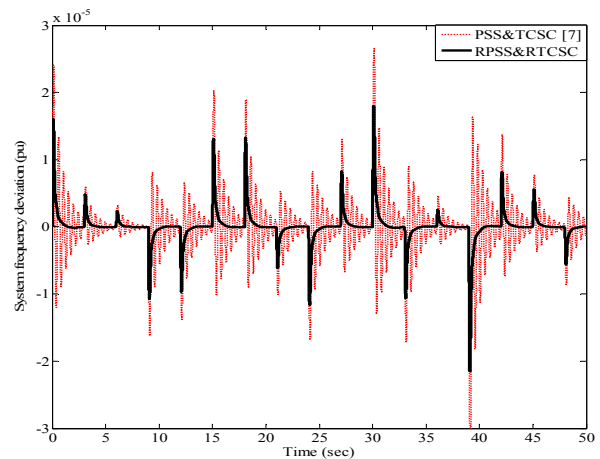


Figure 11. Simulation result of case 2

**Case 2 : Light loading condition**

In case 2, the random power input ( $\Delta P_m$ ) as shown in Figure10 is injected to the system. The response of the system frequency deviation in case 2 is shown in Figure11, the damping effect of PSS and TCSC [7] is deteriorated. On the other hand, the frequency oscillations are effectively stabilized by RPSS and RTCSC. RPSS and RTCSC is rarely sensitive to the weak line condition.

**Case 3 : Heavy loading condition**

In case 3, the electrical power output is increased. Figure 12 shows that the PSS and TCSC [7] fails to damp power system. The frequency oscillation gradually increases and diverges. In

contrast, the proposed RPSS and RTCSC can tolerate this situation. The frequency oscillation is significantly damped. These simulation results confirm that the proposed controller is very robust against various operating conditions.

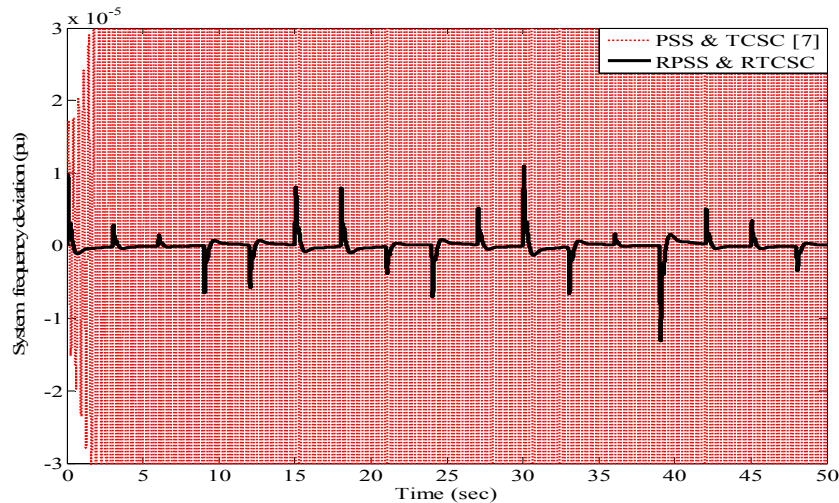


Figure 12. Simulation result of case 3

## 5. Conclusion

In this study, a robust design of coordinated PSS and TCSC has been proposed. The inverse additive perturbation is used to take the robust stability of the controlled power system against system uncertainties. The designed robust controllers are the conventional 1<sup>st</sup> order lead/lag compensator. Moreover, the controllers use only the speed deviation of generator as the feedback signal input. Therefore, the controllers are easy to realize in practical power system. The control effects and robustness of the proposed controller have been evaluated by various case studies. Simulation results confirm that the proposed controller is superior to the conventional controller in terms of the robustness against various uncertainties.

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