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Simultaneous Coordinated Design of TCSC-Based Damping Controller and AVR Based on PSO Technique

***Abstract**. Power system is a nonlinear system that requires accurate and robust control to improve power system stability following the occurrence of disturbance. In order to damp out oscillations, coordinated design problem of TCSC-based damping controller and AVR is formulated as an optimization problem. PSO technique has been employed to solve the optimization problem. Dynamic performance of these controllers has been appraised over a wide range of loading conditions under sever disturbance in SMIB power system. The non-linear time-domain simulation results suggest that the robustness of simultaneous coordinated design of these devices to enhance power system dynamic stability.*

***Streszczenie.** Opisano metodę sterowania stabilnością systemu zasilania przy obecności zakłóceń. Dla tłumienia oscylacji wykorzystano kontroler TCSC a AVR (automatic voltage regulator) jest traktowany jako problem optymalizacyjny. Do sterowania wykorzystano algorytmy rojowe PSO. (**Jednoczesne skoordynowane wykorzystanie tłumienia TCSC i kontrolera napięcia sieci AVR bazujące na technice PSO**)*

Keywords: TCSC-Based Damping Controller, AVR, PSO Technique, Coordinated Design, Power System Dynamic Stability.
Słowa kluczowe: kontroler tłumienia TCSC, kontroler AVR, PSO.

1. Introduction

Damping of power system electromechanical oscillations is an important issue and challenging problem in the power industry [1]. Low frequency oscillations are observed when a disturbance such as sudden change in loads, change in transmission line parameters, fluctuation in the output of the turbine and faults etc occurs in power system. The magnitude of these oscillations may keep growing until loss of synchronism result [2]. The lack of sufficient system damping is the major reason of the continuity and growth of oscillation in power system [3, 4].

Flexible AC Transmission Systems (FACTS) devices are one of the main purposes for enhancement of power system dynamic stability. In recent years, the fast progress in the field of power electronics has provided an appropriate bed in the power industry to utilize the FACTS controllers for damping of power system oscillations [5, 6]. Series FACTS devices are the key devices of the FACTS family, which are identified as effective and economical means to diminish the power system oscillation [7]. Thyristor Controlled Series Compensator (TCSC) is one of the most impressive series compensation devices that can play important role in the control and operation of power systems, such as: diminishing power system oscillation, improving transient stability, scheduling power flow; reducing asymmetrical components, providing voltage support; mitigating sub-synchronous resonance (SSR) phenomenon, and limiting short circuit currents [8-10]. A typical TCSC model comprises of a fixed series capacitor shunted by a Thyristor Controlled Reactor (TCR). The TCR is made by a reactor in series with a bidirectional thyristor valve which is triggered by a phase angle a ranging between 90^0 and 180^0 with respect to the capacitor voltage. The firing angle of the thyristor has been controlled to regulate the reactance of TCSC and its degree of compensation [11, 12]. From the viewpoint of power system dynamic stability, it is essential for TCSC to equip with a supplementary damping controller. For this study, lead-lag structure has been selected as supplementary control device to provide extra damping and mitigate the power system oscillations.

The experimental results have confirmed that the power system transient stability can be significantly improved through appropriate control of generator excitation [13]. The generator excitation system using an Automatic Voltage Regulator (AVR) maintains the terminal voltage magnitude of a synchronous generator on the defined level [14]. It can also improve the transient and the steady-state stability of power systems via controlling the reactive power [15].

A number of conventional methods have been employed for tuning parameters of power system stabilizers. The most common methods are based on the pole placement technique, eigenvalues sensitivities, residue compensation, and also the current control theory. Unfortunately, these conventional methods are time consuming as they are repetitive and need heavy computation burden and slow convergence. In addition, process is sensitive to be trapped in local minima and the obtained response may not be optimal [16]. The progressive methods develop a technique to search for the optimum solutions via some sort of directed random search processes [17]. A suitable trait of the evolutionary methods is that they search for solutions without prior problem perception. In recent years, a number of various ingenious computation techniques namely: Simulated Annealing (SA) algorithm, Evolutionary Programming (EP), Genetic Algorithm (GA), Differential Evolution (DE) and Particle Swarm Optimization (PSO) have been employed by scholars to solve the different optimization problems of electrical engineering. But, the PSO technique can produce an excellent solution within shorter calculation time and stable convergence characteristic than other stochastic techniques [18]. In fact, PSO is a stochastic global optimization approach based on swarm behavior such as fish and bird schooling in nature [19]. Generally, PSO is known as a simple concept, easy to perform, and computationally effective. PSO has a flexible and well-balanced mechanism to enhance the global and local exploration abilities [20].

The high performance of PSO technique to solve the non-linear, non-differentiable, and high-dimensional objectives has been confirmed in many literatures. In this paper, PSO technique is chosen to solve the coordination problem among TCSC-based damping controller and AVR. To verify the robustness of this simultaneous coordination, dynamic performance of these devices has been analyzed and appraised over a wide range of loading conditions under sever disturbance in SMIB power system.

2. Description of the Implemented PSO Technique

PSO is a stochastic global optimization method, which has been motivated by the behavior of organisms, such as fish schooling and bird flocking [21]. PSO has the flexibility than other heuristic algorithms to control the balance between the global and local configuration of the search space. This unique feature of PSO vanquishes the premature convergence problem and enhances the search capability. Also unlike the traditional methods, the solution quality of this technique does not depend on the initial population. Starting anywhere in the search space, PSO algorithm ensures the convergence of the optimal solution. In the current research, the process of PSO technique can be summarized as follows [22-24]:

1) Initial positions of *pbest* and *gbest* are varied. However, using the different direction of *pbest* and *gbest*, all agents piecemeal receive near-by the global optimum.

2) Adjustment of the agent position is perceived by the position and velocity information. However, the method can be used to the separate problem applying grids for XY position and its velocity.

3) Didn't have any incompatibilities in searching procedures even if continuous and discrete state variables are utilized with continuous axes and grids for XY positions and velocities. Namely, the method can be applied to mixed integer non-linear optimization problems with continuous and district state variables easily and naturally.

4) The above statement is based on using only XY axis (two dimensional spaces). Thus, this method can be easily employed for n-dimensional problem.

The modified velocity and position of each particle can be calculated using the current velocity and the distances from $pbest_{j,g}$ to $gbest_g$ as presented in the following equations [25]:

$$\upsilon_{j,g}^{(t+1)} = w \times \upsilon_{j,g}^{(t)} + c_1 + r_1 \times (pbest_{j,g} - x_{j,g}^{(t)}) + c_2 + r_2 \times (gbest_g - x_{j,g}^{(t)}) \quad (1)$$

$$x_{j,g}^{(t+1)} = x_{j,g}^{(t)} + \upsilon_{j,g}^{(t+1)},\ j = 1,2,...n \text{ and } g = 1,2,...,m \quad (2)$$

$$\upsilon_g^{min} \le \upsilon_{j,g}^{(t)} \le \upsilon_g^{max} \quad (3)$$

w produces a balance between global and local explorations requiring less iteration on average to find a suitably optimal solution. It is determined by the following equation:

$$w = w_{max} - \frac{w_{max} - w_{min}}{iter_{max}} \times iter \quad (4)$$

The *jth* particle in the swarm is represented by a d-dimensional vector $x_j=[x_{j,1}, x_{j,2},..., x_{j,d}]$ and its rate of velocity is symbolized by another d-dimensional vector $v_j=[v_{j,1}, v_{j,2},..., v_{j,d}]$. The best previous position of the *jth* particle is represented by $pbest_j=[pbest_{j,1}, pbest_{j,2},..., pbest_{j,d}]$. The index of best particle among all of the particles in the population is represented by the $gbest_g$. In PSO, each particle moves in the search space for seeking the best global minimum (or maximum). The velocity update in a PSO comprises of three parts; namely cognitive, momentum and social parts. The performance of PSO depends upon the balance among these parts. The parameters c_1 and c_2 determine the relative pull of *pbest* and *gbest* and the parameters r_1 and r_2 help in stochastically varying these pulls.

3. Power System Model

3.1. Generator

The SMIB power system with a presence of TCSC as shown in Fig.1 is considered in this research. Also, the excitation system furnished with AVR. In the figure V_T and V_B represent the generator terminal and infinite bus voltage, respectively, and also X_T and X_L are the reactance of the transformer and the transmission line, respectively. The generator is represented by the third-order model including the electromechanical swing equation and the generator internal voltage equation. The swing equation is given as follows:

$$\dot{\delta} = \omega_b(\omega - 1) \quad (5)$$

$$\dot{\omega} = \frac{1}{M}\left[P_m - P_e + D(\omega - 1)\right] \quad (6)$$

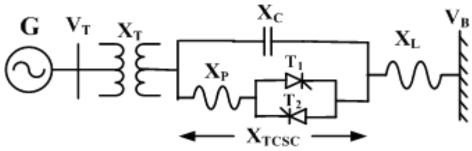

Fig.1. Single line diagram of SMIB power system

Where δ and ω the rotor angle and speed, respectively; ω_b the synchronous speed; P_e and P_m are the output and input powers of the generator, respectively; M and D the inertia constant and damping coefficient, respectively.

The power P_e, the internal voltage $\dot{E}'_q$ and the terminal voltage v_T can be represented as:

$$P_e = v_d i_d + v_q i_q \quad (7)$$

$$\dot{E}'_q = \frac{1}{T_{do}}\left[E_{fd} - (x_d - x'_d)i_d - E'_q\right] \quad (8)$$

$$v_T = \sqrt{v_d^2 + v_q^2} \quad (9)$$

Here, E_{fd} is the field voltage; T'_{do} is the open circuit field time constant; x_d and x'_d are the d-axis reactance and the d-axis transient reactance of the generator, respectively.

The d-axis and q-axis components of armature current and terminal voltage can be calculated as:

$$i_d = \frac{\left[E'_q - v_B \cos\delta\right]}{x'_d + x_{eff}} \quad (10)$$

$$i_q = \frac{\left[v_B \sin\delta\right]}{x_q + x_{eff}} \quad (11)$$

$$v_d = \frac{x_q v_B}{x_q + x_{eff}} \sin\delta \quad (12)$$

$$v_q = \frac{1}{x'_d + x_{eff}}\left[x_{eff} E'_q + v_B x'_d \cos\delta\right] \quad (13)$$

The following equation presents the effective reactance:

$$x_{eff} = x_T + x_L - x_{TCSC}(\alpha) \quad (14)$$

where $x_{TCSC}(\alpha)$ is the TCSC reactance at firing angle α

3.2. Exciter

The IEEE Type ST1A excitation system shown in Fig. 2 is considered in this study. It can be represented as follows:

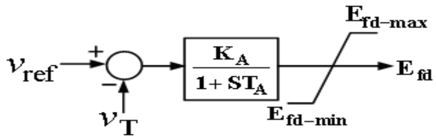

Fig.3. IEEE type ST1A excitation system

$$\dot{E}_{fd} = \frac{1}{T_A}\left[K_A\left(v_{ref} - v_T\right) - E_{fd}\right] \quad (15)$$

In the above equation, K_A and T_A are the gain and time constant of the excitation system.

3.3. TCSC-based damping controller

The block diagram of a TCSC-based lead-lag controller is presented in Fig. 3.

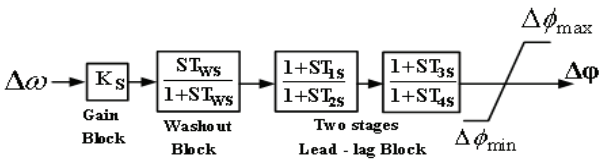

Fig.3. Structure of the TCSC-based damping controller

The effective conduction angle φ during dynamic conditions can be expressed by:

(16) $\phi = \phi_0 + \Delta\phi\,,\ \phi = 2(\pi - \alpha)$

where

(17) $\phi = 2(\pi - \alpha)$

The value of firing angle α is modulated according to the variation in output of TCSC controller Δφ. Φ_0 is the initial value of conduction angle.

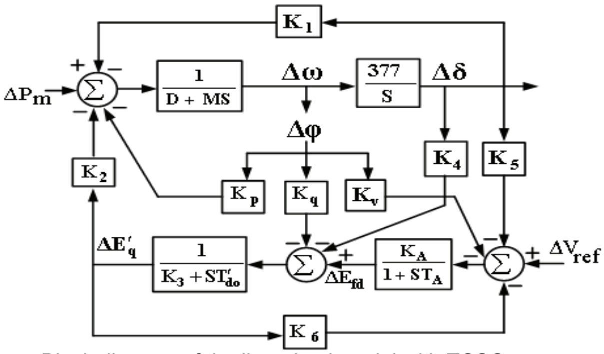

Fig.4. Block diagram of the linearized model with TCSC

3.4. The Linearized Model

In the design of electromechanical mode damping controllers, the linearized incremental model around a nominal operating point is usually employed. The Phillips-Heffron model of the power system with TCSC is derived by linearizing the set of Eq.s (5)–(15) around an operating condition of the power system:

(18)
$$\begin{bmatrix} \Delta\dot{\delta} \\ \Delta\dot{\omega} \\ \Delta\dot{E}'_q \\ \Delta\dot{E}_{fd} \end{bmatrix} = \begin{bmatrix} 0 & \omega_b & 0 & 0 \\ -\frac{K_1}{M} & -\frac{D}{M} & -\frac{K_2}{M} & 0 \\ -\frac{K_4}{T'_{do}} & 0 & -\frac{K_3}{T'_{do}} & \frac{1}{T'_{do}} \\ -\frac{K_A K_5}{T_A} & 0 & -\frac{K_A K_6}{T_A} & -\frac{1}{T_A} \end{bmatrix} \times \begin{bmatrix} \Delta\delta \\ \Delta\omega \\ \Delta E'_q \\ \Delta E_{fd} \end{bmatrix} + \begin{bmatrix} 0 \\ -\frac{K_p}{M} \\ -\frac{K_q}{T'_{do}} \\ -\frac{K_A K_v}{T_A} \end{bmatrix} \times [\Delta\phi]$$

where K_1-K_6, K_p, K_q *and* K_v are linearization constants.

(19)
$$K_2 = \frac{\partial P_e}{\partial E'_q} \qquad K_p = \frac{\partial P_e}{\partial \phi} \qquad K_1 = \frac{\partial P_e}{\partial \delta}$$
$$K_3 = \frac{\partial E_q}{\partial E'_q} \qquad K_q = \frac{\partial E_q}{\partial \phi} \qquad K_4 = \frac{\partial E_q}{\partial \delta}$$
$$K_6 = \frac{\partial v_T}{\partial E'_q} \qquad K_v = \frac{\partial v_T}{\partial \phi} \qquad K_5 = \frac{\partial v_T}{\partial \delta}$$

Fig. 4 shows the block diagram of the SMIB power system with TCSC which is obtained using the set of linearized Eq. (18).

4. The Proposed Approach

4.1. Problem Formulation

From the viewpoint of the washout function the value of T_w is not critical and may be in the range of 1-20 s. The main consideration is that it be long enough to pass stabilizing signals at the frequencies of interest unchanged [3]. The time constant of T_2 and T_4 are respecified [1, 25]. In this study, T_{WS}=10s and T_{2S}= T_{4S} =0.1s are chosen. The other parameters which should be optimized are as follows:

- TCSC-based damping controller: gain (K_A) and time constants (T_{1S} and T_{3S}).
- AVR: gain (K_A) and time constant (T_A).

During the steady-state conditions Δφ and φ_0 are constant. During dynamic conditions, conduction angle φ and subsequently x_{TCSC} *(α)* is modulated to damp power system oscillations. The desired value of the compensation is acquired via change in conduction angle (Δφ) according to the variation in Δω.

4.2. Objective function

There are many different methods to appraise the response performance of a control system, namely: Integral of Time weighted Absolute value of Error (ITAE), Integrated Absolute Error (IAE), Integral of Squared Error (ISE), and Integral of Time weighted Squared Error (ITSE). To evaluate the robustness of simultaneous coordination of TCSC-based damping controller and AVR, F has been selected as the total fitness function [2, 26]:

(20) $$J = \int_{t=0}^{t=t_{sim}} |\Delta\omega|.t.dt$$

(21) $$F = \sum_{i=1}^{N_p} J_i$$

Where, t_{sim} is the time range of the simulation and N_p is the total number of loading conditions. In this study, the PSO technique is applied to solve the optimization problem. The flowchart of the optimization based on simultaneous coordination of TCSC-based damping controller and AVR is presented in Fig. 5 [26].

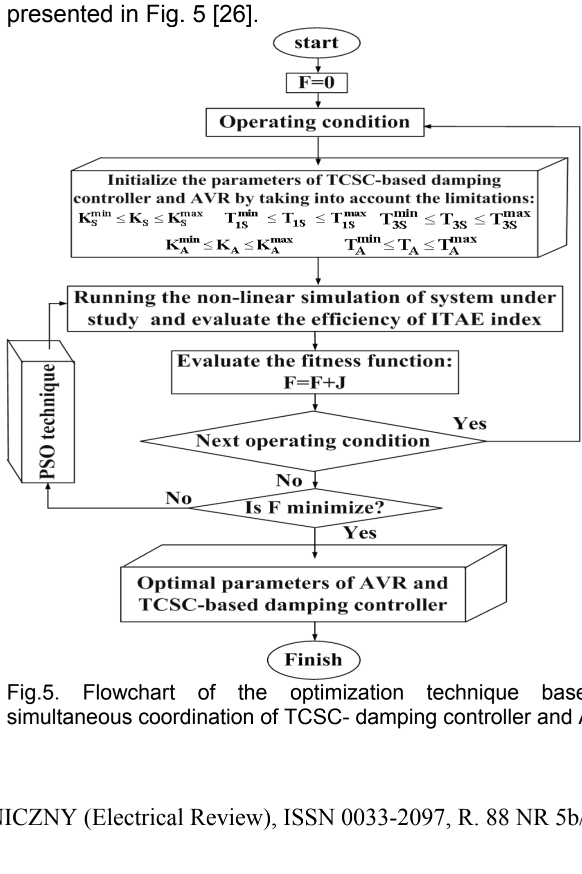

Fig.5. Flowchart of the optimization technique based on simultaneous coordination of TCSC- damping controller and AVR

The time-domain simulation of the non-linear system model is performed for the simulation period. It is aimed to minimize this fitness function in order to improve the system response in terms of the settling time, overshoots and undershoot. The problem constraints are the optimized parameter bounds. Therefore, the design problem is formulated as the following optimization problem:

(22) $$Minimize\ F$$

Subject to:

(23)
$$K_S^{min} \le K_S \le K_S^{max}$$
$$T_{1S}^{min} \le T_{1S} \le T_{1S}^{max}$$
$$T_{3S}^{min} \le T_{3S} \le T_{3S}^{max}$$
For TCSC-based damping controller

$$K_A^{min} \le K_A \le K_A^{max}$$
$$T_A^{min} \le T_A \le T_A^{max}$$
For AVR

5. Simulation Results add Discussions

To evaluate the robustness of simultaneous coordination of TCSC-based damping controller and AVR in order to improve power system dynamic stability, three different loading conditions: light loading, nominal loading and heavy loading are considered. In all cases, the power system is affected by 3-phase fault in power system. AVR and TCSC controller parameters in [3] and [27] are considered as non-coordinating states, respectively. The coordinated design of TCSC-based damping controller and AVR is performed by evaluating the fitness function presented in Eq. (21) with considering the three different loading conditions. Optimal parameters of these controllers are given in Table. 1.

Table. 1.Optimal parameter settings of the AVR and PSS

AVR		TCSC-based damping controller		
K_A	T_A	K_S	T_{1S}	T_{3S}
0.4582	0.1042	0.5009	0.1555	0.1944

The following section results show the effectiveness and robustness of simultaneous coordination of TCSC-based damping controller and AVR to enhance the dynamic stability of power system.

5.1. Nominal Loading

The scheme of proposed coordinated design is apprised for $P_e=1^{pu}$ under 3-phase fault at the infinite bus. Fault is occurred at $t=1s$ that is cleared after 9 cycles. The original system is restored after the clearance of the fault. As described above, PSO-technique is applied to coordinate TCSC-based damping controller and AVR simultaneously in order to damp power system oscillations. Figs. 6 and 7 display the system response under severe disturbance. These figures approve the robustness of simultaneous coordination among TCSC-based damping controller and AVR to diminish the power system oscillations.

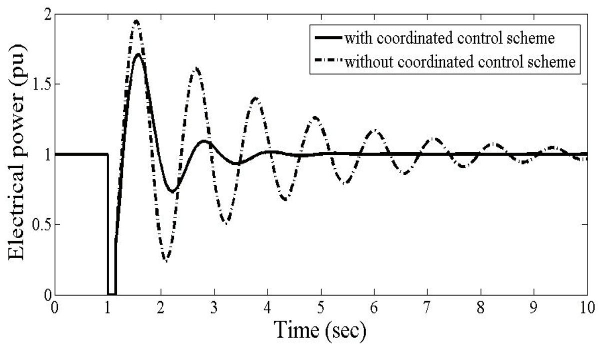

Fig. 6. Electrical power response under nominal loading

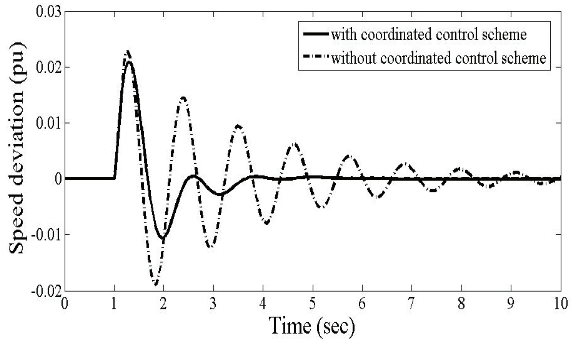

Fig. 7. Rotor speed response under nominal loading

5.2. Light Loading

In this state, the coordination scheme is assessed for $P_e=0.6^{pu}$ under 3-phase fault at the infinite bus at $t=1s$ that fault is cleared 0.2s (12 cycles) later. The original system is restored after the clearance of the fault. The system response with and without coordination scheme is exhibited in Figs. 8 and 9. These figures portray the effectiveness of robust coordinated TCSC-based damping controller and AVR to enhance the dynamic stability of power system.

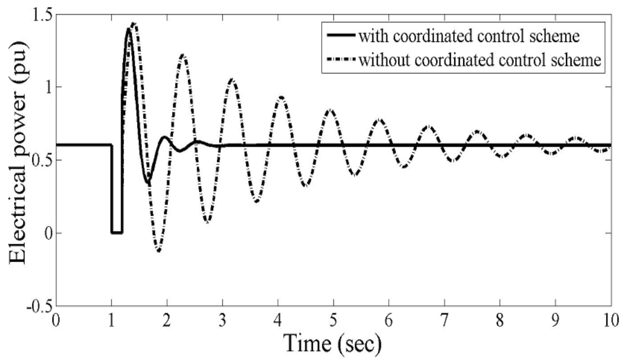

Fig. 8. Electrical power response under light loading

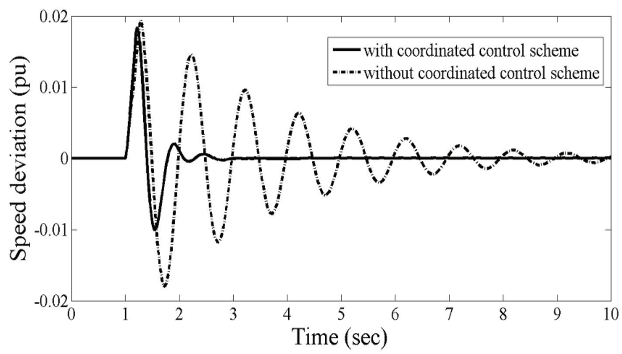

Fig. 9. Rotor speed response under light loading

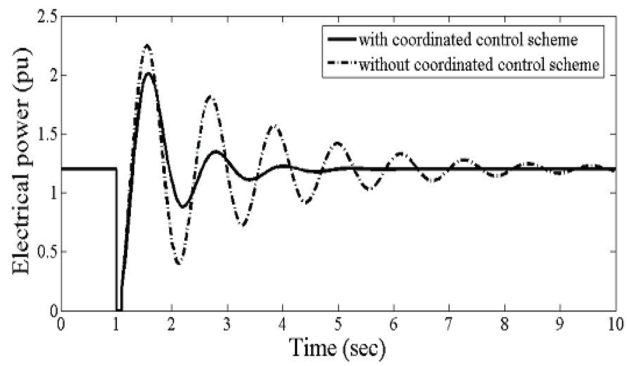

Fig. 10. Electrical power response under heavy loading

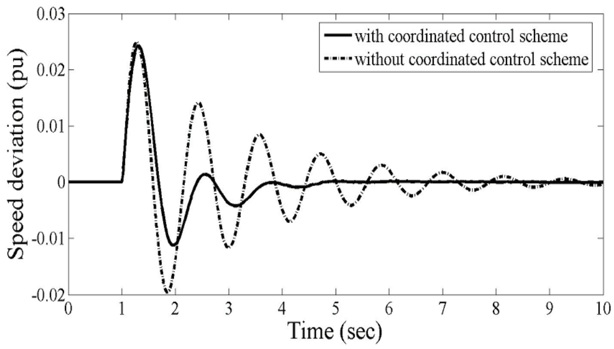

Fig. 11. Rotor speed response under heavy loading

5.3. Heavy Loading

To test the effectiveness of coordinated control scheme, a 3-phase fault is considered at the infinite bus while system is under heavy loading (P_e=1.2^{pu}). Fault is occurred at t=1s and is cleared after 6 cycles. The original system is restored after the clearance of the fault. The system response with and without coordination scheme is shown in Figs. 10 and 11. As it has been expected, these figures reveal that the power system stability is significantly improved with coordinated control among TCSC-based damping controller and AVR.

6. Conclusion

In this paper, a robust control scheme based on simultaneous coordination between of TCSC-based damping controller and AVR is presented to improve dynamic stability of power system. The problem of selecting the controller's parameters is converted to an optimization problem to damp the power system oscillations and enhance dynamic performance of power system. The high performance of PSO technique in order to acquire the optimal solution of the problem has been successfully proved. To confirm the effectiveness of the coordinated control scheme, dynamic performance of these controllers has been evaluated over a wide range of loading conditions under sever disturbance in single-machine infinite-bus power system. The non-linear time-domain simulation results suggest that the robustness of simultaneous coordinated design of TCSC-based damping controller and AVR to enhance power system dynamic stability.

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