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A Robust Approach Based on PSO Technique to Alleviate Power System Oscillation Using SSSC-Based PSD Damping Controller

***Abstract**. The menace of losing stability following a disturbance is one of the results of such a stressed system. SSSC is a kind of series FACTS device which is used in power system primarily to enhance the overall dynamic performance of the system. In order to improve the power system stability, a novel PSD structure is introduced as a supplementary damping controller for SSSC. To evaluate the robustness of proposed damping controller, it has been compared with PI and LL controllers. Also, dynamic performance of these controllers is evaluated under three different conditions of disturbance in SMIB power system. PSO technique has been employed to solve the optimization problem. The obtained results reveal that the SSSC-based PSD damming controller provides robust dynamic performance under different disturbance in power system.*

***Streszczenie**. SSSC jest jednym z komponentów system FACTS który jest używany do poprawy właściwości dynamicznych. Zaproponowano nową strukturę PSD jako dodatkowy sterownik dla SSSC. Sterownik porównano z układami PI i LL. Stwierdzono, że sterownik PSD w układzie SSC zapewnia odporne na zakłócenia właściwości systemu. (**Odporna metoda łagodzenia oscylacji w systemie wykorzystująca SSSC i sterownik PSD**)*

Keywords: SSSC, PSD Damping Controller, PSO Technique, Power System Dynamic Stability.
Słowa kluczowe: SSSC, PSO, stabilność systemów energetycznych

1. Introduction

One of the main concerns in electric power system operation is repression of electromechanical oscillations. If sufficient damping is not available, while a disturbance occurs in power system, the oscillations can be increased and continued for minutes to cause loss of synchronism [1]. The lack of sufficient system damping is the major reason of the continuity and growth of oscillation in power system [2-4]. Flexible ac transmission systems (FACTS) devices are one of the main purposes for damping of the 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]. Static Synchronous Series Compensator (SSSC) is one of important member of FACTS family, which provides the virtual compensation of transmission line impedance by injecting the controllable voltage in series with the transmission line [8, 9]. In the steady state applications, the main target of applying the SSSC in transmission lines is the control of either impedance line or power flow [10], whereas it can be used to damp the power system oscillations and also improve the overall dynamic performance of the power system. The SSSC is characterized by a solid state synchronous Voltage Source Convertor (VSC), which is produce a balanced set of three sinusoidal voltages at the fundamental frequency with rapidly controllable amplitude and phase angle in transmission line. The SSSC by operating in capacitive as well as inductive mode can perform prominent role in controlling the power flow of the system [11, 12]. The efficiency of this device in improving the transient stability of power systems, alleviating the power system oscillation, and improving the dynamic behavior of power system has been reported in [13-16].

From the viewpoint of power system dynamic stability, damping of power system oscillations with SSSC is performed through power modulations by a supplementary damping controller. A number of different classical controllers such as Lead-Lag (LL), Proportional-Integral (PI), and Proportional–Integral-Derivative (PID) have been employed in FACTS devices as supplementary damping controller [8, 17-20]. In this paper a novel Proportional plus Square Derivative (PSD) controller is introduced as a supplementary damping controller for SSSC to enhance all scale of transient stability improvement, including: lesser undershoot, overshoot and settling time.

A variety of conventional design techniques have been applied for tuning controller parameters. The most common methods are based on the pole placement method [21, 22], eigenvalues sensitivities [23, 24], residue compensation [25], and also the current control theory. Unfortunately, the 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 [26]. The progressive methods develop a technique to search for the optimum solutions via some sort of directed random search processes [27]. 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 [28]. 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 [29, 30].

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 optimization problem and optimum tune the parameters of controllers. To verify the robustness of PSD damping controller, it has been compared with PI and LL controllers. Furthermore, dynamic performance of these controllers is analyzed and appraised under three different conditions of disturbance in Single-Machine Infinite-Bus (SMIB) power system. Finally, the non-linear time-domain simulation results reveal that the SSSC-based PSD damping controller provides robust dynamic performance as compared with other controllers.

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 [31]. 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.

In the current research, the process of PSO technique can be summarized as follows [32-34]:

1) Initial positions of *pbest* (personal best of agent i) and *gbest* are (group best) 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[35]

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

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

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

Where *n* is the number of particles in the swarm; *m* is the number of components for the vectors υ_j and x_j, t is the number of generation (iteration); $\upsilon^{(t)}_{j,g}$ is the *gth* component of the velocity of particle *j* at iteration *t*.

c_1 and c_2 are two positive constants, called cognitive $\upsilon^{(t)}_{j,g}$ and social parameters respectively. r_1 and r_2 are random numbers, uniformly distributed in (0, 1). $x^{(t)}_{j,g}$ is the *gth* component of the position of particle *j* at iteration *t*; $pbest_j$ is the *pbest* of particle *j*; *gbest* is the *gbest* of the group.

w is the inertia weight, which produces a balance between global and local explorations requiring less iteration on average to find a suitably optimal solution. It is determined as follows:

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

Where w_{max} is the initial weight, w_{min} is the final weight, *iter* is the current iteration number, $iter_{max}$ is the maximum iteration number. The *jth* particle in the swarm is represented by a d-dimensional vector $x_j=[x_{j,1}, x_{j,2}, \ldots, x_{j,d}]$ and its rate of velocity is symbolized by another d-dimensional vector $v_j=[v_{j,1}, v_{j,2}, \ldots, v_{j,d}]$. The best previous position of the *jth* particle is represented by $pbest_j=[pbest_{j,1}, pbest_{j,2}, \ldots, pbest_{j,d}]$. 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. Single-Machine Infinite-Bus Power System

The SMIB power system has been simulated in MATLAB/SIMULINK environment which is presented in Fig1. Meanwhile, equivalent circuit of this system is shown in Fig2. It is almost similar to the employed system in [4].

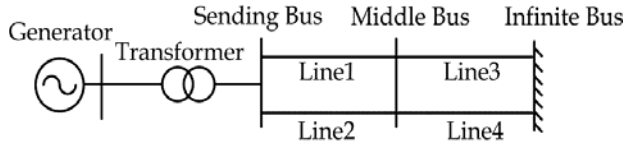

Fig. 1. Single line diagram of SMIB power system

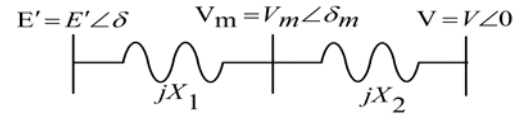

Fig. 2. Equivalent circuit of SMIB power system

3.1. Mathematical Model

The dynamics of the machine in classical model and electrical output power (P_e) of the machine can be represented by the following differential equations [36]:

(5) $$\frac{d\delta}{dt} = \omega$$

(6) $$\frac{d\omega}{dt} = \frac{1}{M}\left(P_m - P_e - D\omega\right)$$

(7) $$P_e = P_{max} \sin\delta$$

(8) $$P_{max} = \frac{E'V}{X_1 + X_2}$$

Where, δ and ω are the rotor angle and rotor speed, respectively; M and D are the inertia constant and damping coefficient, respectively.

3.2. Modelling of SSSC

The SSSC is characterized by a solid state synchronous voltage source convertor (V_S) that can provide inductive or capacitive compensation independent of the line current. It is considered that SSSC is placed on close to bus m in the SMIB system. V_S must be maintained in quadrature with the line current due to the SSSC can exchange only reactive power with the transmission line. The following equation expresses the SSSC voltage [5], [37], [38]:

(9) $$V_S = |V_S| e^{j(\theta \pm \pi/2)}$$

The current of transmission line can be written as:

(10) $$I = -\left[(E' \sin\delta) + j(V - E' \cos\delta)\right] / (X_1 + X_2)$$

Also, the current angle can be extracted from (10):

(11) $$\cos(\theta) = (Re(I)) \Big/ \sqrt{(Re(I))^2 + (Im(I))^2}$$

(12) $$\cos(\theta) = \frac{E' \sin\delta}{\sqrt{E'^{\,2} + V^2 - 2E'V\cos\delta}}$$

Sending and receiving end active powers are expressed by (13) and (14):

(13) $$P_{sending} = Re\left\{(E'\angle\delta).(I\angle\theta)^*\right\}$$

(14) $$P_{receiving} = Re\left\{(V\angle 0).(I\angle\theta)^*\right\}$$

After calculating the (13) and (14), sending and receiving end active powers are presented as follows:

(15) $$P_{sending} = P_{max} \sin(\delta) + \frac{E'V_S}{X_1 + X_2}\cos(\delta - \theta)$$

(16) $$P_{receiving} = P_{max}\ sin(\delta) + \frac{VV_S}{X_1 + X_2} cos(\theta)$$

There are no losses in the transmission line and also active power injection by SSSC, thus:

(17) $$P_{sending} = P_{receiving}$$

Subsequently

(18) $$E'\ cos(\delta - \theta) = V\ cos(\theta)$$

Via combining (12) and (18) with (15) and (16), the sending/receiving active power (P_e) can be written as:

(19) $$P_e = P_{max}\ sin\ \delta \left[1 + f(\delta) V_S\right]$$

Where

(20) $$f(\delta) = \left(E'^{\,2} + V^{2} - 2\,E'\,V\ cos\,\delta\right)^{-\frac{1}{2}}$$

So that, *f(δ)* is positive when δ oscillates in between zero and π. According to Equation (19), P_e can be modulated by controlling the SSSC voltage.

3.3. SSSC-Supplementary Damping Controllers

Due to occurrence of different disturbance in power system, the risk of loss of synchronism is not avoidable. SSSC can play an important role to mitigate the effects of such disturbances in power system. The dynamic performance of SSSC has been well approved, but from the viewpoint of power system dynamic stability, When a SSSC is applied in a power system a supplementary damping controller can be designed to enhance damping of system oscillations. In this paper, a novel PSD structure is introduced for SSSC which is expressed by:

(21) $$V_S = \left(K_p + K_{sd} * \left[\frac{T_d * S}{T_d * S + 1}\right]^{\frac{1}{2}}\right) * \omega$$

The following equations depict the relationship between PI and LL controllers with V_S, which are presented by Equations (22) and (23).

(22) $$V_S = \left(K_p + K_i / S\right) * \omega$$

(23) $$V_S = \left(K_p\ \frac{1+TS}{1+0.3S}\right) * \omega$$

The simulation model for dynamic analysis of power system with presence of SSSC is presented in Fig. 3.

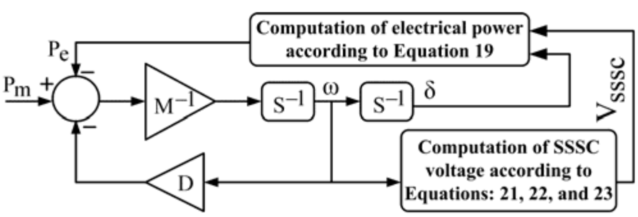

Fig. 3. Simulation diagram of the SMIB power system with SSSC

3.4. Optimum Tune the Parameters of Proposed PSD Controller and Classical Controllers

In this paper, PSO technique is applied to solve the optimization problem and to evaluate the robustness of proposed PSD damping controller in order to damp the power system oscillations. 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) [9, 17, 18, 39]. In this study, the total fitness function is expressed by Equation (25) [1, 40]:

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

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

Where, t_{sim} is the time range of the simulation and N_p is the total number of loading conditions. 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 of SSSC-based damping controllers is formulated as the following optimization problem:

(26) $$Minimize\ F$$

Subject to:

(27) $$\begin{array}{ll} K_P^{min} \le K_P \le K_P^{max} & \\ K_{SD}^{min} \le K_{SD} \le K_{SD}^{max} & \text{for PSD cot rolle} \\ K_P^{min} \le K_P \le K_P^{max} & \\ K_I^{min} \le K_I \le K_I^{max} & \text{for PI cot roller} \\ K_P^{min} \le K_P \le K_P^{max} & \\ T^{min} \le T \le T^{max} & \text{for LL cot roller} \end{array}$$

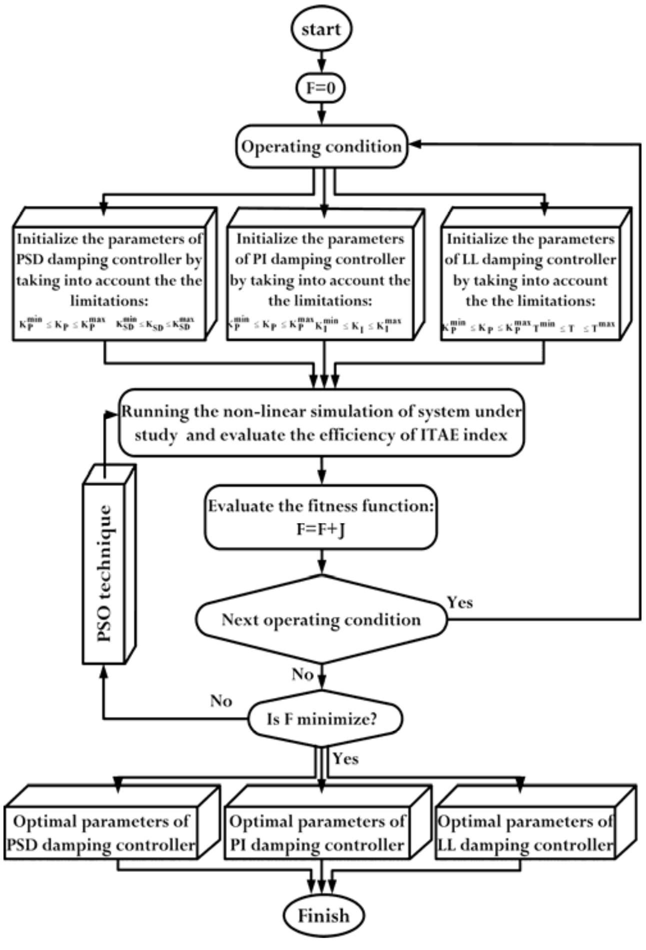

Fig.4. Flowchart of the optimization technique based on optimum tune parameters of SSSC-based damping controllers

PSO-technique is employed to solve the optimization problem and optimal tuning of SSSC-based damping controllers. The flowchart of the optimization based on optimum tune parameters of these damping controllers is described in Fig. 4 [40].

4. Simulation Results

In order to assess the dynamic performance of proposed PSD damping controller and other damping controllers, three different conditions of disturbance are considered which are described in following states. In all three conditions, system status is nominal loading condition ($P=0.7^{pu}$). The optimization of parameters of proposed PSD damping controller and other damping controllers is performed by evaluating the objective function as given in Equation (25), which considers three different conditions of disturbances. The optimal parameters of proposed PSD damping controller and other damping controllers are presented in Table 1.

Table. 1. Optimal parameter settings of the damping controllers

PSD controller		PI controller		LL controller	
K_P	K_{SD}	K_P	K_I	K_P	T
0.3026	0.0969	0.1637	0.0052	0.1846	0.1249

The following section results show the effectiveness and robustness of the SSSC-based PSD damping controller to enhance the dynamic stability of power system under wide range of disturbance conditions in SMIB power system.

4.1. Three Phase Short Circuit

A 3-phase fault occurs in the infinite bus at t=1s, then it is cleared after 0.3s. As described above, PSO-technique is used to optimum tune the parameters of controllers in order to enhance power system stability and approve the dynamic performance of SSSC-based PSD damping controller.

The system response under 3-phase short circuit is exhibited in Fig. 5. This figure approve that the proposed PSD controller is effective and robust than other controllers to reduce the power system oscillations.

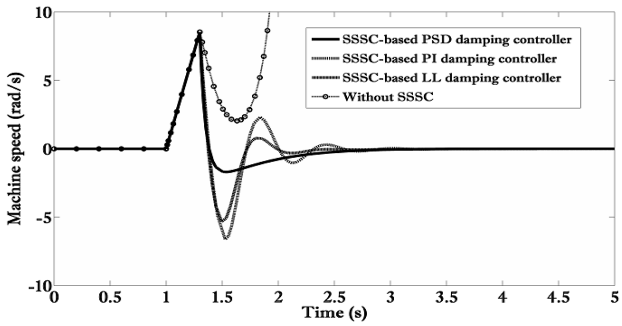

Fig. 5. Rotor speed response under 3-ph fault at infinite bus

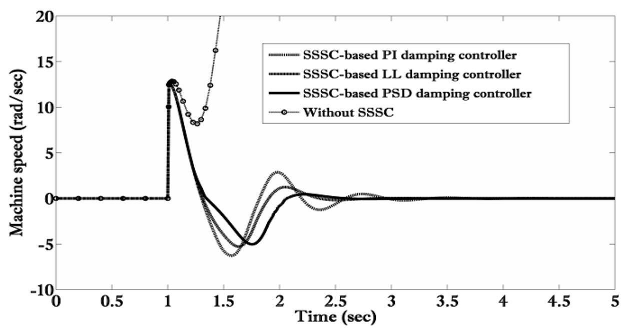

Fig. 6. Rotor speed response under impulse disturbance in mechanical power input

4.2. Impulse Disturbance in Mechanical Power

To evaluate the dynamic performance of proposed PSD damping controller, an impulse signal is considered in mechanical power input at t=1s. The magnitude and duration impulse signal are 30^{pu} and 10ms, respectively. System response under this disturbance is displayed in Fig. 6. It is revealed that SSSC-based PSD damping controller exhibit the best performance as compared with others.

4.3. Change in Mechanical Power

For this case, a step change of 0.3 $^{p.u.}$ is occurred in mechanical power input at t=1s, which is lasted for 5 s. System response under this disturbance is shown in Fig. 7. As discussed before, the power system stability is further improved in the presence of SSSC-based PSD damping controller.

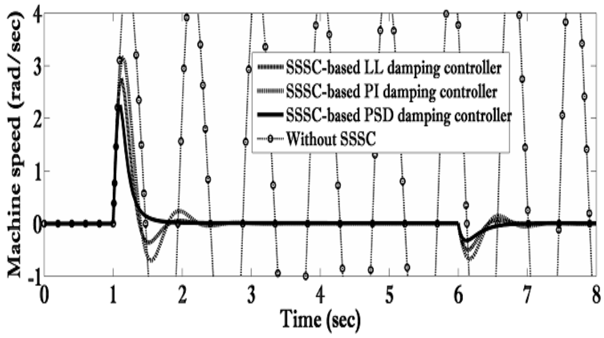

Figure 7: Rotor speed response under step change in mechanical power input

5. Conclusion

In this paper, a novel robust Proportional plus Square Derivative (PSD) structure is presented as a supplementary controller for Static Synchronous Series Compensator (SSSC) to vanquish the instability problem in power system. To evaluate the robustness of proposed PSD damping controller, it has been adequately compared with Lead-Lag (LL) and Proportional-Integral (PI) controllers. Also, the power system dynamic stability enhancement has been evaluated under wide range of disturbance conditions in Single-Machine Infinite-Bus (SMIB) power system. Particle Swarm Optimization (PSO) technique due to have high performance in solving the non-linear, non-differentiable and high-dimensional objectives has been employed to optimally tune the parameters of aforesaid controllers in order to enhance dynamic stability of power system. The results of simulation reveal that the SSSC-based PSD damming controller dramatically improves the power system dynamic stability as compared with others.

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