Controller Design of SSSC for power System Stability Enhancement

M. Ebadian, H. R. Najafi, R. Ghanizadeh

Abstract - In this paper, a novel method is developed for designing the output feedback controller for Static Synchronous Series Compensator (SSSC). In the proposed method, the problem of selecting the output feedback gains for the SSSC controllers is changed into an optimization problem with a time domain-based objective function.Then, it is solved by using the particle swarm optimization (PSO) algorithm that has a strong ability to find the most optimistic results. Only local and available state variables are used as the input signals of each controller for the decentralized design. Therefore, the designed SSSC controller has a simple and easy-to-implement structure. The performance of the proposed controllers is evaluated for both single-machine infinite-bus (SMIB) power system and multi-machine power system. Then, to show the robustness and effectiveness of proposed design approach, the results are presented over a wide variety of system configurations, loading conditions, and disturbances. Analyzing the results reveals that the designed PSO-based output feedback SSSC damping controller has a strong ability in damping power system oscillations. Furthermore, analyzing system performance under different operating conditions shows that the ψ-based controller is superior to the m-based controllers.

Index Terms - SSSC, Particle Swarm Optimization, Damping controller, Power system stability.

I. Introduction

THE main priorities in a power system operation are its security and stability. So, a control system should maintain its frequency and voltage at a fixed level, against any kind of disturbance such as a sudden increase in load, a generator being out of circuit, or failure of a transmission line because of factors such as human faults, technical defects of equipments, natural disasters, etc. Due to the new legislation of electricity market, this situation creates more stress for beneficiaries [1-2]. Low frequency oscillations that are in the range of 0.2 to 3 Hz are created by the development of large power systems and their connection. These oscillations continue to exist in the system for a long time and if not well-damped, the amplitudes of these oscillations increase and bring about isolation and instability of the system [3-5]. Using a Power System Stabilizer (PSS) is technically and economically appropriate for damping oscillations and increasing the stability of power system. Therefore, various methods have been proposed for designing these stabilizers [6-8]. However, these stabilizers cause the power factor to become leading and therefore they have a major disadvantage which leads to loss of stability caused by large disturbances, particularly a three phase fault at the generator terminals [9]. In recent years, using Flexible Alternating Current Transmission Systems (FACTS) has been proposed as one of the effective methods for improving system controllability and limitations of power transfer. By modeling bus voltage and phase shift between buses and reactance of transmission line, FACTS controllers can increase the power transfer capacity in steady state. These controllers are added to a power system for controlling normal steady state but because of their rapid response, they can also be used for improving power system stability through damping the low frequency oscillation [1-6], [9].

Static Synchronous Series Compensator (SSSC) is one of the important members of FACTS family which can be installed in series in the transmission lines. The SSSC is able to effectively control the power flow in power system. The reason for this effectiveness lies in its capability to change its reactance characteristic from capacitive to inductive, and vice verse [10]. Also, in order to improve the dynamic stability of power system, an auxiliary stabilizing signal can be added to the power flow control function of the SSSC [11]. In several references [10-12] the SSSC is used to stabilize frequency, enhance stability and damp power oscillation. In [13], the effect of compensation degree and operation mode of SSSC on small disturbance and transient stability is reported. The modified linearized Phillips-Heffron model has been used in some other researches [14-15] for analyzing a single-machine infinite-bus (SMIB) system equipped with an SSSC. The problem of designing an SSSC-based robust controller is changed to a multi-objective optimization problem with an eigenvalue-based objective function which is composed of the damping factor and the damping ratio of the undamped electromechanical mode. In [15], to improve the transient

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stability, an SSSC-based controller is designed by using an Adaptive Neuro-Fuzzy Inference System (ANFIS) method based on the Artificial Neural Networks (ANN). A coordination scheme for improving the stability of a power system by optimal design of power system stabilizer and SSSC-based controller is proposed in [16]. In this design, time delays caused by sensor and signal transmission are included. A simplified nonlinear method is proposed in [17] in order to improve the transient stability of multi-machine power system by using an SSSC. The dissipation rate of transient energy is used for determining the additional damping provided by an SSSC. Most of the proposals made in these papers are based on small disturbance analysis therefore it is necessary to linearize the system involved. Nevertheless, complex dynamics of the system cannot be fully captured by linear approaches especially during major disturbances. This brings about difficulties in tuning the FACTS controllers because an acceptable performance in large disturbances cannot be guaranteed by controllers tuned to provide desired performance at small signal condition. Therefore, because of its easy online tuning and also lack of assurance of the stability by some adaptive or variable structure techniques, a conventional lead/lag controller structure is usually preferred by the power system utilities. The tuning problem of FACTS controller parameters is a complex issue. So far, various conventional approaches have been reported in the literature which consider the design problems of conventional power system stabilizers. These methods include: the eigenvalue assignment, mathematical programming, gradient procedure for optimization and also the modern control theory. Unfortunately, due to their iterative nature, conventional methods are time-consuming, require heavy computational burden and show slow convergence. Furthermore, the search process is susceptible to get stuck in local minima and consequently the solution obtained may not be optimal [18].

In this paper, a new approach for optimal decentralized designing of output feedback gains of the damping controller of SSSC is investigated. A performance index is defined based on the system dynamics after an impulse disturbance alternately occurs in system and it is organized for a wide range of operating conditions and used to form the objective function of the design problem. The problem of designing a robust output feedback controller is formulated as an optimization problem and then is solved by using the PSO algorithm. The proposed design process for controller with the output feedback scheme is tested on a single-machine infinite-bus (SMIB) and a multi-machine power system. The optimum decentralized design of controller could be achieved because just local and available states ($\Delta\omega$ and ΔV_t) are used as the inputs of each controller. The nonlinear time-domain simulation studies are used to demonstrate the effectiveness of the proposed controller in damping power system oscillations under different operating conditions. Evaluating the results reveals that the proposed output feedback SSSC damping controller has a good robust performance for a wide range of operating conditions and disturbances.

II. PSO Technique

Based on the metaphor of human social interaction, particle swarm optimization is designed for optimizing complicated numerical functions. It is able to mimic the capability of human societies in processing knowledge [19]. The roots of this algorithm can be found in two main component methodologies: artificial life (such as bird flocking, fish schooling and swarming) and evolutionary computation. The key concept in this algorithm is that potential solutions are flown through hyperspace and are accelerated towards better or more optimum solutions. Furthermore, it can be implemented by using simple computer codes and is computationally inexpensive in terms of both memory requirements and speed. It lies somewhere in between evolutionary programming and the genetic algorithms. It keeps track of its coordinates in hyperspace which are associated with its previous best fitness solution, and also of its counterpart corresponding to the overall best value acquired thus far by any other particle in the population. Particles are represented by vectors because this kind of representation is suitable for most optimization problems. Indeed, adaptability, proximity, diverse response, stability and quality are the fundamental principles of swarm intelligence. It is adaptive corresponding to the change of the best group value. The diversity of responses are guaranteed by the allocation of responses between the individual and group values. PSO calculations of higher dimensional space are performed over a series of time steps. The population is responding to the quality factors of the previous best individual values and the previous best group values. The principle of stability is adhered to since the population changes its state if and only if the best group value changes. As it is mentioned in [19], This optimization approach is capable of solving various kinds of problems as GA, yet it does not suffer from some GAs difficulties.It has also been found robust in solving non-linear, non-differentiable and high-dimensional problems. PSO is the search technique for improving the convergence speed and finding the global optimum value of fitness function.

$$v_{id} = w \times v_{id} + c_1 \times rand() \times (P_{id} - x_{id}) + c_2 \times rand() \times (P_{gd} - x_{id}) \tag{1}$$

$$x_{id} = x_{id} + cv_{id} \tag{2}$$

Where P_{id} and P_{gd} are pbest and gbest. So far, several modifications have been proposed in literature for improving the PSO algorithm speed and convergence toward the global minimum. One of these modifications is to introduce a local-oriented paradigm (lbest) with different neighborhoods. It is concluded that gbest version performs best in terms of median number of iterations to converge. However, pbest version with neighborhoods of two is most resistant to local minima. PSO algorithm is further improved via using a time decreasing inertia weight, which leads to a reduction in the number of iterations [20]. Fig. 1 shows the flowchart of the proposed PSO algorithm.

Being simple, fast and easy to be coded are some of the many advantages of this new approach. Also, it requires minimal memory. Furthermore, has some other advantages over GA and evolutionary algorithm. First it has memory i.e. each particle is capable of remembering its best solution (local best) as well as the group best solution (global best). The fact that PSO maintains its initial population is another advantage of this method, and so there is no need to apply operators to the population, a process that is time and memory-storage-consuming. In addition, PSO is based on ‘‘constructive cooperation’’ between particles, in contrast with the genetic algorithms, which are based on ‘‘the survival of the fittest’’.

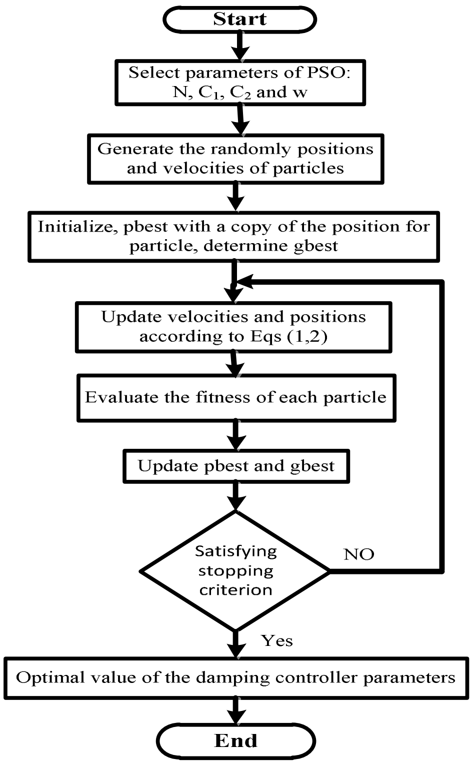


Fig. 1. Flowchart of the proposed PSO algorithm

III. Power System Model

A single-machine infinite-bus (SMIB) power system equipped with SSSC is investigated, as shown in Fig. 2 [10]. The SSSC consists of a boosting transformer with a leakage reactance x_{SCT}, a three-phase GTO based voltage source converter (VSC), and a DC capacitor (CDC). The two input control signals to the SSSC are m and ψ. Signal m is the amplitude modulation ratio of the pulse width modulation (PWM) based VSC. Also, signal ψ is the phase of the injected voltage and is kept in quadrature with the line current (inverter losses are ignored). Therefore, the compensation level of the SSSC can be controlled dynamically by changing the magnitude of the injected voltage. Hence, if the SSSC is equipped with a damping controller, it can be effective in improving power system dynamic stability.

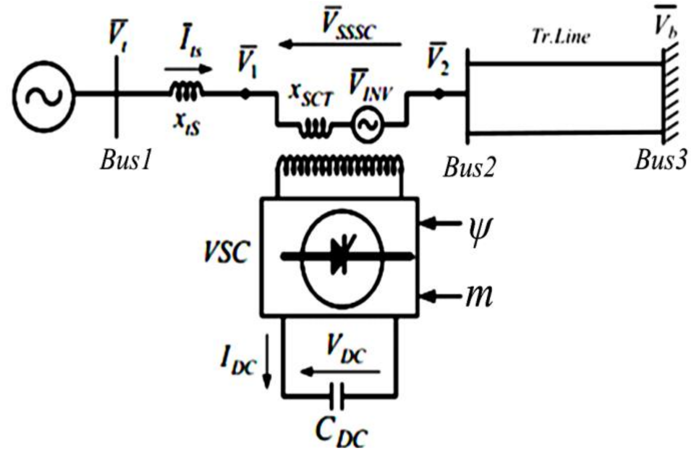


Fig. 2. SMIB power system with SSSC

A. Nonlinear Model of Power System Implemented with SSSC

The dynamic model of the SSSC is required in order to study the effect of the SSSC for enhancing the small signal stability of the power system. By applying Park’s transformation and neglecting the resistance and transients of the transformer, the SSSC can be modeled as [10]:

$$\overline{V}_{INV} = mkV_{DC}(\cos\psi + j\sin\psi) = mkV_{DC}\angle\psi \qquad \psi = \varphi \pm 90^{\circ} \tag{4}$$

$$\dot{V}_{DC} = \frac{dV_{DC}}{dt} = \frac{I_{DC}}{C_{DC}} = \frac{mk}{C_{DC}}(I_{tsd}\cos\psi + I_{tsq}\sin\psi) \tag{5}$$

Where k is the ratio between AC and DC voltage of SSSC voltage source inverter.

And so:

$$I_{tsq} = \frac{V_B\sin\delta + mkV_{DC}\cos\psi}{X_{ts} + X_{SB} + X_{SCT} + X_q} \tag{6}$$

$$I_{tsd} = \frac{E'_q - V_B\cos\delta - mkV_{DC}\sin\psi}{X_{ts} + X_{SB} + X_{SCT} + X'_d} \tag{7}$$

The nonlinear dynamic model of the power system of Fig. 2 is [10]:

$$\dot{\delta} = \omega_b(\omega - 1) \tag{8}$$

$$\dot{\omega} = \frac{1}{M}(P_m - P_e - D\omega) \tag{9}$$

$$\dot{E}'_q = \frac{1}{T'_{do}}(E_{fd} - E_q) \tag{10}$$

$$\dot{E}_{fd} = -\frac{1}{T_A}E_{fd} + \frac{K_A}{T_A}(V_{ref} - V_t) \tag{11}$$

Where:

$$P_e = E'_q I_{tsq} + (X_q - X'_d)I_{tsd}I_{tsq}$$

$$E_q = E'_q + (x_d - x'_d).I_{tsd}$$

$$V_t = \sqrt{(X_q I_{tsq})^2 + (E'_q - X'_d I_{tsd})^2}$$

B. Power System Linearized Model

By linearizing the SMIB system nonlinear differential equations including SSSC around the nominal operating point the following equations can be achieved:

$$\Delta\dot{\delta} = \omega_b \Delta\omega \tag{12}$$

$$\Delta\dot{\omega} = (-\Delta P_e - D\,\Delta\omega)/M \tag{13}$$

$$\Delta\dot{E}'_q = (-\Delta E_q + \Delta E_{fd})/T'_{do} \tag{14}$$

$$\Delta\dot{E}_{fd} = -\frac{1}{T_A}\Delta E_{fd} - \frac{K_A}{T_A}(\Delta V_t) \tag{15}$$

$$\begin{aligned}\Delta\dot{V}_{DC} &= K_7\Delta\delta + K_8\Delta E'_q + K_9\Delta V_{DC}\\ &+K_{dm}\Delta m + K_{d\psi}\Delta\psi\end{aligned} \tag{16}$$

Where:

$$\Delta P_e = K_1\Delta\delta + K_2\Delta E_q{}' + K_{pDC}\,\Delta V_{DC} + K_{pm}\Delta m + K_{p\psi}\,\Delta\psi$$
$$\Delta E_q{}' = K_4\Delta\delta + K_3\Delta E_q{}' + K_{qDC}\,\Delta V_{DC} + K_{qm}\Delta m + K_{q\psi}\,\Delta\psi$$
$$\Delta V_t = K_5\Delta\delta + K_6\Delta E_q{}' + K_{vDC}\,\Delta V_{DC} + K_{vm}\Delta m + K_{v\psi}\,\Delta\psi$$

K_1, K_2,...K_9, K_{pu}, K_{qu}, K_{du} and K_{vu} are linearization constants and are dependent on system parameters and the operating condition. The state space model of power system is given by:

$$\dot{X} = Ax + Bu \tag{17}$$

Where the state vector x , control vector u, A and B are:

$$X = \begin{bmatrix}\Delta\dot{\delta} & \Delta\dot{\omega} & \Delta\dot{E}'_q & \Delta\dot{E}_f & \Delta\dot{V}_{dC}\end{bmatrix}^T ; u = \begin{bmatrix}\Delta\varphi & \Delta m\end{bmatrix}^T$$

$$A = \begin{bmatrix} 0 & \omega_b & 0 & 0 & 0 \\ -\frac{K_1}{M} & -\frac{D}{M} & -\frac{K_2}{M} & 0 & -\frac{K_{pDC}}{M} \\ -\frac{K_4}{T'_{do}} & 0 & -\frac{K_3}{T'_{do}} & -\frac{1}{T'_{do}} & -\frac{K_{qDC}}{T'_{do}} \\ -\frac{K_AK_5}{T_A} & 0 & -\frac{K_AK_6}{T_A} & -\frac{1}{T_A} & -\frac{K_AK_{vDC}}{T_A} \\ K_7 & 0 & K_8 & 0 & K_9 \end{bmatrix}$$

$$B = \begin{bmatrix} 0 & 0 \\ -\frac{K_{pm}}{M} & -\frac{K_{p\psi}}{M} \\ -\frac{K_{qm}}{T_{do}'} & -\frac{K_{q\psi}}{T_{do}'} \\ -\frac{K_AK_{vm}}{T_A} & -\frac{K_AK_{v\psi}}{T_A} \\ K_{dm} & K_{d\psi} \end{bmatrix}$$

IV. PSO-Based Output Feedback Conttroller Design

A power system can be described by a linear time invariant (LTI) state-space model as follows [22]:

$$\begin{aligned}\dot{X} &= Ax + Bu\\ y &= Cx\end{aligned} \tag{18}$$

Where x, y and u represent the linearized state of the system, output and input variable vectors, respectively. Also, A, B and C are constant matrices which have appropriate dimensions and depend on the operating point of the system. The stability of the system when it is affected by a small interruption is defined by the eigenvalues of the state matrix A which are called the system modes. When the power system is subjected to a small disturbance, it remains stable for as long as all eigenvalues have negative real parts. If the real part of one of these system modes is positive, the system is unstable. In this case, the unstable mode can be moved to the left-hand side of the complex plane in the area of the negative real parts by using either the output or the state feedback controller. An output feedback controller has the following structures:

$$u = -Ky \tag{19}$$

Substituting (19) into (18) results in the following state equation:

$$\dot{X} = A_c x \tag{20}$$

Where, A_c is the closed-loop state matrix and is given by:

$$A_c = A - BKC \tag{21}$$

If the feedback gain K is chosen properly, the eigenvalues of closed-loop matrix Ac are moved to the left-hand side of the complex plane and the desired performance of controller can be achieved. The output feedback signals can be selected by using mode observability analysis [23]. After selecting the output feedback signals, merely the selected signals are used in forming (18). Therefore, selecting K for achieving the required objectives is the remaining problem in the design of output feedback controller. The control objective is increasing the critical modes damping to the desired level. It should be mentioned that the four parameters of the SSSC (m, φ) could be modulated in order to create the damping torque. In this paper, m and φ are modulated in order to produce the damping torque. The proposed controller must be capable of working properly under all the operating conditions where the improvement in damping of the critical modes is necessary. Since the selection of the output feedback gains for mentioned SSSC based damping controller is a complex optimization problem. Thus, to acquire an optimal combination, this paper employs PSO [22] to improve optimization synthesis and find the global optimum value of objective function. In order to form the objective function of the design problem, a performance index based on the system dynamics after an impulse disturbance alternately occurs in the system is defined. The Integral of time multiplied absolute value of the Error (ITAE) is taken as the objective function in this research. Since the operating conditions are often varied in power systems, a performance index for a wide range of operating points is defined as follows:

For single-machine infinite-bus power system:

$$J = \sum_{i=1}^{NP} \int_{0}^{tsim} \left|\Delta\omega_i\right| t \, dt \tag{22}$$

For multi-machine power system:

$$J = \sum_{i=1}^{NP} \sum_{i=1}^{n} \int_{0}^{tsim} \left|\Delta\omega_i\right| t \, dt \tag{23}$$

Where, NP is the total number of operating points for which the optimization is carried out, $\Delta\omega$ is the speed deviation of the machines and t_{sim} is the simulation time range. In order to calculate the objective function, the time domain simulation of the power system model is performed for the simulation period. The goal is to minimize this objective function in order to improve the system response in terms of the settling time and overshoots. The design problem can be formulated as the following constrained optimization problem, where the constraints are the controller parameters bounds :

$$\begin{gathered} \text{Minimize } J \text{ Subject to} \\ K_1^{min} \le K_1 \le K_1^{max},\ K_2^{min} \le K_2 \le K_2^{max} \end{gathered} \tag{24}$$

For multi-machine power system:

$$\begin{gathered} \text{Minimize } J \text{ Subject to} \\ K_1^{min} \le K_1 \le K_1^{max},\ K_2^{min} \le K_2 \le K_2^{max} \\ K_3^{min} \le K_3 \le K_3^{max},\ K_4^{min} \le K_4 \le K_4^{max} \\ K_5^{min} \le K_5 \le K_5^{max},\ K_6^{min} \le K_6 \le K_6^{max} \end{gathered} \tag{25}$$

Typical ranges of the optimized parameters are [-100–100], [-10–10], [-10–10], [-10–10], [-50–50], [-50–50] for K_1, K_2, K_3, K_4, K_5 and K_6 respectively. In order to solve this optimization problem and search for an optimum set of output feedback controller parameters, the proposed approach uses PSO algorithm. The optimizing process of SSSC controller parameters is performed by evaluating the objective cost function as given in (24) and (25), which considers a multiple of operating conditions and under various disturbances.

In order to acquire better performance, number of particles, particle size, number of iteration, c_1, c_2, and c are chosen as 30, 2, 50, 2, 2 and 1, respectively. Also, the inertia weight, w, is linearly decreasing from 0.9 to 0.4. It should be noticed that PSO algorithm is run several times and then optimal set of output feedback gains for the SSSC controllers is selected.

V. Results and Discussions

The SimPowerSystems (SPS) toolbox [24] is used for all simulations and damping controller design. SPS is a MATLAB-based modern design software which allows engineers and scientists to easily and quickly build models for simulating power systems by using SIMULINK environment.

Various libraries of SPS include models of typical power equipment such as machines, lines, transformers, and power electronics. Useful graphical user interface (GUI) tools are provided by the 'Powergui' block of SPS for analyzing the developed models. It is capable of performing load flows and initializing the three-phase networks containing three-phase machines so that the simulation could be started in steady state.

A. Single-machine infinite-bus power system

The SimPowerSystems blockset is used to develop the model of example power system shown in Fig. 2. The system is composed of a of 2100 MVA, 13.8 kV, 60 Hz hydraulic generating unit, connected to a 300 km long double-circuit transmission line through a 3-phase 13.8/500 kV step-up transformer and a 100 MVA SSSC.

The model of the system under study has been developed using SimPowerSystem Toolbox in MATLAB/SIMULINK environment and PSO program has been written (in .m file). To calculate the objective function, this model is simulated in a separate program considering a severe disturbance. The value of objective function is extracted form the SIMULINK mode by using 'To Workspace', then it is evaluated and used in PSO program.

The controllers are designed at nominal operating conditions for the system subjected to a certain severe disturbance (3-phase fault). Various operating conditions and contingencies are considered for the system with and without controller in order to show the robustness of the proposed design approach. Table 1 shows the optimized parameters that are obtained under nominal operating condition. These paremeters are used as the controller parameters in all cases. Two different operating conditions i.e. light and nominal, are considered and simulations are carried out under different fault disturbances and fault clearing sequences.

TABLE I
Optimized controller parameters for SMIB power system

controller	K_1	K_2
ψ	80.5412	0.0255
m	-88.1211	-5.3372

A.1. Case 1: Nominal loading condition, 3-phase self clearing fault

The behavior of the proposed controllers is verified at nominal loading condition (P_e=0.8 pu, δ_0= 48.4°) under a severe disturbance. At t = 1s, a 3-cycle, 3-phase fault occurs at the middle of the transmission line that connects bus 2 and bus 3. Once the fault is cleared, the original system is restore. Fig. 3 a–c show the response of system under this severe disturbance. The plots in these figures show speed deviation, electrical power deviation and SSSC injected voltage respectively. These figures clearly show that under this severe disturbance, system is oscillatory if there is no control. However, much better damping characteristics to low frequency oscillations is provided by the proposed controllers. Also, they can quickly stabilize the system by modulating the SSSC injected voltage.

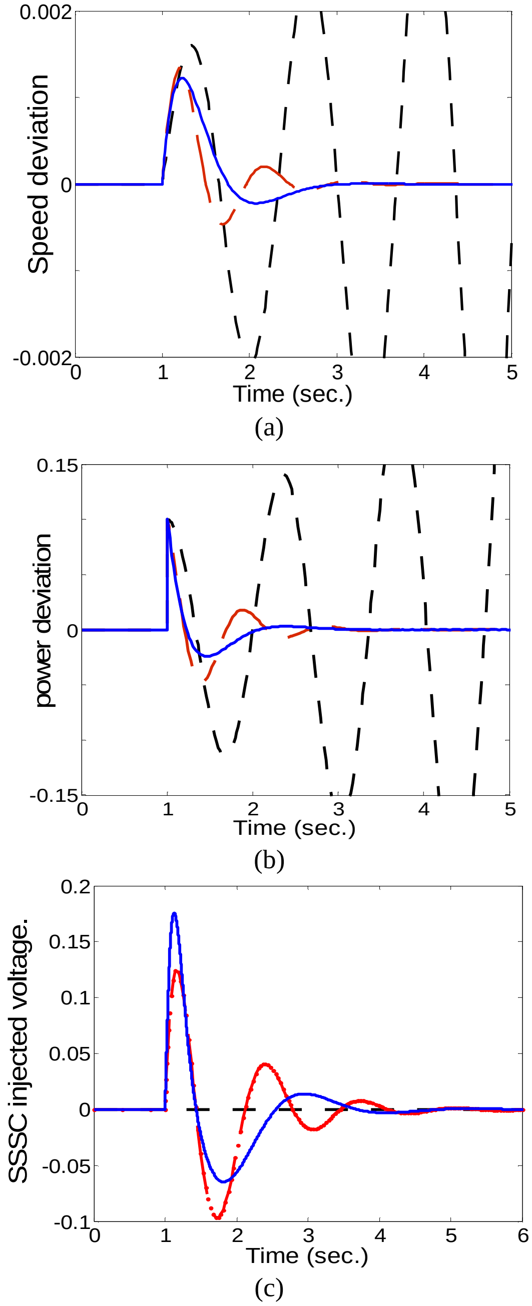


Fig. 3. Dynamic responses under case 1 loading condition (a) $\Delta\omega$, (b) ΔP_e and (c) SSSC injected voltage: Dash-dotted (without controller), Dotted (m-based controller), Solid (ψ-based controller)

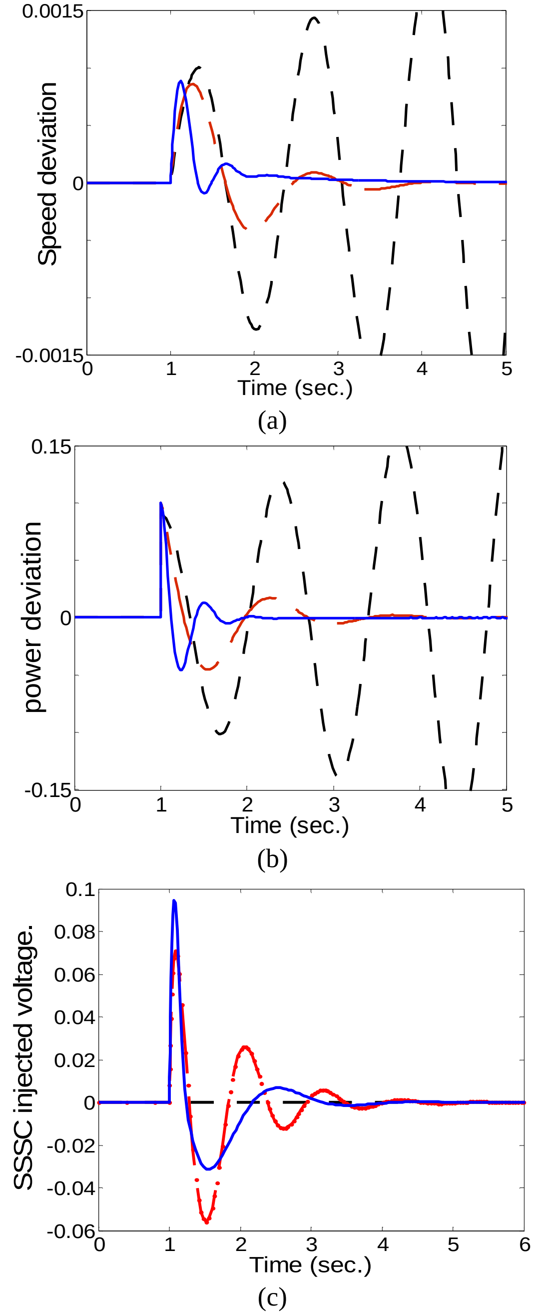


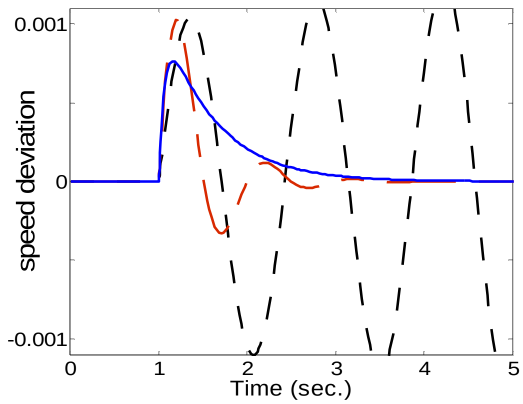
Fig. 4. Dynamic responses under case 2 loading condition (a) Δω, (b) ΔPe and (c) SSSC injected voltage: Dash-dotted (without controller), Dotted (m-based controller), Solid (ψ-based controller)

A.2. Case 2: Light loading condition, 3-phase fault cleared by line tripping

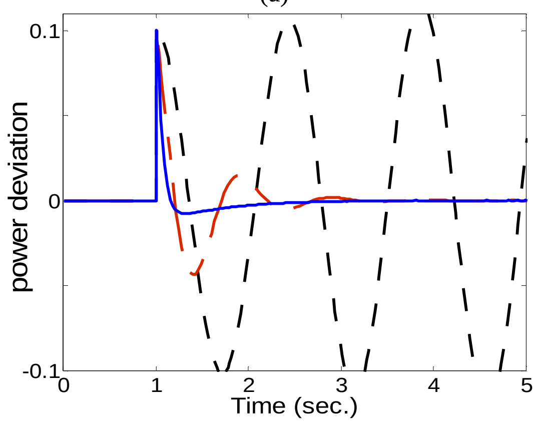
The robustness of the controllers is tested by changing the generator loading to light loading condition i.e. δ_0= 29.47°, and P_e= 0.5 pu, also by considering a 3-cycle, 3-phase fault in the transmission line near bus 3 at t = 1 s. The fault is cleared through opening the faulty line then the line is reclosed after 3-cycles. Fig. 4 a-c shows the speed deviation, electrical power deviation and SSSC injected voltage under this contingency. This figure clearly depicts the robustness of proposed controllers for changes in operating condition and fault location.

A.3. Case 3: Heavy loading condition, small disturbance

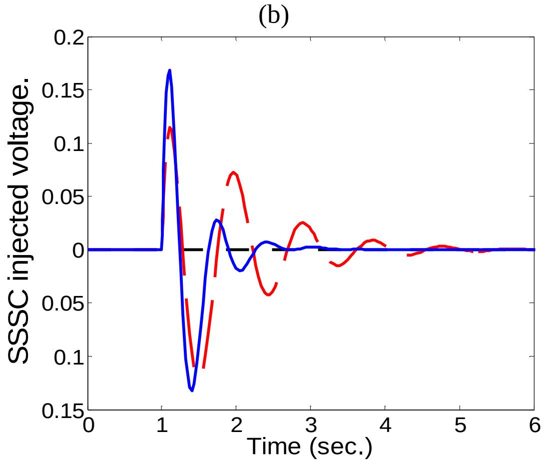
By disconnecting load at bus 1 at t = 1 s for 100 ms at heavy loading condition i.e. P_e= 1.0 pu, and δ_0= 60.73°, the effectiveness of the proposed controllers is also examined at heavy loading condition. System speed deviation, electrical power deviation and SSSC injected voltage response under the above contingency are shown in Fig. 5 a-c from which it is obvious that the proposed controllers that are designed at nominal loading condition for a 3-phase fault disturbance, effectively damp the power system oscillations and quickly stabilizes the system when operating condition and contingency change.



(a)



(b)



(c)

Fig. 5. Dynamic responses under case 3 loading condition (a) $\Delta\omega$, (b) ΔPe and (c) SSSC injected voltage: Dash-dotted (without controller), Dotted (m-based controller), Solid (ψ-based controller)

From the above conducted tests, it can be concluded that ψ-based damping controller is superior to the m-based damping controller and enhance greatly the dynamic stability of power systems.

B. Extension to three-machine six-bus power system

The proposed technique for designing SSS-based damping controller is extended to a power system with three machines and six-bues which is shown in Fig. 6. It is similar to the power systems used in Refs. [16], [25]. The system is composed of three generators and it is divided into two subsystems that are connected by an intertie. After a disturbance, these subsystems swing against each other and bring about instability. The line is sectionalized and an SSSC is assumed on the mid-point of the tieline in order improve the stability of the system. The relevant data for the system is provided in Ref. [25].

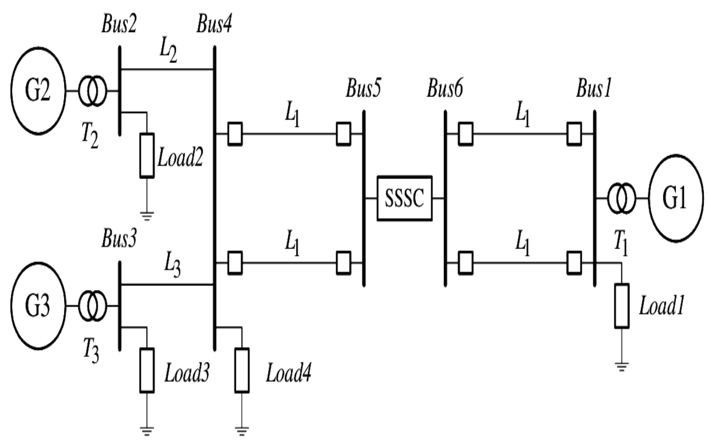


Fig. 6. Three-machine six-bus power system.

The same approach as explained in Section V.A for single-machine case is used for optimizing the parameters of SSSC-based damping controller for a case with three machines. Speed deviations and terminal voltage deviations of generators G_1, G_2 and G_3 are selected as the input signal of the SSSC-based controller. Table 2 shows the optimized values of the controller. Simulation studies are carried out and presented under different contingencies.

TABLE II.
PSO OPTIMIZED CONTROLLER PARAMETERS FOR MULTI-MACHINE POWER SYSTEM.

Parameters	controller	
	ψ	m
K_1	78.6413	-82.1312
K_2	0.0453	-6.3271
K_3	0.5275	-9.3471
K_4	0.0586	-3.3679
K_5	30.0655	-37.3578
K_6	45.0245	-48.3573

The following cases are considered:

B.1 Case 1: Three-phase fault disturbance

A 3-cycle, 3-phase self clearing fault is applied at one of the line sections between bus 1 and bus 6 near bus 6 at t = 1 s. The original system is restored after the fault clearance. The system response is shown in Fig. 7a–c. From these figures it can be seen that, inter-area of oscillations are highly oscillatory without controllers. The proposed controllers significantly improve the power system stability by suppressing these oscillations by modulating the SSSC injected voltage.

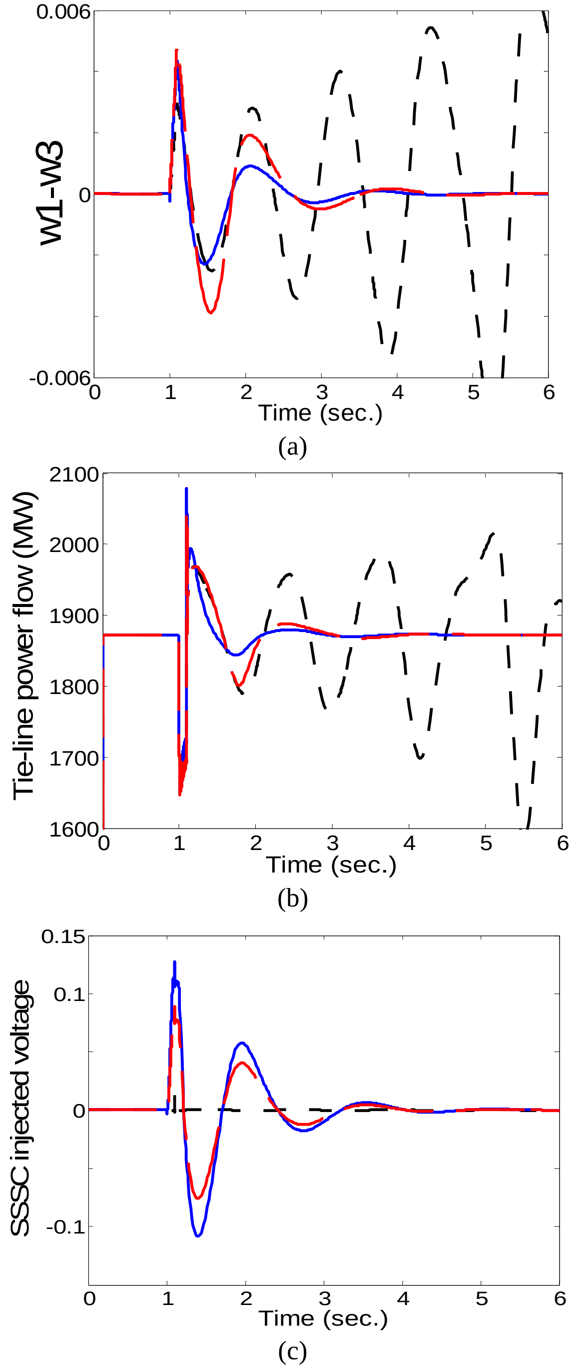


Fig. 7. Dynamic responses under case 1 loading condition (a) Δω, (b) Tie-line power flow and (c) SSSC injected voltage: Dash-dotted (without controller), Dotted (m-based controller), Solid (ψ-based controller)

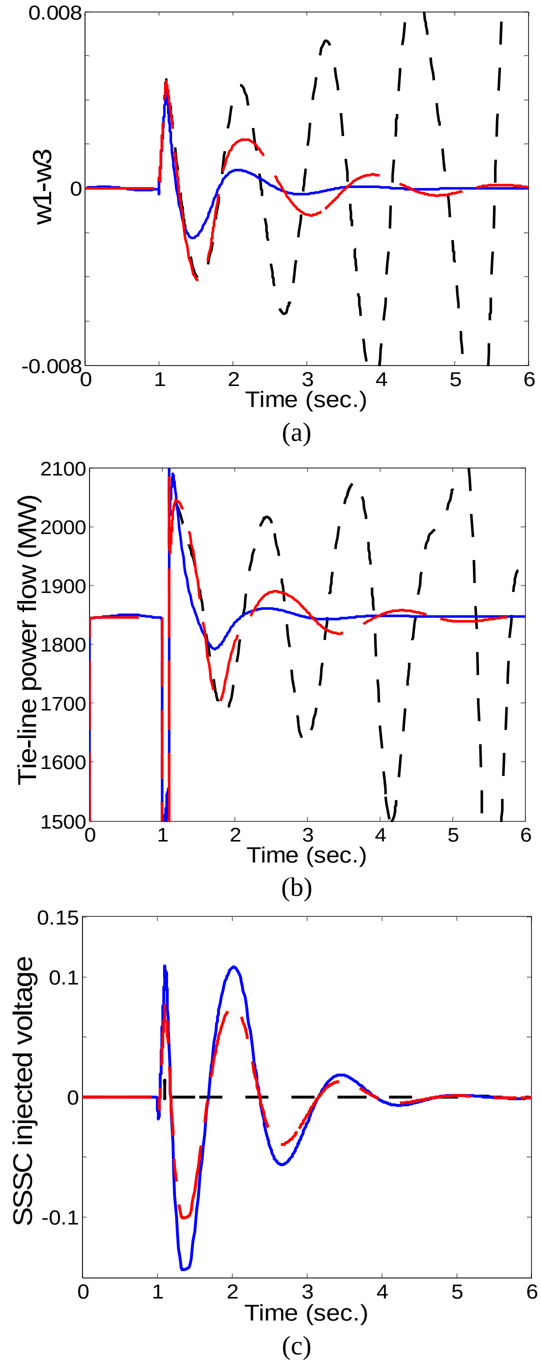


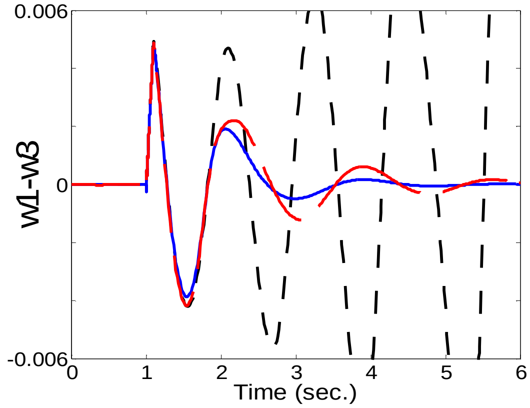
Fig. 8. Dynamic responses under case 2 loading condition (a) Δω, (b) Tie-line power flow and (c) SSSC injected voltage: Dash-dotted (without controller), Dotted (m-based controller), Solid (ψ-based controller)

B.2. Case 2: Line outage disturbance

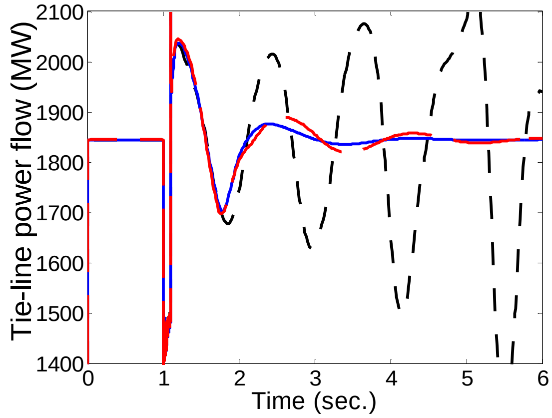
One of the parallel transmission lines between bus 1 and bus 6 is tripped off at t = 1 s in order to test the robustness of the controllers to type of disturbance. This line is reclosed after 3-cycles and after the line recloser, the original system is restored. The system response for the above contingency is shown in Fig. 8 a-c.

B.3. Case 3: Small disturbance

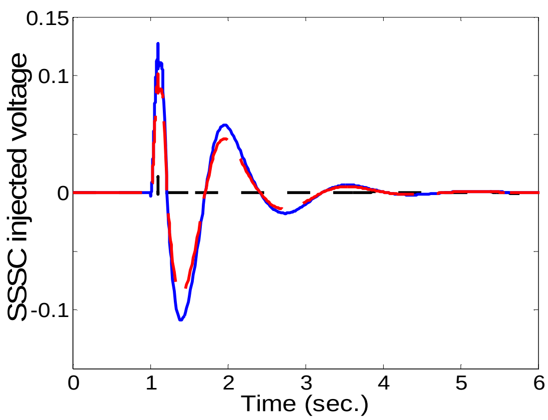
To complete this study, the performance of the proposed controllers is also investigated under small disturbance. At t = 1.0 s the load at bus 4 is disconnected for 100 ms (this is considered as a small disturbance). The system response for the above contingency is shown in Fig. 9 a-b. These figures clearly show that the proposed controller is robust and provides efficient damping even under small disturbance conditions.



(a)



(b)



(c)

Fig. 9. Dynamic responses under case 3 loading condition (a) $\Delta\omega$, (b) Tie-line power flow and (c) SSSC injected voltage: Dash-dotted (without controller), Dotted (m-based controller), Solid (ψ-based controller)

VI. Conclusion

In this paper, a robust output feedback SSSC based damping controller has been successfully designed by using the particle swarm optimization (PSO) algorithm. First, the designing problem of robustly selecting the parameters of output feedback controller is changed into an optimization problem, then, it is solved by the PSO technique with a time domain-based objective function. Only $\Delta\omega$ and ΔV_t which are local and available state variables are used as the input signals of each controller, so the implementation of the designed stabilizers is made more feasible. In order to show the effectiveness of the proposed design approach, simulation results are presented for various loading conditions and disturbances. It is revealed that the proposed controllers are robust to fault location and change in operating conditions and improve the stability by generating proper stabilizing output control signals. Eventually, the proposed design approach is extended to a multi-machine power system and simulation results are presented to show the effectiveness of the proposed controllers to damp modal oscillations in a multi-machine power system. The proposed control scheme is adaptive, simple to implement, yet is valid over a wide range of operating conditions.

VII. References

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