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DESIGN OF OUTPUT FEEDBACK SSSC CONTROLLER FOR DAMPING OF ELECTROMECHANICAL OSCILLATIONS USING MOHBMO

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Abstract- In this paper, the modified linearized Phillips-Heffron model is utilized to theoretically analyze a single-machine infinite-bus (SMIB) installed with SSSC. Then, the result of this analysis is used for assessing the potential of an SSSC supplementary controller to improve the dynamic stability of a power system. This is carried out by measuring the electromechanical controllability through singular value decomposition (SVD) analysis. This controller is tuned for simultaneously shifting the undamped electromechanical modes to a prescribed area in the s-plane. The issue of designing a robustly SSSC-based controller is considered and formulated as an optimization problem according to the eigenvalue-based multi-objective function consisting of the damping ratio of the undamped electromechanical modes and the damping factor. Next, considering its high capability to find the most optimistic results, the Honey Bee Mating Optimization (HBMO) algorithm is used to solve this optimization problem. A wide range of operating conditions are considered in design process of the proposed damping controller in order to guarantee the its robustness. The effectiveness of the proposed controller is demonstrated through eigenvalue analysis, controllability measure, nonlinear time-domain simulation and some performance indices studies. The results show that the tuned HBMO based SSSC controller which is designed by using the proposed multi-objective function has an outstanding capability in damping power system low frequency oscillations, also it significantly improves the power systems dynamic stability.

Keywords: Power System Dynamic Stability, Static Synchronous Series Compensator (SSSC), Multiobjective Honey Bee Mating Optimization (MOHBMO).

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 doubled stress for beneficiaries [1-2]. Low frequency oscillations that are in the range of 0.2-3 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].

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 [4-6]. 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 [7]. 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 cause increment in power transfer 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 [1-4], [7-9].

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 versa [10]. Also, in order to improve the oscillation stability of power system, an auxiliary stabilizing signal can be added on the power flow control function of the SSSC [12]. In several references [10-13] the SSSC is used to stabilize frequency, enhance stability and damp power oscillation. In some other papers [13], the effect of compensation degree and operation mode of SSSC on small disturbance and transient stability is reported. 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 complex issue. So far, various conventional approaches have been reported in the literature which consider to 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 [14].

In this paper the problem of robust SSSC based damping controller design is formulated as a multi-objective optimization problem. The multi-objective problem is concocted to optimize a composite set of two eigenvalue-based objective functions comprising the desired damping factor, and the desired damping ratio of the lightly damped and undamped electromechanical modes. The controller is automatically tuned with optimization of an eigenvalue based multi-objective function by HBMO to simultaneously shift the lightly damped and undamped electromechanical modes to a prescribed zone in the s-plane so that the relative stability is guaranteed and the time domain specifications concurrently secured. The effectiveness of the proposed controller is demonstrated through eigenvalue analysis, nonlinear time simulation studies and some performance indices to damp low frequency oscillations under different operating conditions. Results evaluation show that the proposed multi-objective function based tuned damping controller achieves good robust performance for a wide range of operating conditions and is superior to controllers designed by using single objective functions.

II. HBMO ALGORITHM

Bees are social insects that can only survive inside their colony. A bee activity shows various features such as group work and communication. In the bees social life usually there is a queen which lays eggs and has a longer life expectancy than other bees and usually, depending on the season, has about 60000 or more workers. Its life expectancy is about 5 or 6 years whereas the other bees especially the workers have a life expectancy that hardly reaches one year. Males or drones die after mating [16-17]. Insemination ends by the gradual deaths of drone bees. Each drone can take part in mating process just for one time whereas queen can take part for several times. These features have made the mating process of bees more interesting than those of other insects.

Mathematical description of the bee colony optimization:

A drone bee probabilistically mates a queen with the following probabilistic function:

$$\mathrm{prob}(D,Q)=\exp(-\Delta(f)/s(t)) \tag{1}$$

where, prob(D,Q) is the probability of adding the sperm of the drone bee D, into the womb of the queen Q (probability of successful mating), $\Delta(f)$ is the difference between fitness functions of the queen and the drone , and $s(t)$ is the speed of queen at t. After each transfer in space, the speed and energy of queen is reduced according to the following equation:

$$s(t+1)=\alpha\times s(t) \tag{2}$$

$$E(t+1)=E(t)-\gamma \tag{3}$$

In Equations (2) and (3), α is a factor which varies between zero and one (for reducing queen speed) and γ is a coefficient in [0, 1] which represents the amount of reduced energy after each mating process.

First, the queen speed is generated randomly. At the beginning of during-flight mating, males chosen by queen are generated randomly in Equation (1). If mating is successful, the male's sperm will be stored in queen womb. By combining the queen and males genotypes a new baby is formed which can be grown by workers. One of the major differences between HBMO and old evolutionary algorithms is that the sperm storage takes place in queen womb because the queen uses it to produce a new solution for a baby with the highest level of capability. The following steps are considered for implementing HBMO algorithm:

Step 1: defining input data.
Step 2: generating initial population.
Step 3: calculating the objective function.
Step 4: classifying initial population according to the objective function values.
Step 5: choosing the queen; the bee that has greater fitness value than other is chosen as the queen.
Step 6: randomly generating the queen speed.
Step 7: Choosing initial population of male bees.
Step 8: generating sperm womb of queen in flight mating.
Step 9: egg-laying process of bees.
Step 10: Feeding the chosen babies and the queen with a jelly material by worker bees.
Step 11: calculating the value of objective function for the created set of solutions.
Step 12: checking the stopping criterion of the algorithm or the number of iterations.

At the end of the algorithm, if the stopping criterion is satisfactory, the queen will be selected as the final solution otherwise it returns to the third step and all the previous steps are repeated till the stopping criterion is met. The computational flowchart of HBMO is shown in detail in Figure 1.

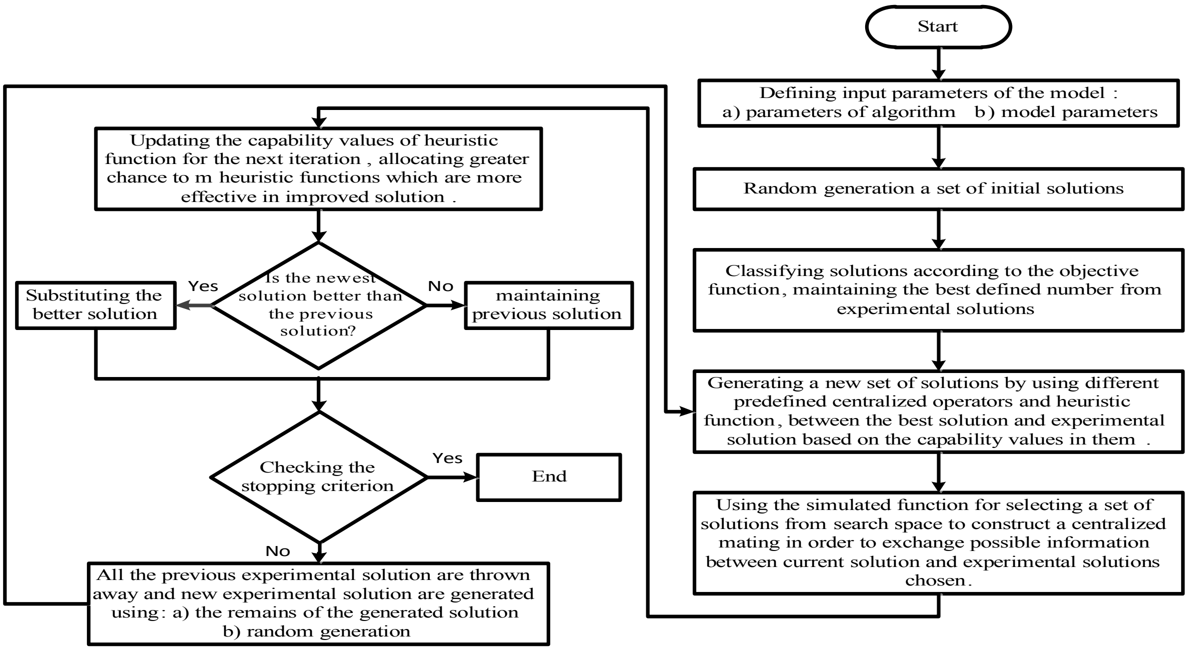


Figure 1. The flowchart of HBMO algorithm

III. POWER SYSTEM MODEL

A single-machine infinite-bus (SMIB) power system installed with SSSC is investigated, as shown in Figure 2 [9]. 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 (C_{DC}). 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.

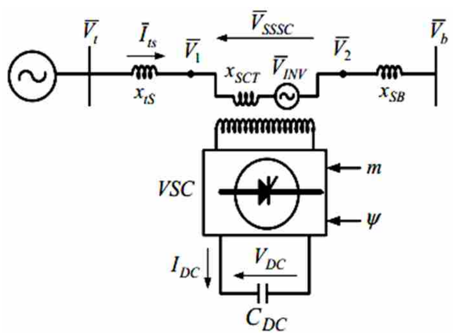


Figure 2. Single-machine infinite-bus power system with SSSC

A. Power System Nonlinear Model 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. The system data is given in the Appendix. By applying Park's transformation and neglecting the resistance and transients of transformer, SSSC can be modeled as [12]:

$$\bar{I}_{ts} = I_{tsd} + jI_{tsq} = I_{ts}\angle\varphi \qquad (4)$$

$$\bar{V}_{INV} = mkV_{DC}(\cos\psi + j\sin\psi) = mkV_{DC}\angle\psi$$
$$\psi = \varphi \pm 90° \qquad (5)$$

$$\dot{V}_{DC} = \frac{dV_{DC}}{dt} = \frac{I_{DC}}{C_{DC}} = \frac{mk}{C_{DC}}(I_{tsd}\cos\psi + I_{tsq}\sin\psi) \qquad (6)$$

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

$$I_{tsq} = \frac{V_B\sin\delta + mkV_{DC}\cos\psi}{X_{ts} + X_{SB} + X_{SCT} + X_q} \qquad (7)$$

$$I_{tsd} = \frac{E'_q - V_B\cos\delta - mkV_{DC}\sin\psi}{X_{ts} + X_{SB} + X_{SCT} + X'_d} \qquad (8)$$

The nonlinear dynamic model of the power system of Figure 2 is [9]:

$$\dot{\delta} = \omega_b(\omega - 1) \qquad (9)$$

$$\dot{\omega} = \frac{1}{M}(P_m - P_e - D\omega) \qquad (10)$$

$$\dot{E}'_q = \frac{1}{T'_{do}}(E_{fd} - E_q) \qquad (11)$$

$$\dot{E}_{fd} = -\frac{1}{T_A}E_{fd} + \frac{K_A}{T_A}(V_{ref} - V_t) \qquad (12)$$

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:

$$\Delta\dot{\delta} = \omega_b\Delta\omega \qquad (13)$$

$$\Delta\dot{\omega} = (-\Delta P_e - D\Delta\omega)/M \quad (14)$$

$$\Delta\dot{E}'_q = (-\Delta E_q + \Delta E_{fd})/T'_{do} \quad (15)$$

$$\Delta\dot{E}_{fd} = -\frac{1}{T_A}\Delta E_{fd} - \frac{K_A}{T_A}(\Delta V_t) \quad (16)$$

$$\Delta\dot{V}_{DC} = K_7\Delta\delta + K_8\Delta E'_q + K_9\Delta V_{DC} + K_{dm}\Delta m + K_{d\psi}\Delta\psi \quad (17)$$

where,

$$\Delta P_e = K_1\Delta\delta + K_2\Delta E'_q + K_{pDC}\Delta V_{DC} + K_{pm}\Delta m + K_{p\psi}\Delta\psi \quad (18)$$

$$\Delta E'_q = K_4\Delta\delta + K_3\Delta E'_q + K_{qDC}\Delta V_{DC} + K_{qm}\Delta m + K_{q\psi}\Delta\psi \quad (19)$$

$$\Delta V_t = K_5\Delta\delta + K_6\Delta E'_q + K_{vDC}\Delta V_{DC} + K_{vm}\Delta m + K_{v\psi}\Delta\psi \quad (20)$$

K_1, K_2, …, K_9, K_{pu}, K_{au}, K_{du} and K_{vu} are linearization constants and are dependent on system parameters and the operating condition.

$$\dot{x} = Ax + Bu \quad (21)$$

$$A = \begin{bmatrix} 0 & \omega_b & 0 & 0 & 0 \\ -\frac{K_1}{M} & -\frac{D}{M} & -\frac{K_2}{M} & 0 & -\frac{K_{pDC}}{M} \\ -\frac{K_4}{T'_{do}} & 0 & -\frac{K_3}{T'_{do}} & -\frac{1}{T'_{do}} & -\frac{K_{qDC}}{T'_{do}} \\ -\frac{K_A K_5}{T_A} & 0 & -\frac{K_A K_6}{T_A} & -\frac{1}{T_A} & -\frac{K_A K_{vDC}}{T_A} \\ K_7 & 0 & K_8 & 0 & K_9 \end{bmatrix}$$

$$B = \begin{bmatrix} 0 & 0 \\ -\frac{K_{pm}}{M} & -\frac{K_{p\psi}}{M} \\ -\frac{K_{qm}}{T'_{do}} & -\frac{K_{q\psi}}{T'_{do}} \\ -\frac{K_A K_{vm}}{T_A} & -\frac{K_A K_{v\psi}}{T_A} \\ K_{dm} & K_{d\psi} \end{bmatrix}$$

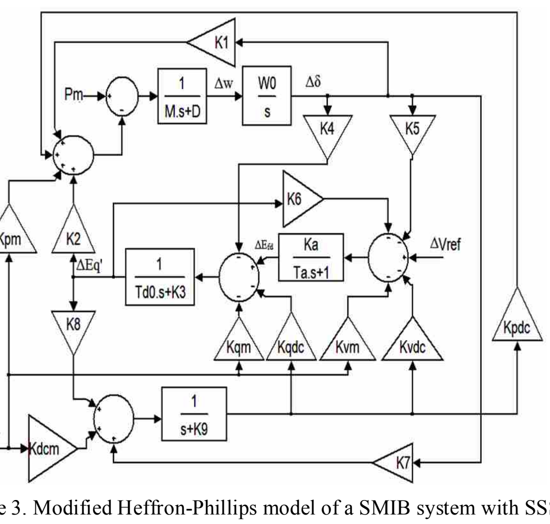


Figure 3. Modified Heffron-Phillips model of a SMIB system with SSSC

The block diagram of the linearized dynamic model of the SMIB power system with SSSC is shown in Figure 3.

C. SSSC BASED DAMPING CONTROLLER

The SSSC damping controller structure is shown in Figure 4, where u can be m or ψ. It comprises gain block, signal washout block and lead-lag compensator [3].

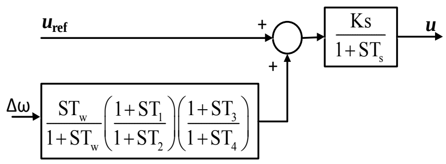


Figure 4. SSSC with lead-lag controller

IV. SSSC CONTROLLER DESIGN USING HBMO

In this proposed method, parameters of SSSC controller are optimally adjusted for dynamic stability of entire system. Considering the fact that the selection of gains of output feedback for SSSC as a damping controller is a complicated optimization problem, thus to increase the system damping for electromechanical modes, a multi-objective function based on eigenvalues is considered which includes two separate objective functions that form a compound objective function with an appropriate weight ratio. The HBMO algorithm is used to obtain optimum values for the objective function. The multi- objective function with an appropriate weight ratio is considered as following:

$$J_1 = \sum_{j=1}^{NP}\sum_{\sigma_i \geq \sigma_0}(\sigma_0 - \sigma_i)^2$$

$$J_2 = \sum_{j=1}^{NP}\sum_{\xi_i \leq \xi_0}(\xi_0 - \xi_i)^2 \quad (22)$$

$$J = J_1 + aJ_2$$

where $\sigma_{i,j}$ and $\zeta_{i,j}$ are real part and damping ratio of ith eigenvalue in jth operating point respectively. The value of α is equal to 10 and NP is equal to the number of operating points in optimization problem. By considering J_1, the dominant eigenvalues are transferred to the left side of the line $s = \sigma_0$ in the S-plane according to Figure 5(a). This provides relative stability in the system. Similarly, if we consider objective function J_2, the maximum overshoot of eigenvalues becomes limited and eigenvalues are transmitted to the specified area which is shown in Figure 5(b). Multi-purpose objective function J transmits the eigenvalues of the system to the specified area shown in Figure 5(c).

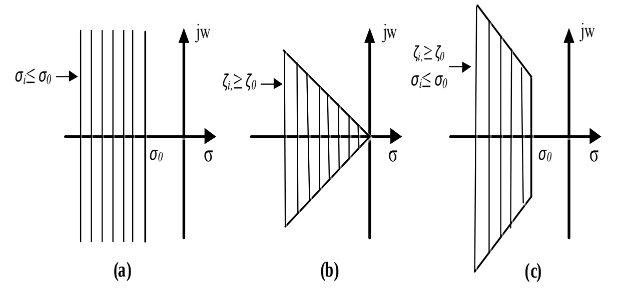


Figure 5. Region of eigenvalue location for the objective function

The designing problem is formulated as a constrained optimization problem where constraints are as follows:

$$K_{\min} \le K \le K_{\max}$$
$$T_{1\min} \le T_1 \le T_{1\max}\ ,\ T_{2\min} \le T_2 \le T_{2\max} \quad (23)$$
$$T_{3\min} \le T_3 \le T_{3\max}\ ,\ T_{4\min} \le T_4 \le T_{4\max}$$

The proposed method uses HBMO intelligent algorithm to solve optimization problem to obtain the optimal set of controller parameters. The objective function given in Equation (23) takes place in different performance conditions of system, the desired performance conditions are considered as in Table 1.

Table 1. Loading condition

Operating conditions	P (pu)	Q (pu)	X_L(pu)
Normal	0.8	0.2629	0.6
Light	0.4	0.1314	0.6
Heavy	1.2	0.36	0.6

In this work the range of optimization parameters is selected between [1-100] for k, also the range of parameters for T_1, T_2, T_3 and T_4 is selected between [0.01-1]. For achieving a better performance of HBMO, the number of queens, drones, and workers, the size of womb and the maximum number of mating process are considered 1, 100, 1000, 50 and 30 respectively. The proposed optimization algorithms have been implemented several times then; a set of optimal values is selected. Table 2 shows final values of optimized parameters with both ψ and m controller for multiobjective function J.

Table 2. The optimal parameter settings of the proposed controllers based on the different objective function

Controller parameters	m controller	ψ controller
K	76.45	83.11
$T1$	0.91	0.92
$T2$	0.021	0.044
$T3$	0.213	0.87
$T4$	0.501	0.507

V. SIMULATION RESULTS

In order to demonstrate the effectiveness and robustness of the proposed controller, against severe turbulence and the damping of oscillations caused by it, power system using the proposed model, is simulated in Matlab software. To make sure that the obtained results are reliable, this simulation is evaluated with eigenvalue analysis method and nonlinear time-domain simulation, which is shown as follows.

A. EIGENVALUE ANALYSIS

The electromechanical modes and the damping ratios obtained for all operating conditions both with and without proposed controllers in the system are given in Table 3. When SSSC is not installed, it can be seen that some of the modes are poorly damped and in some cases, are unstable (highlighted in Table 3). It is also clear that the system damping with the proposed ψ based tuned SSSC controller are significantly improved.

B. NONLINEAR TIME-DOMAIN SIMULATION

The single-machine infinite-bus system shown in Figure 2 is considered for nonlinear simulation studies. The 6-cycle 3-phase fault at t = 1 s, on the infinite bus has occurred, at all loading conditions given in Table 1, to study the performance of the proposed controller. The speed deviation and electrical power deviation based on the ψ and m controller in three different loading conditions are shown in Figures 6, 7 and 8. It can be seen that the HBMO based SSSC controller tuned using the multi-objective function achieves good robust performance and provides superior damping.

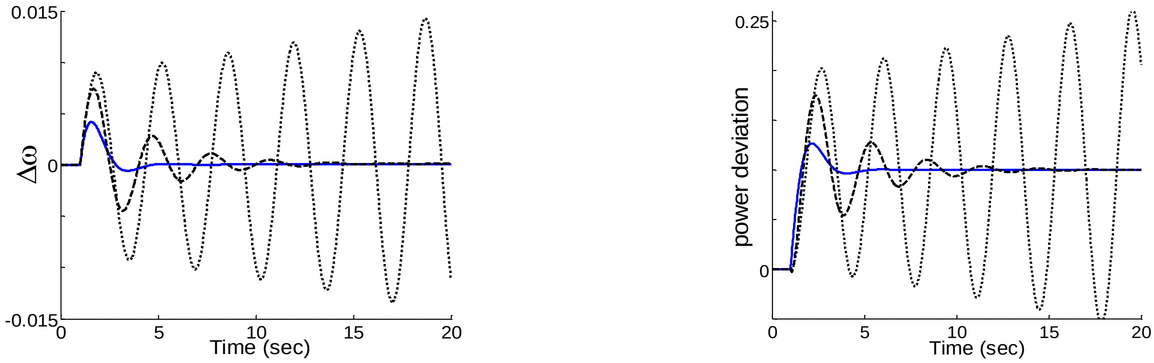
From the above conducted test, it can be concluded that ψ based damping controller is superior to the m based damping controller and enhance greatly the dynamic stability of power systems.

Table 3. Eigenvalues and damping ratios of electromechanical modes with and without ψ and m controller

Operating conditions	Type of controller		
	Without controller	m (damping ratio)	ψ (damping ratio)
Nominal loading condition	-9.43 ± 12.12i, (0.6140) 0.567 ± 3.869i, (-0.145) -2.132	-1.13 ± 5.32i, (0.2077) -1.73 ± 8.127i, (0.208) -23.12 ± 18.15i, (0.78) -1.32, -2.001 -100.37	-1.83 ± 4.19i, (0.4002) -2.14 ± 10.39i, (0.2017) -34.13 ± 21.325i, (0.84) -1.13, -1.45 -104.17
Light loading condition	-9.782 ± 13.69i, (0.5813) 0.129 ± 4.892i, (-0.026) -2.739	-1.78 ± 5.68i, (0.299) -1.98 ± 6.43i, (0.294) -13.26 ± 15.69i, (0.64) -1.204, -3.701 -99.59	-1.13 ± 5.87i, (0.1890) -4.199 ± 7.41i, (0.4930) -15.176 ± 17.1i, (0.665) -1.705, -1.459 -109.057
Heavy loading condition	-8.375 ± 11.59i, (0.585) 0.761 ± 4.70i, (-0.1598) -1.47	-1.013 ± 4.45i, (0.2219) -3.109 ± 7.36i, (0.3891) -33.17 ± 11.69i, (0.941) -1.29, - 4.477 -40.001	-1.38 ± 5.14i, (0.2592) -3.989 ± 8.19i, (0.437) -71.09 ±19.21i, (0.965) -1.19,-14.52 -67.24

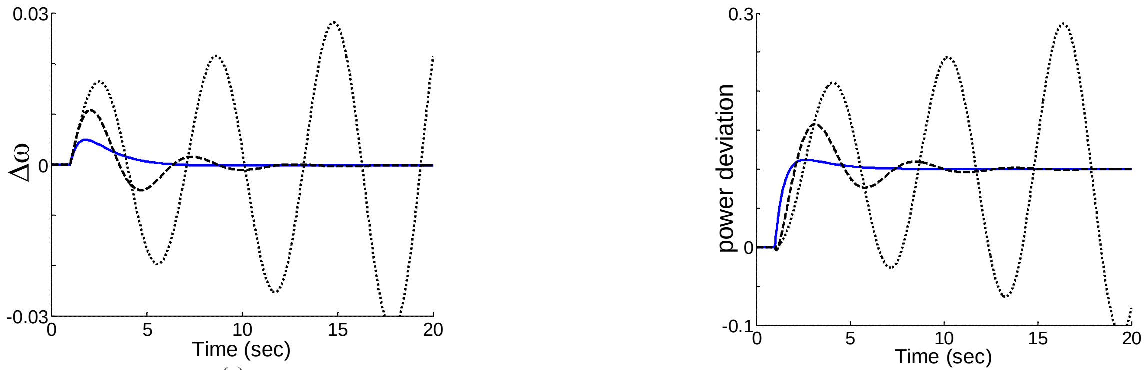
VI. CONCLUSIONS

In this paper, transient stability performance improvement by a SSSC controller has been investigated. The stabilizers are tuned to simultaneously shift the undamped electromechanical modes of the machine to a prescribed zone in the s-plane. A multi-objective problem is formulated to optimize a composite set of objective functions comprising the damping factor, and the damping ratio of the undamped electromechanical modes. The design problem of the controller is converted into an optimization problem which is solved by HBMO technique with the eigenvalue-based multi-objective function. The effectiveness of the proposed SSSC controllers for improving transient stability performance of a power system is demonstrated by a weakly connected example power system subjected to different severe disturbances. The eigenvalue analysis and nonlinear time-domain simulation results show the effectiveness of the proposed controller using multi-objective function and their ability to provide good damping of low frequency oscillations.



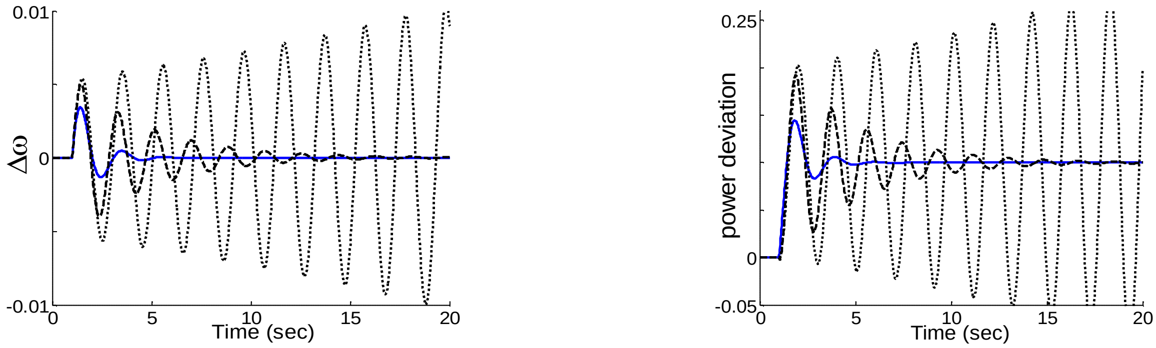
(a) (b)

Figure 6. Dynamic responses for (a) $\Delta\omega$, (b) ΔP at normal loading condition: Solid (ψ controller), Dashed (m controller) and Dotted (without controller)



(a) (b)

Figure 7. Dynamic responses for (a) $\Delta\omega$, (b) ΔP at light loading condition: Solid (ψ controller), Dashed (m controller) and Dotted (without controller)



(a) (b)

Figure 8. Dynamic responses for (a) $\Delta\omega$, (b) ΔP at heavy loading condition: Solid (ψ controller), Dashed (m controller) and Dotted (without controller)

APPENDIX

The nominal parameters and operating condition of the system are listed in Table 4.

Table 4. System parameters

Generator	M = 8 MJ/MVA X_q=0.6 pu	T'_{do}=5.044 X'_d=0.3 pu	X_d=1 pu D=4
Excitation system	K_A=80	T_A=0.05 s	
Transformers	X_T=0.1 pu	X_{SDT}=0.1 pu	
Transmission line	X_L=0.6 pu		
SSSC parameters	C_{DC}=0.25 T_S=0.05	V_{DC}=1 X_{SCT}=0.15	K_S=1.2

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