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FACTS Control Parameters Identification for Enhancement of Power System Stability

Ali Ahmadian, Masoud Aliakbar Golkar
The Electrical Engineering Department of K.N. Toosi University of Technology, Tehran, Iran.
Email: ali.ahmadian1367@gmail.com (Corresponding author)
golkar@kntu.ac.ir.

ABSTRACT

The aim of this paper is to investigate a novel approach for output feedback damping controller design of STATCOM in order to enhance the damping of power system low frequency oscillations (LFO). The design of output feedback controller is considered as an optimization problem according with the time domain-based objective function which is solved by a honey bee mating optimization algorithm (HBMO) that has a strong ability to find the most optimistic results. The effectiveness of the proposed controller are tested and demonstrated through nonlinear time-domain simulation studies over a wide range of loading conditions. The simulation study shows that the designed controller by HBMO has a strong ability to damping of power system low frequency oscillations. Moreover, the system performance analysis under different operating conditions show that the φ based controller is superior to the C based controller.

KEYWORDS: FACTS, STATCOM, Honey Bee Mating Optimization, Damping Controller, Low Frequency Oscillations, Power System, Dynamic Stability

1. INTRODUCTION

One of the most important aspects in electric system operation is stability of power systems. By the development of interconnection of large electric power systems, low frequency oscillations have become a serious problem in power system. This oscillation occur as result of a sudden increase in the load, loss of one generator or switching out of a transmission line during a fault [1]. Once started, they would continue a long period of time. In some cases, they continue to grow, causing system separation if no adequate damping is available. In recent years, flexible AC transmission system (FACTS) devices are one of the most effective ways to improve power system operation controllability and power transfer limits. Through the modulation of bus voltage, phase shift between buses, and transmission line reactance, FACTS devices can cause a substantial increase in power transfer limits during steady-state [2]. These devices are addition to normally steady-state control of a power system but, due to their fast response, FACTS can also be used for power system stability enhancement through improved damping of power swings [3]. The real power flow with primary function of FACTS devices, can be regulated to reduce the low frequency oscillation and enhance power system stability. Static synchronous compensator (STATCOM) is a member of FACTS family that is connected in shunt with the system. From the power system dynamic stability viewpoint, the STATCOM provides better damping characteristics than the SVC as it is able to transiently exchange reactive power with the system, so it can improve oscillation stability better than SVC[4], because of it’s greater reactive current output capability at depressed voltage, faster response, better control stability, lower harmonics and smaller size, etc[5]. The STATCOM is based on the principle that a voltage-source inverter generates a controllable AC voltage source behind a transformer-leakage reactance so that the voltage difference across the reactance produces active and reactive power exchange between the STATCOM and the transmission network. Several trials have been reported in the literature to dynamic models of STATCOM in order to design suitable controllers for power flow, voltage and damping controls [6]. Wang [7] established the linearized Phillips-Heffron model of a power system installed with a STATCOM and demonstrated the application of the model in analyzing the damping effect of the STATCOM. Further, no effort seems to have been made to identify the most suitable STATCOM control parameter, in order to arrive at a robust damping controller. Intelligent controllers have the potential to overcome the above mentioned problems. Fuzzy-logic-based controllers have, for example, been used for controlling a STATCOM [8]. The performance of such controllers can further be improved by adaptively updating their parameters. Also, although using the robust control methods[9], the uncertainties are directly introduced to the synthesis, but due to the large model order of power systems the order resulting controller will be very large in general, which is not feasible because of the computational economical difficulties in implementing. In general, for the simplicity of practical implementation of the controllers, output feedback controller with feedback signals available at the location of the each controlled device is most favourable[10,11]. HBMO algorithm can be used to solve many of the same kinds of problems as GA[8] and does not suffer from of GA’s difficulties. The honey bee is one of the social insects that can just survive as a member of colony. The activity of honey bee suggests many characteristics like together working and communication.

In this paper, the optimal tuning of the output feedback gains for the STATCOM based damping controller is considered as an optimization problem and HBMO technique is used for searching optimized parameters. The effectiveness and robustness of the proposed controller is demonstrated through the eigenvalue analysis ,nonlinear time-domain simulation studies to damping low frequency oscillations under different operating conditions and network structure. Results evaluation show that the HBMO based tuned damping controller achieves good performance for a wide range of operating conditions, and the φ based controller is superior to the C based controller.

2. Honey Bee Mating Optimization

The honey bee is one of the social insects that can just survive as a member of colony. The activity of honey bee suggests many characteristics like together working and communication. A honey bee colony normally includes of a single egg-laying queen with which it's life-span is more than other bees; that with depend upon that seasons usually have more than 60,000 workers or more. A colony may contain a queen during it's life-cycle. That is named monogynous one. Only the queen is fed by "royal jelly." "Nurse bee" take care of this gland and feed it to queen. The royal jelly causes the queen bee biggest bee in the hive. Several hundred drones live with queen and its workers. Queen bee life-span is about 5 or 6 years, whereas rest of the bees, specially worker bees, oven their period of living do not reach to 1 year. The drones die after mating process.

The drones act in father function in the colony, thet are haploid and amplify or multiply their mother's genome without changing their genetics combinations, but mutation. So, drones are agents that anticipate one of the mother's gametes and by the sake of that female can do genetically like males. Broods, that be cared by workers, improve from fertilized or unfertilized eggs. They represent potential queens and prospective drones respectively. In marriage process, the queens in mating period, their mate flight of the nest to the far places.

Insemination ends with the gradual death of drones, and by the sake of that queens receive the "mating sign." Any drone can take part in mating process just one time, but the queens mate several times. These features make bee mating very interesting among insects. A drone mates with a queen probabilistically using an annealing function like this:

$$\Pr ob(D,Q) = \exp(-\Delta f \ / S(t)) \tag{1}$$

Where *Prob(D,Q)* is probability of adding drone's sperm D to queen's spermatheca *Q, Δ(f)* is perfect difference of fitness D and queen, and s(t) is speed of the queen at time t. The mating is high either when queen's speed level is high, or when drone's fitness is equal with queen's. After every transition, speed of queen will decrease according to the following equations:

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

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

Where: α is a factor $\epsilon(0,1)$ and γ is the amount of energy, E(t) reduction after each transition. The algorithm starts with three user-defined parameters and one predefined parameter. The predefined parameter is the number of workers (W), representing the number of heuristics encoded in the program. The three user-defined parameters are the number of queens, the queen's spermatheca size representing the maximum number of mating per queen in a single mating flight, and the number of broods that will be born by all queens. The energy and speed of each queen at the start of each mating flight is initialized at random. A number of mating flights are realized. At the commence of a mating flight, drones are generated randomly and the queen selects a drone using the probabilistic rule in Eq. (1). If mating done successfully, storing of drone's sperm in queen's spermatheca occur. using of combination of drone's and queen's genotaypes, generate a new brood, which can be improved later by employing workers to conduct local search. Main difference (or one of them) HBMO algorithm from classic evolutionary algorithms that is storing of many different drone's sperm in spermatheca by queen cause which the queen use of them to create new solution for fittest of broods, which gives the possibility to have fittest broods more. The rule of workers is brood caring and for the sake of that they are not separated of population and used to grow the broods that produced by queen. Every worker has different capability for production in solutions

3. POWER SYSTEM MODELING

A single machine infinite bus power (SMIB) system installed with a STATCOM in Figure 1 is adopted in this paper to demonstrate the proposed method. The synchronous generator is delivering power to the infinite-bus through a double circuit transmission line and a STATCOM. The system data is given in the Appendix. The system consists of a step down transformer (SDT) with a leakage reactance XSDT, a three phase GTO-based voltage source converter, and a dc capacitor [7].

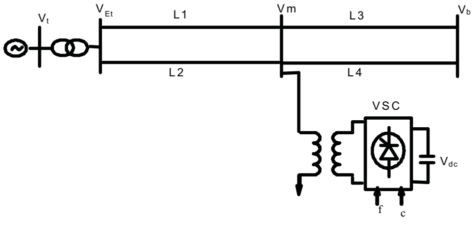


Fig. 1. SMIB power system equipped with STATCOM

The VSC generates a controllable AC voltage source behind the leakage reactance. The voltage difference between the STATCOM bus AC voltage, $v_{L(t)}$ and $v_{0(t)}$ produces active and reactive power exchange between the STATCOM and the power system, which can be controlled by adjusting the magnitude V_0 and the phase φ.

The dynamic relation between the capacitor voltage and current in the STATCOM circuit are expressed as [7]:

$$\bar{I}_{Lo} = I_{Lod} + jI_{Loq} \tag{4}$$

$$V_o = cV_{dc}(\cos\varphi + j\sin\varphi) = cV_{dc}\angle\varphi \tag{5}$$

$$\dot{V}_{dc} = \frac{I_{dc}}{C_{dc}} = \frac{c}{C_{dc}}(I_{Lod}\cos\varphi + I_{Loq}\sin\varphi) \tag{6}$$

Where for the PWM inverter $c = mk$ and k is the ratio between AC and DC voltage depending on the inverter structure, m is the modulation ratio defined by the PWM and the phase c is also defined by the PWM. The C_{dc} is the dc capacitor value and I_{dc} is the capacitor current while i_{Lod} and i_{Loq} are the d-and q-components of the STATCOM current, respectively.

The dynamics of the generator and the excitation system are expressed through a third order model given as[7, 8]:

$$\dot{\delta} = \omega_0(\omega - 1) \tag{7}$$

$$\dot{\omega} = (P_m - P_e - D\Delta\omega)/M \tag{8}$$

$$\dot{E}'_q = (-E_q + E_{fd})/T'_{do} \tag{9}$$

$$\dot{E}_{fd} = (-E_{fd} + K_a(V_{ref} - V_t))/T_a \tag{10}$$

The expressions for the power output, terminal voltage, and the d-q axes currents in the transmission line and STATCOM, respectively, are:

$$I_{tld} = \frac{(1 + \frac{X_{LB}}{X_{SDT}})e'_q - \frac{X_{LB}}{X_{SDT}}mV_{dc}\sin\varphi - V_b\cos\varphi}{X_{tL} + X_{LB} + \frac{X_{tL}}{X_{LB}} + (1 + \frac{X_{LB}}{X_{SDT}})x'_d} \tag{11}$$

$$I_{tlq} = \frac{\frac{X_{LB}}{X_{SDT}}mV_{dc}\cos\varphi + V_b\sin\varphi}{X_{tL} + X_{LB} + \frac{X_{tL}}{X_{LB}} + (1 + \frac{X_{LB}}{X_{SDT}})x_q} \tag{12}$$

$$I_{Lod} = \frac{e'_q - (x'_d + X_{tL})I_{tLq} - mV_{dc}\sin\varphi}{X_{SDT}} \tag{13}$$

$$I_{Loq} = \frac{mV_{dc}\cos\varphi - (x'_d + X_{tL})I_{tLq}}{X_{SDT}} \tag{14}$$

$$X_{tL} = X_T + \frac{X_L}{2};\quad X_{LB} = \frac{X_L}{2} \tag{15}$$

Where: X_T, x'_d and x_q are the transmission line reactance, d-axis transient reactance, and q-axis reactance, respectively. The linearized model of this case is given in [8].

4. OUTPUT FEEDBACK DAMPING CONTROLLER

A power system can be described by a Linear Time Invariant (LTI) state space model as follows [12]:

$$\dot{x} = Ax + Bu \tag{16}$$

$$y = Cx \tag{17}$$

Where *x, y* and *u* denote the system linearized state, output and input variable vectors, respectively. A, B and C are constant matrixes with appropriate dimensions which are dependent on the operating point of the system. The system modes define the stability of the system when it is affected by a small interruption. As long as all eigenvalues have negative real parts, the power system is stable when it is subjected to a small disturbance. An output feedback controller has the following structures [13]:

$$u = -Gy \tag{18}$$

Substituting (18) into (16) the resulting state equation is:

$$\dot{x} = A_C x \tag{19}$$

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

$$A_C = A - BGC \tag{20}$$

Only the local and available state variables $\Delta\omega$, ΔP_e and ΔV_t are taken as the input signals of each controller, so the implementation of the designed stabilizers becomes more feasible. By properly choosing the feedback gain G, 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[5].

4.1 HBMO-Based output feedback damping controller design

Two control parameters of the STATCOM (φ and C) are to modulation in order to produce the damping torqueThe two control parameters of the STATCOM (φ and C) modulated in order to produce the damping torque. Since the selection of the output feedback gains for mentioned STATCOM based damping controller is a complex optimization problem. Thus, to acquire an optimal combination, this paper employs HBMO to improve optimization synthesis and find the global optimum value of objective function. In this study, an Integral of Time multiplied Absolute value of the Error (ITAE) is taken as the objective function. Fur our optimization problem, objective function is time domain-based objective function:

$$J = \sum_{i=1}^{Np} \int_{0}^{t_{sim}} |\Delta\omega_i| t\,dt \tag{21}$$

Where, the *tsim* is the time range of simulation and N_p is the total number of operating points for which the optimization is carried out. The design problem can be formulated as the following constrained optimization problem, where the constraints are the controller parameters bounds:

Minimize J Subject to:

$$G_1^{\min} \le G_1 \le G_1^{\max}$$
$$G_2^{\min} \le G_2 \le G_2^{\max}$$
$$G_3^{\min} \le G_3 \le G_3^{\max}$$

The proposed approach employs HBMO to solve this optimization problem and search for an optimal set of controller parameters. The optimization of controller parameters is carried out by evaluating the objective function as given in equation (21), which considers a multiple of operating conditions. The operating conditions are given in Table 1.

Table 1. Loading conditions.

Loading conditions	P_e(pu)	Q_e(pu)	X_L
nominal	0.8	0.15	0.3
light	0.2	0.01	0.3
heavy	1.2	0.4	0.3

In order to acquire better performance, size of spermathecha, number of variables, maximum number of mating flight, N_{queen}, N_{brood}, and $N_{workers}$ is chosen as 50, 5, 30, 1, 50 and 1000, respectively. The final values of the optimized parameters with objective function, *J,* are given in Table 2.

Table 2. The optimal parameter settings

Optimized Parameter	C	φ
G_1	195.69	118.44
G_2	2.9721	1.4633
G_3	1.7249	1. 6796

5. NONLINEAR TIME-DOMAIN SIMULATION RESULTS

In this section, the performance of the proposed controller under transient conditions is verified by applying a small disturbance of 0.2 pu input torque is applied to the machine at *t* = *1* sec. The study is performed at three different operating conditions. The results are shown in Figures 2 and 3. It is also clear from the figures that the first swing stability is greatly improved with the coordinated design approach. The time domain simulation was performed and the consequent results reveal the suitable damping function of the HBMO based designed controller.

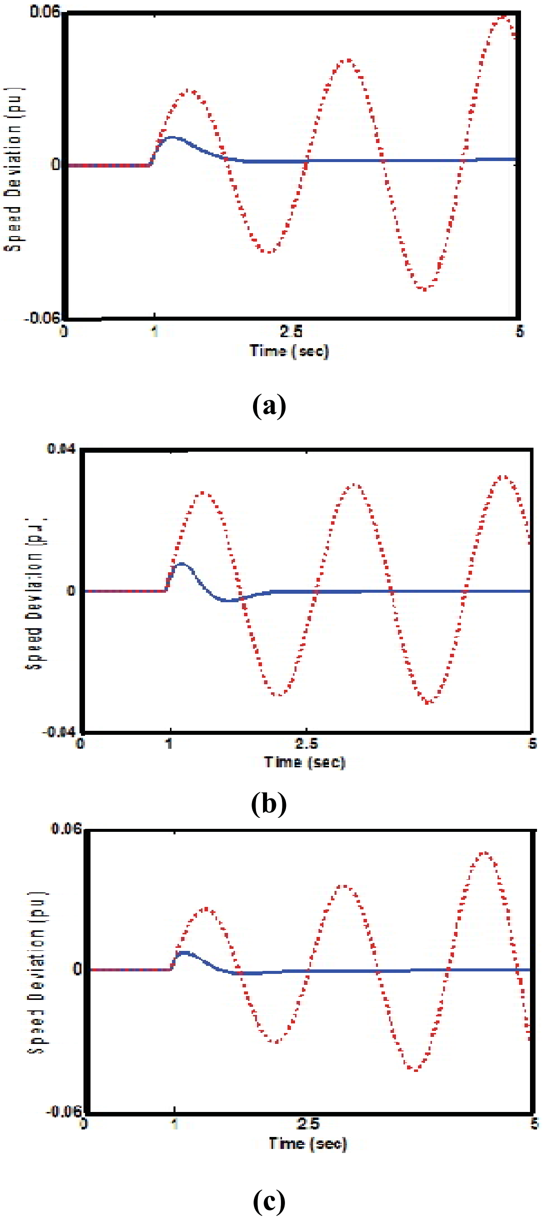
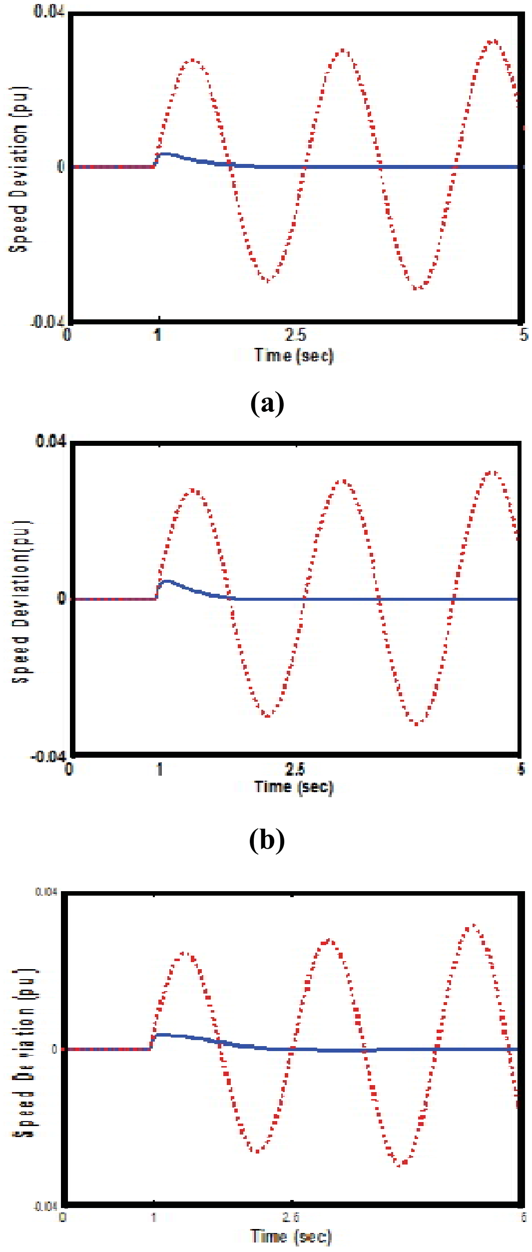


Fig. 2. Dynamic responses at (a) nominal (b) light (c) heavy loading; Solid (HBMO based C

controller), and Dotted (without controller)



(a)

(b)

(c)

Fig. 3. Dynamic responses for Δω at (a) nominal (b) light (c) heavy loading conditions; Solid (HBMO based φ controller), and Dotted (without controller)

6. CONCLUSIONS

The honey bee mating optimization (HBMO) algorithm has been successfully applied to the optimal designing of the STATCOM with output feedback damping controller. The design problem of the selecting output feedback is converted into an optimization problem which is solved by a HBMO technique with the time domain-based objective function. The robust design has been found to be very effective for a range of operating conditions of the power system. The effectiveness of the proposed STATCOM controllers for improving transient stability performance of a power system are demonstrated by a weakly connected example system subjected to severe disturbance. The nonlinear time-domain simulation results show the robustness of the proposed controller and their ability to provide good damping of low frequency oscillations. Moreover, the φ-based stabilizer provides better damping characteristics and enhances greatly the first swing stability compared to the C-based stabilizer.

APPENDIX A

System Data

Generator	M=8MJ/M	$T'_{do} = 5.044$ s	$X_d = 1$pu
	$X_q = 0.6$p.u	$X'_d = 0.3$pu	$D = 0$
Excitation System		$K_a = 50$	$T_a = 0.05$s
Transformers		$X_T = 0.1pu$	X_{SDT}=0.1pu
Transmission Line		$X_q = 0.4$pu	
DC link Parameter		$V_{DC} = 1pu$	$C_{DC} = 1pu$
STATCOM Parameter		$C = 0.25$	$\varphi = 52^\circ$
		$K_s = 1$	$T_s = 0.05$

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