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HBMO Based Output Feedback Damping Controller for STATCOM

Original scientific paper

The aim of this paper is to investigate a novel approach for output feedback damping controller design of the static synchronous compensator (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 to the time domain-based objective function solved by a honey bee mating optimization (HBMO) algorithm that has a strong ability to find the most optimistic results. To validate the accuracy of results a comparison with genetic algorithm (GA) has been made. The effectiveness of the proposed controller are tested and demonstrated through eigenvalue analysis and nonlinear time-domain simulation studies over a wide range of loading conditions. The simulation study shows that the designed controller by HBMO performs better than GA in finding the solution.

Key words: STATCOM, Honey Bee Mating Optimization, Damping Controller, Low Frequency Oscillations

Regulator prigušenja za statički sinkroni kompenzator temeljen na HBM optimizaciji. U ovome radu istražene su metode za sintezu regulatora prigušenja za statički sinkroni kompenzator (STATCOM) u svrhu povećanja prigušenja nisko frekvencijskih oscilacija u energetskim sustavima. Sinteza regulatora je razmatrana kao optimizacijski problem u vremenskoj domeni koji je riješen pomoću HBM algoritma optimizacije (eng. *Honey bee mating*) koji ima svojstvo pronalaska najoptimističnijeg rezultata. U svrhu provjere rezultata napravljena je usporedba s rješenjem koje daje genetski algoritam. Efikasnost predloženog regulatora testirana je uz pomoć analize svojstvenih vrijednosti i nelinearnih simulacija u vremenskoj domeni za različite uvjete. Simulacijski rezultati pokazuju da se korištenjem regulatora s HBM optimizacijom postižu bolji rezultati nego korištenjem genetskog algoritma.

Ključne riječi: STATCOM, HBM optimizacija, regulator prigušenja, nisko frekvencijske oscilacije

1 INTRODUCTION

Stability of power system is one of the most important aspects in electric system operation. By the development of interconnection of large electric power systems, low frequency oscillations have become a serious problem in power system. This oscillation occurs 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 [2]. Thus, Damping of low-frequency electro-mechanical oscillation is very important for the system secure operation. To enhance system damping and increase dynamic stability, the installation of supplementary excitation control, power system stabilizer (PSS), is a sample, effective and economical method to solution this problem [3, 4]. However, PSSs suffer a drawback of be-

ing liable to cause great variations in the voltage profile and they may even result in leading power factor operation and losing system stability under severe disturbances, especially those three-phase faults which may occur at the generator terminals [5]. 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 [6]. 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 [7]. The real power flow with primary function of FACTS devices can be regulated to reduce the low frequency oscillation and enhance power system stability. Recently, several FACTS

devices have been implemented and installed in practical power systems such as static VAR compensator (SVC), thyristor controlled series capacitor (TCSC), and thyristor controlled phase shifter (TCPS) [8,9]. 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 exchange transiently reactive power with the system. it can improve oscillation stability better than SVC [10, 11], because of it's greater reactive current output capability at depressed voltage, faster response, better control stability, lower harmonics and smaller size, etc [12]. 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 can produce 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 [13]. Wang [14] 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. Furthermore, no efforts seem 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 of overcoming the above mentioned problems. Fuzzy-logic-based controllers have, for example, been used for controlling a STATCOM [15]. The performance of such controllers can be improved by adaptively updating their parameters. Although using the robust control methods [16], the uncertainties are directly introduced to the synthesis. Due to the large model order of power systems, the order resulting controller will be very large in general. This is not feasible because of the computational economical problems 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 favorable [17, 18]. The HBMO algorithm can be used to solve many of the same kinds of problems as GA (see Appendix A) and does not suffer from of GA's problems. 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 both HBMO and GA techniques are used for searching optimized parameters. The effectiveness and robustness of the proposed controller are demonstrated through the eigenvalue analysis, nonlinear time-domain simulation studies to damp 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 is superior to designed controller using GA technique.

The remainder of this paper is organized in four major sections. A brief description of HBMO optimization technique is presented in Section 2. In Section 3 the modeling of the example power system with STATCOM and controller design is presented. Simulation Results are given and discussed in Section 4 and conclusions are presented in Section 5.

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 its life-span is more than other bees; and depend upon those seasons usually has more than 60,000 workers or more. A colony may contain a queen during its life-cycle. That is named monogynous one. Only the queen is fed by royal jelly. Nurse bees takes care of this gland and feed it to queen. The royal jelly makes the queen bee to be the 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, especially worker bees, life times do not reach to 1 year. The drones die after mating process.

The drones play the father role in the colony that are haploid and amplify or multiply their mother's genome without changing their genetic combinations, except 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, 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 mates fly from the nest to the far places [19].

Insemination ends with the gradual death of drones, and by the sake of those 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 process very interesting among other insects.

2.1   Operation principle of HBMO

The queen plays the most important role in mating process in nature and also HBMO algorithm. The spermatheca is a place for sperm of drones and queen's, all drones, however are originally haploid; after successful, the drone's

sperm is stored in the queen's spermatheca. A brood is reproduced by coming of some genes of drones into the brood genotype. A brood has no thing only one genotype. Therefore, the HBMO algorithm would be constructed by the following five important stages [20]:

1. The algorithm starts with mating flight, where a queen selects drones probabilistically from the spermatheca. A drone is selected from list randomly for the generating broods.

2. Generating new broods by combining of drone's genotypes and the queens.

3. Using of workers to lead local searching on broods.

4. Adaptation of worker's ability, based on the improvement of broods.

5. Substitution of queen's workers by stronger and aptitude broods.

When all queens completed their mating flights, start breeding. All of broods after generation are sorted according to fitness, i.e. their weakness or health. The best brood is replaced by the worst queens until all queens will the best and there is no need to broods. After completing of mating, remaining broods finally are killed so that new mating process begins. The main steps in the HBMO algorithm are presented in Fig. 1.

2.2 Original HBMO algorithm

A drone mates with a queen probabilistically using an annealing function like this:

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

Where $\Pr ob(D,Q)$ is probability of adding drone's sperm D to queen's spermatheca Q, $\Delta(f)$ is the perfect difference of fitness D of queen, and $S(t)$ is the speed of the queen at time t. The mating is high whether queen's speed level is high, drone's fitness is equal with queen's. After every transition, the speed of queen will decrease according to the following equations:

$$s(t+1) = \alpha \times s(t) \qquad (2)$$

$$E(t+1) = E(t) - \gamma \qquad (3)$$

Where, α is a factor ε (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
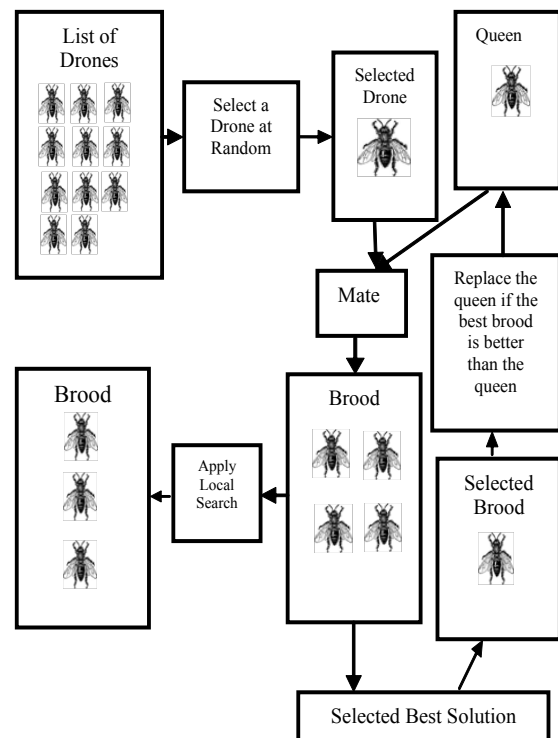

Fig. 1. The HBMO algorithm

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 (1). If mating is done successfully, storage of drone's sperm in queen's spermatheca occur. Combination of drone's and queen's genotypes, generate a new brood, which can be improved later by employing workers to conduct local search. One of the main difference between HBMO algorithm and classic evolutionary algorithms is storing of many different drone's sperm in spermatheca by queen which the uses some of them to create a new solution for fittest of broods, and gives the possibility to have more fittest broods. The role of workers is brood caring and for the sake of that they are not separated of population and are used to grow the broods generated by the queen. Every worker has different capability for producing in solutions. The computational flow chart of HBMO algorithm is shown in Fig. 2.

3 POWER SYSTEM MODELING

A single machine infinite bus power (SMIB) system installed with a STATCOM shown in Fig. 3, which is widely used for studies of power system oscillations, 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 B. 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 [14].

The VSC generates a controllable AC voltage source behind the leakage reactance. The voltage difference between the STATCOM bus AC voltage, v_L and $v0(t)$ 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 [14]:

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

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

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

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 [14, 15]:

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

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

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

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

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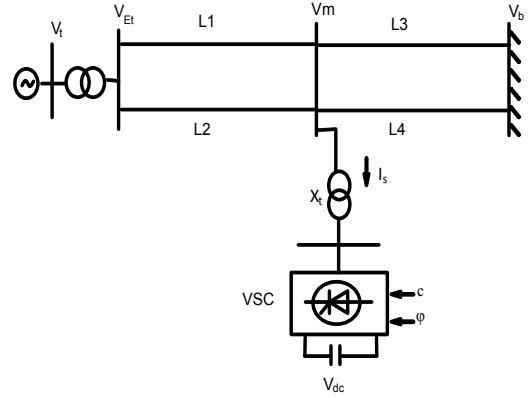

Fig. 3. SMIB power system equipped with STATCOM

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

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

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

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

Where, $X_{tL} = X_T + \frac{X_L}{2}$; $X_{LB} = \frac{X_L}{2}$ the X_T, x'_d and x_q are the transmission line reactance, d-axis transient reactance, and q-axis reactance, respectively. A linear dynamic model is obtained by linearizing the nonlinear model round an operating condition.

3.1 Power system linearized model

A linear dynamic model is obtained by linearizing the nonlinear model around an operating condition. The linearized model of power system as shown in Fig. 3 is given as follows:

$$\Delta\dot{\delta} = \omega_0\Delta\omega \tag{15}$$

$$\Delta\dot{\omega} = (-\Delta P_e - D\Delta\omega)/M \tag{16}$$
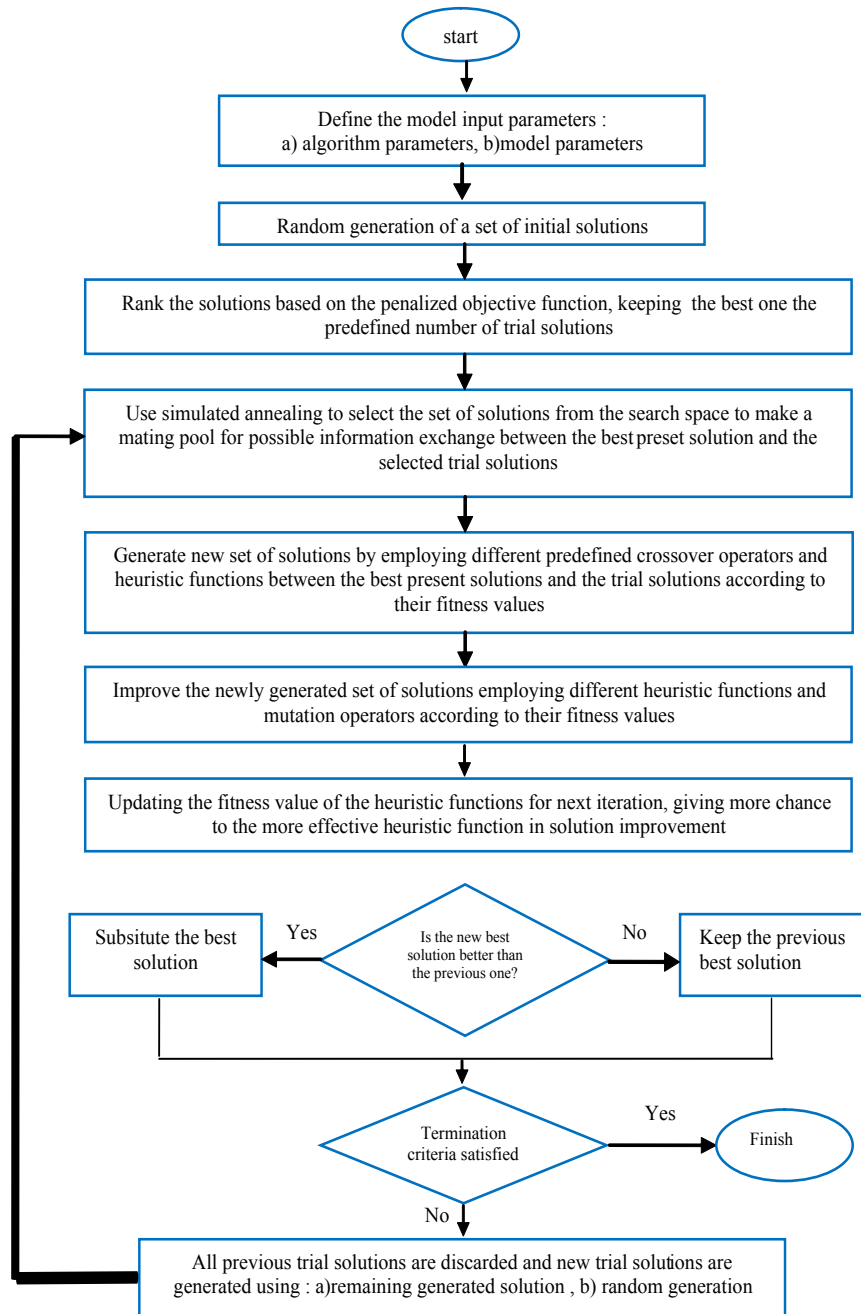
$$\Delta\dot{E}' = (-\Delta E_q + \Delta E_{fd})/T'_{do} \tag{17}$$

Fig. 2. Flowchart of the HBMO algorithm

$$\Delta\dot{E}_{fd} = (K_A(\Delta v_{ref} - \Delta v) - \Delta E_{fd})/T_A \qquad (18)$$

$$\begin{aligned}\Delta\dot{v}_{dc} &= K_7\Delta\delta + K_8\Delta E_q' - K_9\Delta v_{dc}\\ &+ K_{dc}\Delta c + K_{d\phi}\Delta\phi\end{aligned} \qquad (19)$$

$$\Delta P_e = K_1 \Delta\delta + K_2 \Delta E'_q + K_{pdc}\Delta v_{dc} \\ +K_{pc}\Delta c + K_{p\phi}\Delta\phi \tag{20}$$

$$\Delta E'_q = K_4 \Delta\delta + K_3 \Delta E'_q + K_{qdc}\Delta v_{dc} \\ +K_{qc}\Delta c + K_{q\phi}\Delta\phi \tag{21}$$

$$\Delta V_t = K_5 \Delta\delta + K_6 \Delta E'_q + K_{vdc}\Delta v_{dc} \\ +K_{vc}\Delta c + K_{v\phi}\Delta\phi \tag{22}$$

The $K_1, K_2, ..., K_9, K_{pu}, K_{qu}$ and K_{vuare} linearization constants. The state-space model of power system is given by:

$$\dot{x} = Ax + Bu \tag{23}$$

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

$$x = \begin{bmatrix} \Delta\delta & \Delta\omega & \Delta E'_q & \Delta E_{fd} & \Delta v_{dc} \end{bmatrix}^T; \tag{24}$$

$$u = \begin{bmatrix} \Delta c & \Delta\phi \end{bmatrix}^T \tag{25}$$

$$A = \begin{bmatrix} 0 & w_0 & 0 & 0 & 0 \\ -\frac{K_1}{M} & 0 & -\frac{K_2}{M} & 0 & -\frac{K_{pdc}}{M} \\ -\frac{K_4}{T'_{do}} & 0 & -\frac{K_3}{T'_{do}} & -\frac{1}{T'_{do}} & -\frac{K_{qdc}}{T'_{do}} \\ -\frac{K_A K_5}{T_A} & 0 & -\frac{K_A K_6}{T_A} & -\frac{1}{T_A} & -\frac{K_A K_{vdc}}{T_A} \\ K_7 & 0 & K'_8 & 0 & -K_9 \end{bmatrix};$$

$$B = \begin{bmatrix} 0 & 0 \\ -\frac{K_{pc}}{M} & -\frac{K_{p\phi}}{M} \\ -\frac{K_{qc}}{T'_{do}} & -\frac{K_{q\phi}}{T'_{do}} \\ -\frac{K_A K_{vc}}{T_A} & -\frac{K_A K_{v\phi}}{T_A} \\ K_{dc} & K_{d\phi} \end{bmatrix}$$

The block diagram of the linearized dynamic model of SMIB power system with STATCOM is shown in Fig. 4.

3.2 Output feedback damping controller

A power system can be described by a Linear Time Invariant (LTI) state space model as follows [21, 22]:

$$\dot{x} = Ax + Bu \tag{26}$$

$$y = Cx \tag{27}$$

Fig. 4. Modified Heffron-Phillips transfer function model

Where, *x*, *y* and *u* denote the system linearized state, output and input variable vectors, respectively. The *A*, *B* and *C* are constant matrixes with appropriate dimensions which are dependent on the operating point of the system. The eigenvalues of the state matrix *A* that are called 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 [23]:

$$u = -Gy \tag{28}$$

Substituting (28) into (26) the resulting state equation is:

$$\dot{x} = A_C . x \tag{29}$$

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

$$A_C = A - BGC \tag{30}$$

Only the local and available state variables $\Delta\omega$, ΔPe and ΔVt 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 A_C are moved to the left-hand side of the complex plane and the desired performance of controller can be achieved [12].

3.3 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 torque. φ parameter is the setting of capacitor voltage is on the controlling part, which in relation to capacitor reference voltage and in comparison with capacitor voltage, the amount of angle phase of converter be computed. The DC-voltage regulator controls the DC voltage across the DC capacitor of the STATCOM. C parameter is the controller duty of AC voltage, setting of terminal voltage is in amount of requested reference, that is be accomplished by converter output voltage from the way of changing magnitude. In the proposed method, we must tune the STATCOM controller parameters optimally to improve overall system dynamic stability. Since the selection of the output feedback gains for mentioned STATCOM based damping controller is a complex optimization problem. 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. For our optimization problem, objective function is time domain-based objective function:

$$J = \sum_{i=1}^{Np} \int_0^{t_{sim}} |\Delta\omega_i| \,.t dt \qquad (31)$$

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. It is aimed to minimize this objective function in order to improve the system response in terms of the setting time and overshoots. 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 (31), which considers a multiple of operating conditions. The operating conditions are given in Table 1.

In order to acquire better performance, number of queen, N_{drone}, N_{brood}, size of the queen's spermatheca, decreasing factor and $N_{workers}$ are chosen as 1, 100, 100, 50, 0.98 and 1000, respectively[19]. In order to facilitate comparison with genetic algorithm the design and tuning

Table 1. Loading conditions

Loading condition	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
Case 4	The 30% increase of line reactance X_L at nominal loading condition.		
Case 5	The 30% increase of line reactance X_L at heavy loading condition.		

Table 2. The optimal parameter settings of the proposed controllers

Parameters	Type of Controller			
	HBMO Algorithm		**Genetic Algorithm**	
	C	*Φ*	*C*	*φ*
G1	195.69	118.44	174.71	127.11
G2	2.9721	1.4633	2.8341	1.0341
G3	1.7249	1. 6796	4.1481	2.7132

of damping controller for STATCOM are used. Typical ranges of the optimized parameters are [100- 200] for G_1 and [0.01-10] for G_2 and G_3. The final values of the optimized parameters with objective function, *J*, are given in Table 2.

4 SIMULATION RESULTS

4.1 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 controller is not installed, it can be seen that some of the modes are unstable (highlighted in Table 3). It is also clear that the system damping and dynamic stability with the proposed method based tuned output feedback damping controller are significantly improved. Moreover, it can be seen that electromechanical mode controllability via φ is higher than that *C* input control signal.

4.1.1 Scenario 1

To assess the performance of the proposed method, 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 Fig. 5 and 6.

Table 3. Eigenvalues of electromechanical modes

Type of controller	Nominal	Light	Heavy	Case 4	Case 5
Without controller	**0.1782±i2.7537,** -0.0747,-93.6950, -6.8523,-1.8914, -2.0201	**0.0835±i2.7890,** -0.1221,-92.3635, -7.9069,-1.6684, -1.3719	**0.3571±i4.0832,** -0.0643,-97.5684, -7.3950,-2.7223, -1.6413	**0.1866±i3.3350,** -0.0777,-92.2980, -8.2866,-1.7144, -1.1975	**0.2853±i3.8670,** -0.0803,-91.8602, -8.9192,-3.9097, -1.9095
C	-3.523±i4.926, -0.719 -3.165,-1.391 -123.436,-0.1793	-2.912±i4.317, -0.7802 -2.231,-6.912 -119.75,-0.2034	-23.931±i11.65, -0.703 -3.154,-1.418 -123.37,-0.2194	-3.187±i4.786, -0.609 -3.095,-1.404 -131.62,-0.1086	-29.191±i12.174, -0.89 -3.066,-1.426 -130.37,-0.2194
φ	-6.823± i3.153, -0.726 -2.324 ±i4.114, -0.513 -2.36, -0.1509 -91.582	-3.427±i5.839, -0.5236 -6.517±4.109 -2.854, -0.9819 -95.154	-6.148 ± i3.634, -0.96 -2.534± i3.5408,- 0.5403 -3.128, -0.1509 -96.644	-6.348±i2.549, -.747, -3.149±i3.9142, -0.717,-3.27, -0.1672,-93.876	-5.395±i2.749, -0.607, -1.872±i2.9834, -0.806,- 3.963, -0.852,-84.932

4.1.2 Scenario 2

In this scenario, the performance of the proposed controller under transient conditions is verified by applying a 6-cycle three-phase fault at *t = 1 sec,* at the middle of the L1 transmission line. The fault is cleared by permanent tripping of the faulted line. The results are shown in Fig. 7 and 8.

To evaluate the performance of the proposed design approach the response with the proposed controllers are compared with: the response of the controller designed with GA and without controller state. The speed deviation of generator at nominal, light and heavy loading conditions with three proposed state are shown in Fig. 5-8. It is clear from these figures that, in without state the system becomes instable; severity and time instability is different in conditions and various scenarios; but in controller design states, the system is stable. Moreover, the controller design based on output feedback damping controller by the proposed approach significantly improves the stability performance of the power system and electromechanical oscillations are well damped out. This state is the best of states of stability.

5 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

Table 4. System Parameters

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

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 non-linear 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 controller provides better damping characteristics and enhances greatly the first swing stability compared to the *C*-based controller.

APPENDIX A   FIRST APPENDIX

The nominal parameters of the case study system are listed in Table 4.

APPENDIX B   GENETIC ALGORITHM

Genetic algorithms are stochastic search techniques based on the mechanism of natural selection and survival of the fittest [24]. Further, they combine function evaluation with randomized and/or well-structured exchange of information among solutions to arrive at global optimum.
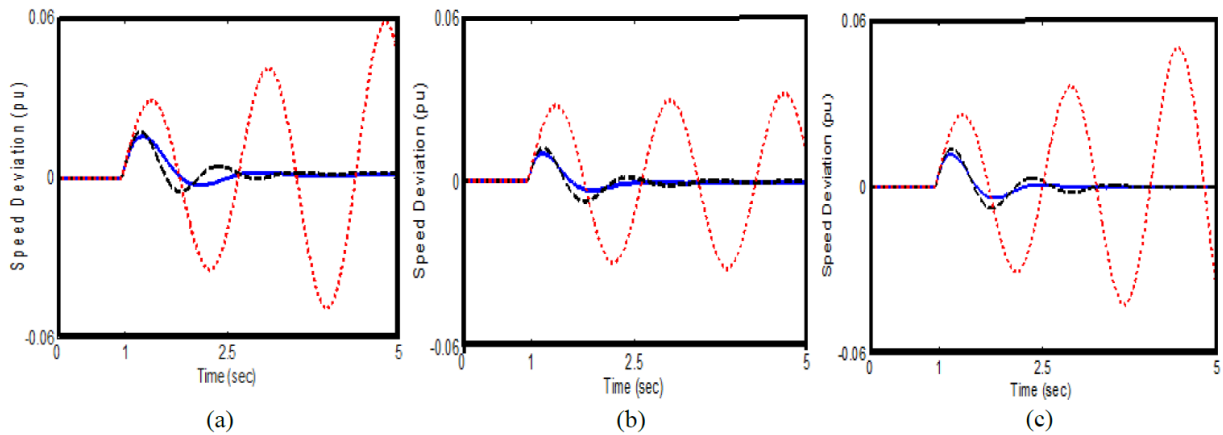
Fig. 5. Dynamic responses for $\Delta\omega$ in scenario 1 at (a) nominal (b) light (c) heavy loading conditions; Solid (HBMO based C controller), Dashed (GA based C controller) and Dotted (without controller)
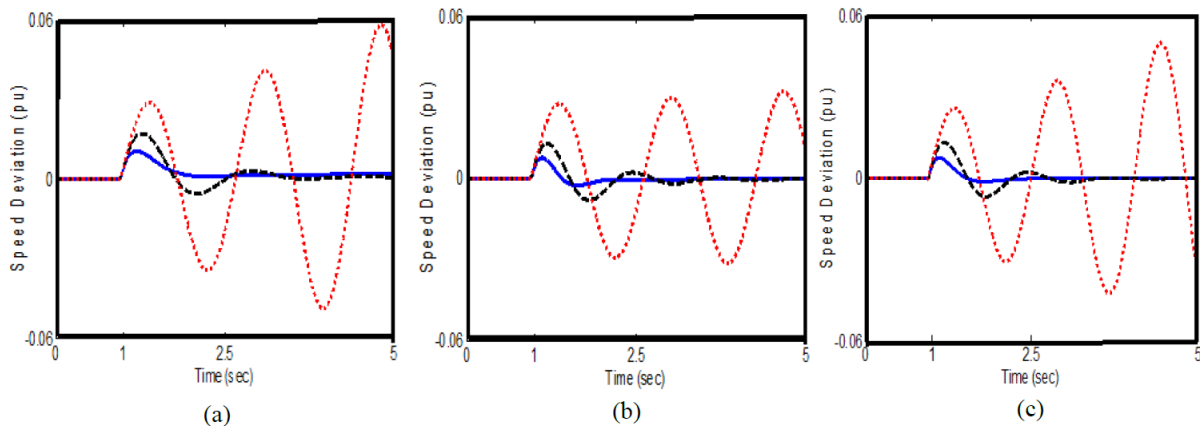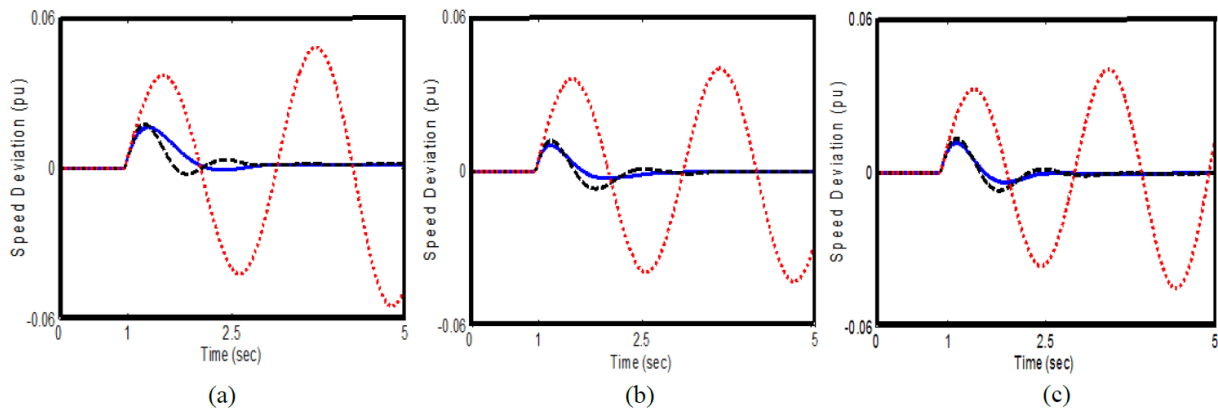

Fig. 6. Dynamic responses for $\Delta\omega$ in scenario 12 at (a) nominal (b) light (c) heavy loading conditions; Solid (HBMO based φ controller), Dashed (GA based φ controller) and Dotted (without controller)

The architecture of GA implementation can be segregated into three constituent phases namely: initial population generation, fitness evaluation and genetic operations. The GA control parameters, such as population size, crossover probability and mutation probability are selected, and an initial population of binary strings of finite length is randomly generated. Given a random initial population GA operates in cycles called generations, as follows [25]:

- Each member of the population is evaluated using a fitness function.

- The population undergoes reproduction in a number of iterations. One or more parents are chosen stochastically, but strings with higher fitness values have higher probability of contributing an offspring.

- Genetic operators, such as crossover and mutation are applied to parents to produce offspring.

- The offspring are inserted into the population and the process is repeated.

The crossover is the kernel of genetic operations. It promotes the exploration of new regions in the search space using randomized mechanism of exchanging information between strings. Two individuals placed in the mating pool during reproduction are randomly selected. A crossover point is then randomly selected and information from one parent up to the crossover point is exchanged with the other parent. Performance method is illustrated below for the used simple crossover technique.

Parent 1: 1011↓ 1110 offspring 1: 10111011

Parent 2: 1010 ↓1011 offspring 2: 1010 1110

Fig. 7. *Dynamic responses for* $\Delta\omega$ *in scenario 2 at (a) nominal (b) light (c) heavy loading conditions; Solid (HBMO based C controller), Dashed (GA based C controller) and Dotted (without controller)*
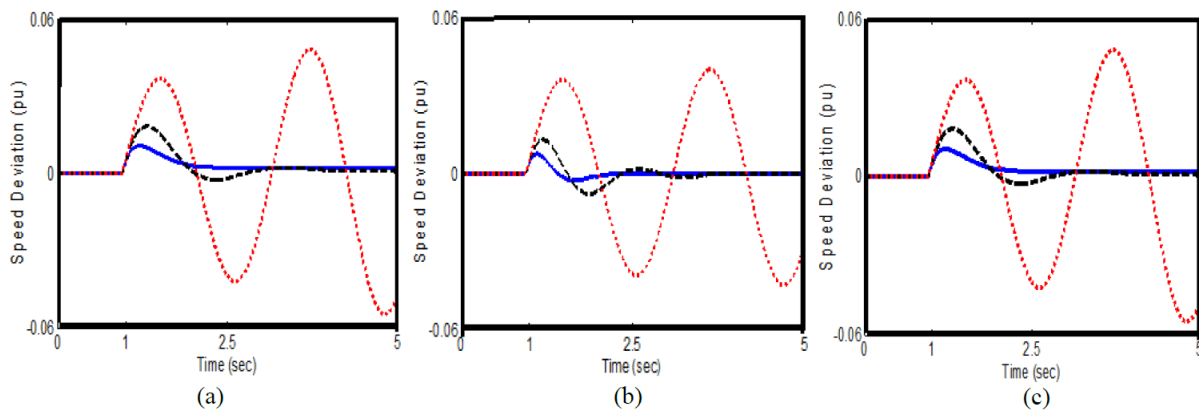

Fig. 8. *Dynamic responses for* $\Delta\omega$ *in scenario 2 at (a) nominal (b) light (c) heavy loading conditions; Solid (HBMO based* φ *controller), Dashed (GA based* φ *controller) and Dotted (without controller)*

Another process also considered in this work is the mutation process of randomly changing encoded bit information for a newly created population individual. Mutation is generally considered as a secondary operator to extend the search space and cause escape from a local optimum when used prudently with the selection and crossover schemes. For the purpose of optimization of (25), routine from GA [25] is used. Using each set of controller parameters the time domain simulation is performed and the fitness function value is determined. The flow chart of GA algorithm is shown in Fig. 9. While applying GA, a number of parameters are required to be specified. Optimization is terminated by the pre-specified number of generations for genetic algorithm.

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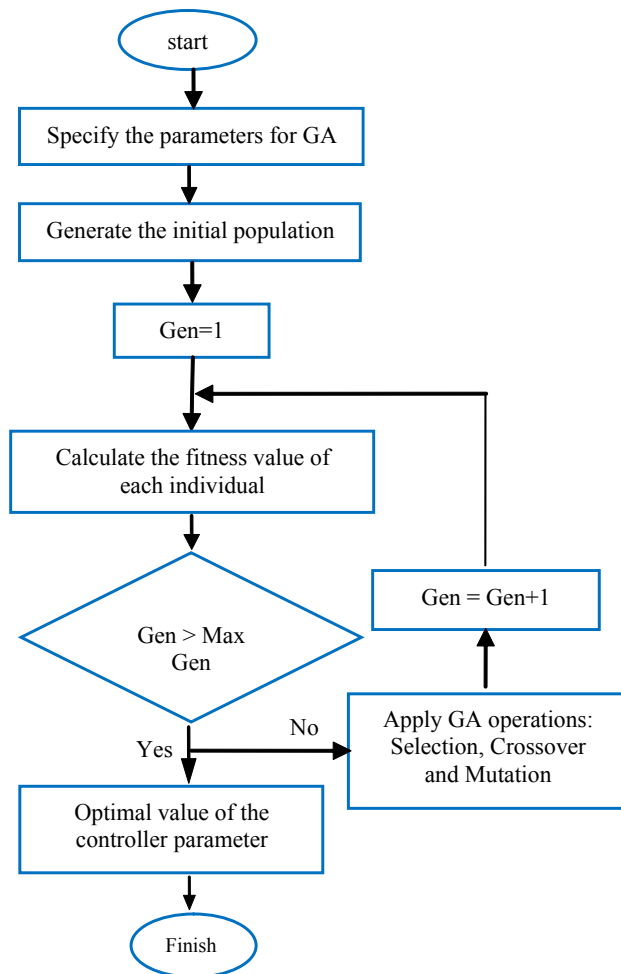
Fig. 9. Flowchart of the Genetic Algorithm

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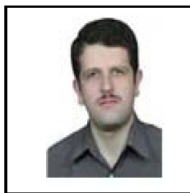
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