Bacteria Foraging: A New Technique for Optimal Design of FACTS Controller to Enhance Power System Stability

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Abstract- This paper proposes Bacteria Foraging Optimization Algorithm (BFOA) based Static Var Compensator (SVC) for the suppression of oscillations in a multimachine power system. The proposed design problem of SVC over a wide range of loading conditions is formulated as an optimization problem with an eigenvalue based objective function. BFOA is employed to search for optimal controller parameters. The performance of the proposed technique has been evaluated with the performance of Genetic Algorithm (GA) to demonstrate the superior efficiency of the proposed BFOA in tuning SVC controller. Simultaneous tuning of the Bacteria Foraging based SVC (BFSVC) gives robust damping performance over a wide range of operating conditions in compare to optimized SVC controller based on GA (GASVC).

Key-Words: - SVC; Multimachine Power System; Genetic Algorithm; Bacteria Foraging; D- Shape.

1. Introduction

The power transfer in an integrated power system is constrained by transient stability, voltage stability and small signal stability. These constraints limit a full utilization of available transmission corridors. Flexible AC Transmission System (FACTS) is the technology that provides the needed corrections of the transmission functionality in order to fully utilize the existing transmission facilities and hence, minimizing the gap between the stability limit and thermal limit [1].

Recently, there has been a surge of interest in the development and use of FACTS controllers in power transmission systems [2 – 6]. These controllers utilize power electronics devices to provide more flexibility to AC power systems. The most popular type of FACTS devices in terms of application is the Static Var Compensator (SVC). This device is well known to improve power system properties such as steady state stability limits, voltage regulation and var compensation, dynamic over voltage and under voltage control, and damp power system oscillations. The SVC is an electronic generator that dynamically controls the flow of power through a variable reactive admittance to the transmission network.

In last few years, many researchers have posed techniques for designing SVC to enhance the damping of electromechanical oscillations of power systems and improve power systems stability. A robust control theory in designing SVC controller to damp out power system swing modes is presented in [7]. An adaptive network based fuzzy inference system (ANFIS) for SVC is discussed in [8] to improve the damping of power systems. A multi input, single output fuzzy neural network is developed in [9] for voltage stability evaluation of the power systems with SVC. A method of determining the location of a SVC to improve the stability of power system is introduced in [10]. A systematic approach for designing SVC controller, based on wide area signals, to enhance the damping of power system oscillations is presented in [11]. Genetic Algorithm (GA) optimization technique is employed for the simultaneous tuning of a PSS and a SVC based controller in [12]. A state estimation problem of power systems incorporating various FACTS devices is addressed in [13]. A novel hybrid method for simulation of power systems equipped with SVC is suggested in [14]. The design of SVC with delayed input signal using a state space model based on Pade approximation method is presented in [15]. A new optimization algorithm known as Bacterial Foraging Optimization Algorithm (BFOA) for designing SVC to damp power system electromechanical oscillations for single machine infinite bus system is introduced in [16]. BFOA based Thyristor Controlled Series Capacitor (TCSC) for the suppression of oscillations in a multimachine power system is addressed in [17]. An application of probabilistic theory to the coordinated design of PSSs and SVC is employed in [18]. The application of the decentralized modal control method for pole placement in multimachine power system utilizing FACTS devices is developed in [19]. Coordination between two different FACTS devices is investigated via implementation of intelligent GA technique to increase the capacity of power transfer in [20]. Graphic-based simulation and optimal PI controller design of a SVC using MATLAB's SIMULINK is presented in [21]. A novel method using Bees Algorithm is discussed in [22] to determine the optimal allocation of FACTS devices for maximizing the available transfer capability of power transactions between source and sink areas in the deregulated power system.

Recently, global optimization technique like GA, has attracted the attention in the field of controller parameter optimization [23]. Unlike other techniques, GA is a population based search algorithm, which works with a population of strings that represent different solutions. Therefore, GA has implicit parallelism that enhances its search capability and the optima can be located swiftly when applied to complex optimization problems. Unfortunately recent research has identified some deficiencies in GA performance [24]. This degradation in efficiency is apparent in applications with highly *epistatic* objective functions (i.e. where parameters being optimized are highly correlated). Also, the premature convergence of GA degrades its performance and reduces its search capability.

BFOA is proposed as a solution to the above mentioned problems and drawbacks [25]. Moreover, BFOA due to its unique dispersal and elimination technique can find favourable regions when the population involved is small. These unique features of the algorithms overcome the premature convergence problem and enhance the search capability. Hence, it is suitable optimization tool for power system controllers.

This paper proposes a new optimization algorithm known as BFOA for optimal designing of damping controller for SVC in a multimachine power system to alleviate power system oscillations. The design problem of the proposed controller is formulated as an optimization problem and BFOA is employed to search for optimal controller parameters. An eigenvalue based objective function reflecting the combination of damping factor and damping ratio is optimized for different operating conditions. Simulations results assure the effectiveness of the proposed controller in providing good damping characteristic to system oscillations over a wide range of loading conditions. Also, these results validate the superiority of the proposed method in tuning controller compared with GA.

2. Bacteria foraging optimization: A brief overview

The survival of species in any natural evolutionary process depends upon their fitness criteria, which relies upon their food searching and motile behaviour. The law of evolution supports those species who have better food searching ability and either eliminates or reshapes those with poor search ability. The genes of those species who are stronger gets propagated in the evolution chain since they possess ability to reproduce even better species in future generations. So a clear understanding and modelling of foraging behaviour in any of the evolutionary species, leads to its application in any nonlinear system optimization algorithm. The foraging strategy of *Escherichia coli* bacteria present in human intestine can be explained by four processes, namely chemotaxis, swarming, reproduction, and elimination dispersal [25-26].

2.1 Chemotaxis

The characteristics of movement of bacteria in search of food can be defined in two ways, i.e. swimming and tumbling together knows as chemotaxis. A bacterium is said to be 'swimming' if it moves in a predefined direction, and 'tumbling' if moving in an altogether different direction. Mathematically, tumble of any bacterium can be represented by a unit length of random direction $\varphi(j)$ multiplied by step length of that bacterium $C(i)$. In case of swimming, this random length is predefined.

2.2 Swarming

For the bacteria to reach at the richest food location (i.e. for the algorithm to converge at the solution point), it is desired that the optimum bacterium till a point of time in the search period should try to attract other bacteria so that together they converge at the desired location (solution point) more rapidly. To achieve this, a penalty function based upon the relative distances of each bacterium from the fittest bacterium till that search duration, is added to the original cost function. Finally, when all the bacteria have merged into the solution point, this penalty function becomes zero. The effect of swarming is to make the bacteria congregate into groups and move as concentric patterns with high bacterial density.

2.3 Reproduction

The original set of bacteria, after getting evolved through several chemotactic stages reaches the reproduction stage. Here, best set of bacteria (chosen out of all the chemotactic stages) gets divided into two groups. The healthier half replaces with the other half of bacteria, which gets eliminated, owing to their poorer foraging abilities. This makes the population of bacteria constant in the evolution process.

2.4 Elimination and dispersal

In the evolution process, a sudden unforeseen event can occur, which may drastically alter the smooth process of evolution and cause the elimination of the set of bacteria and/or disperse them to a new environment. Most ironically, instead of disturbing the usual chemotactic growth of the set of bacteria, this unknown event may place a newer set of bacteria nearer to the food location. From a broad perspective, elimination, and dispersal are parts of the population level long distance motile behavior. In its application to optimization, it helps in reducing the behavior of *stagnation* (i.e. being trapped in a premature solution point or local optima) often seen in such parallel search algorithms. The detailed mathematical derivations as well as theoretical aspect of this new concept are presented in [26-27].

3. Problem statement

3.1 Power system model

A power system can be modelled by a set of nonlinear differential equations are:

$$\dot{X} = f(X,U) \quad (1)$$

Where X is the vector of the state variables and U is the vector of input variables. In this study $X = [\delta, \omega, E'_q, E_{fd}, V_f]^T$ and U is the SVC output signals. Here, δ and ω are the rotor angle and speed, respectively. Also, E'_q, E_{fd} and V_f are the internal, the field, and excitation voltages respectively.

In the design of SVC, the linearized incremental models around an equilibrium point are usually employed. Therefore, the state equation of a power system with n machines and m SVC can be written as:

$$\dot{X} = AX + Bu \quad (2)$$

Where A is a $5n \times 5n$ matrix and equals $\partial f / \partial X$ while B is a $5n \times m$ matrix and equals $\partial f / \partial U$. Both A and B are evaluated at a certain operating point. X is a $5n \times 1$ state vector and U is a $m \times 1$ input vector.

3.2 Modelling of SVC

The thyristor controlled reactor (TCR) in parallel with a fixed capacitor bank shown in Fig. 1, is used in this paper to develop the desired SVC model. The system is then shunt connected to the AC system through a set up transformer to bring the voltages up to the required transmission levels.

It is obvious from (3) and Fig. 2, if the firing angle α of the thyristors is controlled; SVC is able to control the bus voltage magnitude [8]. Time constant (T_r) and gain (K_r) represent the thyristors firing control system.

$$\dot{B}_e = \frac{1}{T_r}\left[-B_e + K_r(V_{ref} - V_t + V_s)\right] \quad (3)$$

The variable effective susceptance of the TCR is given by

$$B_V = -\frac{(2\pi - 2\alpha + \sin 2\alpha)}{\pi X_L} \quad \pi/2 \le \alpha \le \pi \quad (4)$$

Where X_L is the reactance of the fixed inductor of SVC. The effective reactance is

$$X_e = X_C \frac{\pi / r_x}{\sin 2\alpha - 2\alpha + \pi(2 - 1/r_x)} \quad (5)$$

Where $X_e = -1/B_e$ and $r_x = X_e / X_L$.

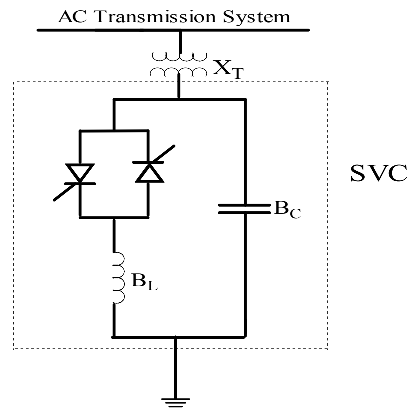

Fig. 1. SVC equivalent circuit.

An auxiliary stabilizing signal from speed can be imposed on the SVC control loop. The block diagram of a SVC with auxiliary stabilizing signal is shown in Fig. 2. This controller may be considered as a lead lag compensator. It comprises gain block, signal washout block, limiters and two stages of lead lag compensator. The parameters of the damping controllers are obtained using the BFOA algorithm.

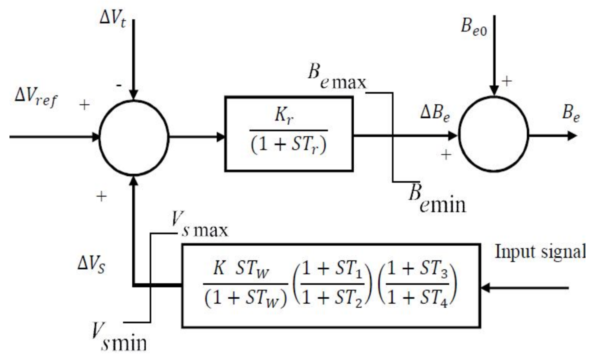

Fig. 2. Block diagram of SVC.

3.3 System under study and SVC location

Fig. 3 shows the single line diagram of the test system used. Details of system data are given in [28]. The participation matrix can be used in mode identification. Table (1) shows the eigenvalues, and frequencies associated with the rotor oscillation modes of the system. Examining Table (1) indicates that the 0.2371 Hz mode is the interarea mode with G1 swinging against G2 and G3. The 1.2955 Hz mode is the intermachine oscillation local to G2. Also, the 1.8493 Hz mode is the intermachine mode local to G3. The positive real part of eigenvalue of G1 indicates instability of the system. The system and generator loading levels are given in Table (2).

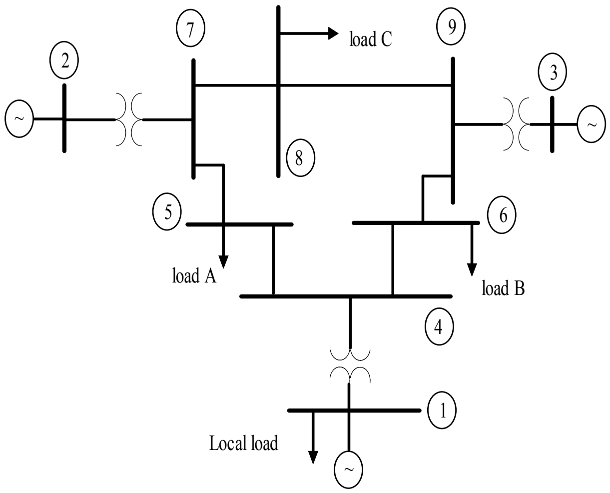

Fig. 3. System under study.

Table (1) The eigenvalues, and frequencies of the rotor oscillation modes of the system.

Generator	Eigenvalues	Frequencies	Damping ratio ζ
G1 G2 G3	**+0.15 ± 1.49j** -0.35 ± 8.14j -0.67 ± 11.62j	0.2371 1.2295 1.8493	**-0.1002** 0.0430 0.0576

Table (2) Loading of the system (in p.u)

	Light		Normal case		Heavy	
Generator	P	Q	P	Q	P	Q
G1	0.965	0.22	1.716	0.6205	3.57	1.81
G2	1.0	-0.193	1.63	0.0665	2.2	0.713
G3	0.45	-0.267	0.85	-.1086	1.35	0.43
Load	P	Q	P	Q	P	Q
A	0.7	0.35	1.25	0.5	2.0	0.9
B	0.5	0.3	0.9	0.3	1.8	0.6
C	0.6	0.2	1.00	0.35	1.6	0.65
at G1	0.6	0.2	1.00	0.35	1.6	0.65

In order to determine the suitable placement of the SVC in the system, two strategies will be shown below. The first one is based on studying the effect of load percentage while the second is concerned with the line outage on system voltages [29]. Tables (3 and 4) show the effect of load percentage and line outage on bus voltages of the system. It can be noticed that the voltages are affected significantly at buses numbered 5 and 6, respectively which are load buses. The reasons that cause the significant voltage change are the connection of these buses with the longest lines in the system which has greater resistances and reactances than the others. Consequently, the choice of buses number 5 or 6 for placing the SVC controller is expected to be the more suitable choice. Because both of them are close to machine number 1 which causes the system instability due to its unstable mechanical mode. Moreover, bus number 5 is the worst one and will be considered in this paper as the best location for installing the SVC controller.

Table (3) Effect of load percentage on load bus voltages

% Load	**0.25**	**0.50**	**0.75**	**1.00**	**1.25**	**1.50**	**1.75**
Bus 4	1.06	1.05	1.04	1.03	1.01	0.99	0.98
Bus 5	1.06	1.04	1.02	0.99	0.96	**0.94**	**0.90**
Bus 6	1.06	1.05	1.03	1.01	0.99	0.97	**0.94**
Bus 7	1.05	1.04	1.04	1.03	1.01	1.00	0.98
Bus 8	1.05	1.04	1.03	1.02	0.99	0.98	0.96
Bus 9	1.05	1.05	1.04	1.03	1.02	1.01	1.00

Table (4) Effect of line outage on load bus voltages

line	**4-5**	**4-6**	**5-7**	**6-9**	**7-8**	**8-9**
Bus 4	1.039	1.028	0.996	1.005	1.016	1.022
Bus 5	**0.839**	0.998	**0.938**	0.968	0.974	0.989
Bus 6	1.020	**0.942**	0.975	0.964	0.999	1.009
Bus 7	0.988	1.022	1.017	1.016	1.019	1.010
Bus 8	0.989	1.006	1.001	1.005	0.969	0.978
Bus 9	1.024	1.017	1.019	1.023	1.013	1.034

4. Objective function

To maintain stability and provide greater damping, the parameters of the SVC may be selected to minimize the following objective function:

$$J_t = \sum_{j=1}^{np} \sum_{\sigma_{ij} \ge \sigma_0} (\sigma_0 - \sigma_{ij})^2 + \sum_{j=1}^{np} \sum_{\xi_{ij} \ge \xi_0} (\xi_0 - \xi_{ij})^2 \qquad (6)$$

This will place the system closed loop eigenvalues in the D-shape sector characterized by $\sigma_{ij} \le \sigma_0$ and $\xi_{ij} \rangle \xi_0$ as shown in Fig. 4.

Where, np is the number of operating points considered in the design process, σ and ξ are the real part and the damping ratio of the eigenvalue of the operating point. In this study, σ_0 and ξ_0 are chosen to be -0.5 and 0.1 respectively [30]. To reduce the computational burden in this study, the value of the wash out time constant T_W is fixed to 10 second, and tuning of T_1 to T_4 are undertaken to achieve the net phase lead required by the system. Typical ranges of the optimized parameters are [1- 100] for K and [0.06-1.0] for T_1 to T_4. Based on the objective function J_t optimization problem can be stated as: Minimize J_t subjected to:

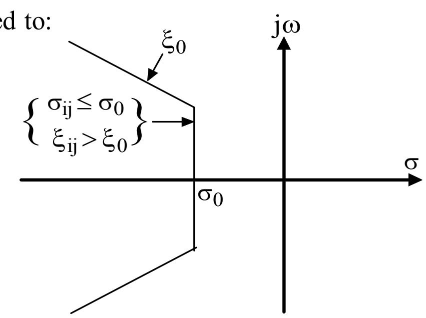

Fig. 4. A D-shape sector in the s-plane.

$K^{\min} \le K \le K^{\max}$

$T_1^{\min} \le T_1 \le T_1^{max}$

$T_2^{\min} \le T_2 \le T_2^{max}$

$T_3^{\min} \le T_3 \le T_3^{max}$

$T_4^{\min} \le T_4 \le T_4^{max}$ (7)

This study focuses on optimal tuning of SVC using BFOA algorithm. The aim of the optimization is to search for the optimum controller parameters setting that reflect the settling time and overshoots of the system. On the other hand, the goals are improving the damping characteristics under all operating conditions and various loads and finally designing a low order controller for easy implementation.

5. Bacteria foraging algorithm

In this paper, optimization using BFOA is carried out to find the parameters of SVC damping controller. The algorithm of the proposed technique involves two steps.

[Step- 1] Initialization

i) p is the number of parameters to be optimized.

ii) S is the number of bacteria to be used for searching the total region.

iii) N_S is the swimming length after which tumbling of bacteria will be undertaken in a chemotactic loop.

iv) N_C is the number of iteration to be undertaken in a chemotactic loop. ($N_C > N_S$).

v) N_{re} is the maximum number of reproduction to be undertaken.

vi) N_{ed} is the maximum number of elimination and dispersal events to be imposed over the bacteria.

vii) P_{ed} is the probability with which the elimination and dispersal will continue.

viii) P (1-p, 1-S, 1) is the location of each bacterium which is specified by random numbers on [-1, 1].

ix) The value of C (i) which is assumed to be constant in this case for all the bacteria to simplify the design strategy.

x) The values of $d_{attract}$, $\omega_{attract}$, $h_{repelent}$ and $\omega_{repelent}$.

[Step-2] Iterative algorithm for optimization

This section models the bacterial population chemotaxis, swarming, reproduction, elimination and dispersal (initially, j=k=l=0). For the algorithm updating θ^i automatically results in updating of P.

[1] Elimination-dispersal loop: l=l+1

[2] Reproduction loop: k=k+1

[3] Chemotaxis loop: j=j+1

a) For i=1, 2,…, S, calculate cost function value for each bacterium i as follows.

- Compute value of cost function $J(i, j, k, l)$.

Let $J_{sw}(i, j, k, l) = J(i, j, k, l) + J_{cc}(\theta^i(j, k, l), P(j, k, l))$.

J_{cc} is defined by the following equation

$$J_{cc}(\theta, P(j,k,l))) = \sum_{i=1}^{S} J_{cc}(\theta, \theta^i(j,k,i))$$

$$= \sum_{i=1}^{S}\left[-d_{attract}\, exp\left(-\omega_{attract}\sum_{m=1}^{p}(\theta_m-\theta_m^i)^2\right)\right]$$

$$+\sum_{i=1}^{S}\left[h_{repelent}\, exp\left(-\omega_{repelent}\sum_{m=1}^{p}(\theta_m-\theta_m^i)^2\right)\right] \quad (8)$$

- Let $J_{last} = J_{sw}(i, j, k, l)$ to save this value since one may find a better cost via a run.
- End of For loop

b) For i=1, 2,….S take the tumbling/swimming decision.

- Tumble: generate a random vector $\Delta(i) \in \Re^p$ with each element $\Delta_m(i)$ m=1,2,…p,
- Move: Let $\theta^i(j+1,k,l) = \theta^i(j,k,l) + C(i)\frac{\Delta(i)}{\sqrt{\Delta^T(i)\Delta(i)}}$

Fixed step size in the direction of tumble for bacterium i is considered.

Compute $J(i, j+1, k, l)$ and

$J_{sw}(i,j+1,k,l) = J(i,j+1,k,l) + J_{cc}(\theta^i(j+1,k,l), P(j+1,k,l))$

Swim

i) Let m=0 (counter for swim length).

ii) While $m < N_S$ (have not climbed down too long)

- Let m=m+1
- If $J_{sw}(i, j+1, k, l) < J_{last}$ (if doing better), let $J_{last} = J_{sw}(i, j+1, k, l)$ and let

  $\theta^i(j+1,k,l) = \theta^i(j,k,l) + C(i)\frac{\Delta(i)}{\sqrt{\Delta^T(i)\Delta(i)}}$

  and use this $\theta^i(j+1,k,l)$ to compute the new $J(i, j+1, k, l)$
- Else, let $m = N_S$. This is the end of the while statement.

iii) Go to next bacterium (i+1) if $i \ne S$

[4] If j< N_c, go to [step 3]. In this case, continue chemotaxis, since the life of the bacteria is not over.

[5] Reproduction

a) For the given k and l, and for each i=1, 2,..S, let

$$J^{i}_{health} = \min_{j \in \{1...N_c\}} \{J_{sw}(i,j,k,l)\}$$ be the health of the bacterium i(a measure of how many nutrients it got over its life time and how successful it was at avoiding noxious substance). Sort bacteria in order of ascending cost J_{health}.

b) The $S_r = S/2$ bacteria with highest J_{health} values die and other S_r bacteria with the best value split.

[6] If k< N_{re} , go to [step 2]. In this case, one has not reached the number of specified reproduction steps, so one starts the next generation in the chemotactic loop.

[7] Elimination-dispersal: for $i = 1,2,...., N$, with probability P_{ed} , eliminate and disperse each bacterium, and this result in keeping the number of bacteria in the population constant. To do these, if you eliminate a bacterium, simply disperse one to a random location on the optimization domain. If $l < N_{ed}$, then go to [step 2]; otherwise end.

The detailed mathematical derivations as well as theoretical aspect of this new concept are presented in [25-26].

6. Results and simulations

In this section different comparative cases are examined to show the effectiveness of the proposed BFOA method for optimizing controller parameters.

Fig. 5. shows the variations of objective function with two different optimization techniques. The objective functions decrease monotonically over generations of GA and BFOA. The final value of the objective function is J_t=0 for both algorithms, indicating that all modes have been shifted to the specified D-shape sector in the S-plane and the proposed objective function is satisfied. Moreover, BFOA converges at a faster rate (52 generations) compared to that for GA (86 generations).

Table (5), shows the system eigenvalues, and damping ratio of mechanical mode with three different loading conditions. It is clear that the system with open loop is unstable for light, normal, and heavy loading respectively. Moreover, BFSVC shift substantially the electromechanical mode eigenvalues to the left of the S-plane and the values of the damping factors with the proposed BFSVC are significantly improved to be (σ =-0.75,-0.72,-0.97) for light, normal, and heavy loading respectively. Hence compared to the open loop and GASVC, BFSVC greatly enhances the system stability and improves the damping characteristics of electromechanical modes. Results of SVC parameters set values based on the proposed objective function using BFOA, and GA are given in Table (6).

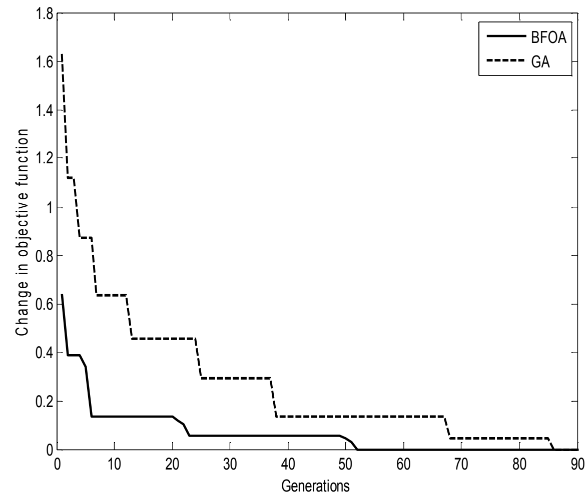

Fig. 5. Variations of objective function.

Table (5) Mechanical modes and ζ under different loading conditions and controllers.

	No Controller (NC)	GASVC	BFSVC
Light load	-0.84 ± 9.96j, 0.084 -0.61 ± 7.61j, 0.079 +0.06 ± 0.97j,-0.062	-1.73 ± 9.83j,0.17 -2.49 ± 7.26j, 0.32 -0.73 ± 0.79j, 0.678	-2.98 ± 9.65j, 0.29 -3.58 ± 7.56j, 0.42 -0.75 ± 0.77j, 0.697
Normal load	-0.67 ± 11.62j,0.058 -0.35 ± 8.14j, 0.043 +0.15 ± 1.49j, -0.10	-1.57 ± 11.58j, 0.13 -1.91 ± 8.79j, 0.21 -0.65 ± 0.83j,0.61	-3.14 ± 11.35j, 0.26 -2.78 ± 9.00j, 0.295 -0.72 ± 0.78j, 0.678
Heavy load	-0.51 ± 11.91j, 0.043 -0.19 ± 8.01j, 0.024 +0.04 ± 1.78j, -0.023	-1.27 ± 12.01j,0.11 -1.09 ± 8.80j, 0.123 -0.91 ± 0.84j, 0.73	-2.89 ± 11.8j, 0.24 -1.96 ± 8.84j, 0.22 -0.97 ± 0.83j, .602

Table (6) Parameters of SVC damping controller.

	GA	BFOA
Parameters of lead lag circuit	K=59.6483 T_1=0.5728 T_2=0.4732 T_3=0.6485 T_4=0.3558	K=47.7363 T_1=0.6289 T_2=0.4927 T_3=0.6934 T_4=0.4081

6.1 Response for normal load condition:

The effectiveness of the performance of the proposed controller under severe disturbance is verified by applying a three phase fault of 6 cycle duration at 1.0 second near bus 7. Fig. 6, shows the response of Δw_{13} for normal loading condition. This Figure indicates the capability of the BFSVC in reducing the settling time and damping power system oscillations. Moreover, the settling time of these oscillations is T_s =3.0, and 3.3

second for BFSVC and GASVC respectively. Moreover, the system is unstable for open loop case. Hence, the proposed BFSVC is capable of providing sufficient damping to the system oscillatory modes compared with GASVC and open loop case.

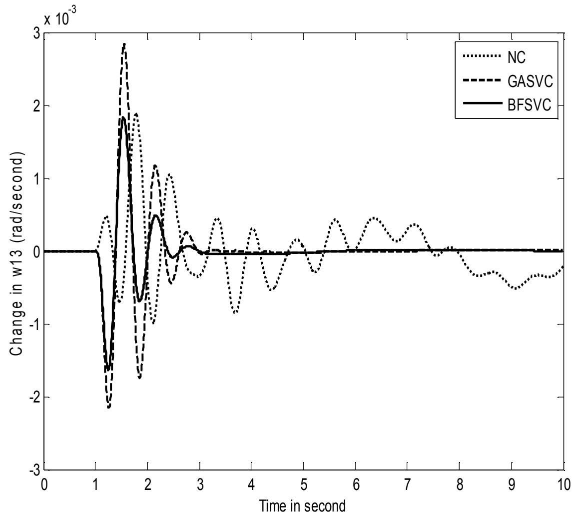

Fig. 6. Change in Δw_{13} for normal load.

6.2 Response for heavy load condition:

Fig. 7, shows the system response at heavy loading condition with fixing the controller parameters. From this Figure, it can be seen that the response with the proposed BFSVC shows good damping characteristics to low frequency oscillations and the system is more quickly stabilized than GASVC. The settling time of oscillations is T_s =2.8, and 3.2 second for BFSVC and GASVC respectively. Also, the system is unstable for open loop case. Hence, the proposed BFSVC extend the power system stability limit and the power transfer capability.

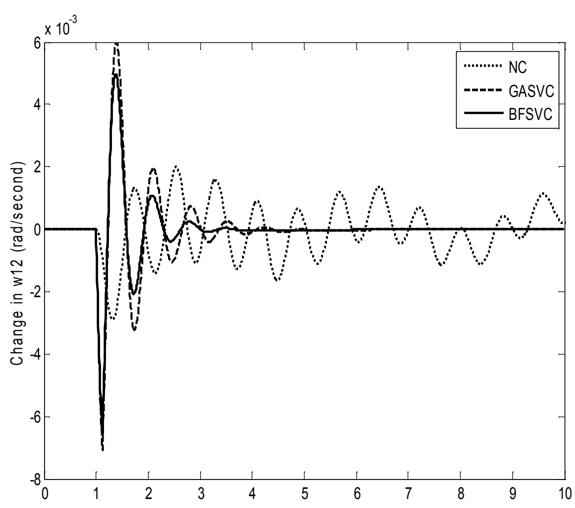

Fig. 7. Change in Δw_{12} for heavy load.

6.3 Robustness and performance index:

To demonstrate the robustness of the proposed controller, a performance index: the Integral of the Time multiplied Absolute value of the Error (ITAE) is being used as:

$$ITAE = \int_0^{30} t\left(\left|\Delta w_{12}\right| + \left|\Delta w_{23}\right| + \left|\Delta w_{13}\right|\right)dt \qquad (9)$$

Where $\Delta w_{12} = \Delta w_1 - \Delta w_2$, $\Delta w_{23} = \Delta w_2 - \Delta w_3$, and $\Delta w_{13} = \Delta w_1 - \Delta w_3$. It is worth mentioning that the lower the value of this index is, the better the system response in terms of time domain characteristics. Numerical results of performance robustness for all cases are listed in Table (7). It can be seen that the values of these system performance characteristics with the BFSVC are smaller compared to these of GASVC. This demonstrates that the overshoot, undershoot, settling time and speed deviations of all units are greatly reduced by applying the proposed BFOA based tuned SVC.

Table (7) Values of performance index.

	ITAE*10^{-5}	
	GASVC	BFSVC
Light load	14	9
Normal load	63	53
Heavy load	71	59

7. Conclusions

This paper proposes a new optimization algorithm known as BFOA for optimal designing of damping controller for SVC in a multimachine power system to suppress power system oscillations. The design problem of the proposed controller is formulated as an optimization problem and BFOA is employed to search for optimal controller parameters. An eigenvalue based objective function reflecting the combination of damping factor and damping ratio is optimized for different operating conditions. Simulations results assure the effectiveness of the proposed controller in providing good damping characteristic to system oscillations over a wide range of loading conditions. Also, these results validate the superiority of the proposed method in tuning controller compared with GA over wide range of operating conditions.

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Appendix

The system data are as shown below:

a) Excitation system: $K_A = 400$; $T_A = 0.05$ second; $K_f = 0.025$; $T_f = 1$ second.

b) SVC Controller: T_r = 15 msecond, α_0 =140, K_r =50.

c) Bacteria parameters: Number of bacteria =10; number of chemotatic steps =10; number of elimination and dispersal events = 2; number of reproduction steps = 4; probability of elimination and dispersal = 0.25.

d) Genetic parameters: Max generation=150; Population size=50; Crossover probabilities=0.75; Mutation probabilities =0.1.