Optimal Design of SVC and Thyristor-Controlled Series Compensation Controller in Power System

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Abstract— *In this paper, the optimal location and tuning parameters of Static Var Compensator (SVC), Proportional-Integral-Derivative (PID) stabilizer with low pass filter and Thyristor Controlled Series Compensator (TCSC) controllers using multi objective Honey Bee Mating Optimization (HBMO) to damp small signal oscillations in a multi machine power system has been implemented. Whereas, the performance of Flexible AC Transmission (FACT) devices highly depends upon its parameters and suitable position in the power network which is based on proposed algorithm. To demonstrate the validity of the proposed method, 10-machine 39-bus power system has been considered. Obtained results demonstrate the validity of proposed method.*

Keywords: FACTs devices, PID, Small signal stability, HBMO.

I. Introduction

Recently, power demand increases substantially and, on the other hand, the expansion of power generation and transmission is limited due to limited resources and environmental restrictions. So, the existing transmission systems should be utilized effectively by operating them closer to their thermal limits. This aim can be provided by reliable and high-speed Flexible AC Transmission System (FACTS) devices [1-3] such as static VAR compensator (SVC), Thyristor-Controlled Phase Shifter (TCPS), and Thyristor Controlled Series Capacitor (TCSC). FACTS are designed to enhance power system stability by increasing the system damping in addition to their primary functions such as voltage and power flow control.

The stability of power system is the core of power system security protection which is one of the most important problems researched by electrical engineers [1]. The fast-acting static excitation systems, used to improve transient stability limits, contribute strongly to the diminution of low frequency oscillation damping. The conventional lead-lag compensators have been widely used as the Power System Stabilizers (PSSs) [1-5]. However, the problem of PSS parameter tuning is a complex exercise. Beside of new control techniques with different structure, Proportional Integral Derivative (PID) type controller is still widely used for industrial applications [6-7]. Accordingly, it performs well for a wide class of process. Furthermore, they give robust performance for a wide range of operating conditions and easy to implement. Also, FACTs devices are too employed to enhance small signal stability which are based on high-voltage and high-speed power electronics devices [8-10]. This ability increase the controllability of power flows and voltages enhancing the utilization and stability of existing systems.

The optimal placement of FACTS controller in power system networks has been reported in scientific literatures based on different aspects. A method to obtain optimal location of TCSC has been suggested in [11] based on real power performance index and reduction of system VAR loss. In [10] optimal allocation of SVC using Genetic Algorithm (GA) has been investigated to achieve the optimal power flow (OPF) with lowest cost generation in power system. But the optimal allocations of SVC, PID and TCSC controllers using multi objective Honey Bee Mating Optimization (HBMO) have been

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considered in this paper. Simulations are carried out on a typical multi-machine electric power systems; 10-machine 39-bus. Obtained simulation results confirm the enhances of small signal stability of proposed method in power system.

II. Problem Definition

The system dynamics of the synchronous machine can be expressed as a set of five first order linear differential equations given in Eqs. (1)–(5) [12].

$$\dot{\delta}_i = \omega_b(\omega_i - 1) \tag{1}$$

$$\dot{\omega}_i = (P_{mi} - P_{ei} - D_i(\omega_i - 1))/M_i \tag{2}$$

$$\dot{E}'_{qi} = (E_{fdi} - (x_{di} - x'_{di})i_{di} - E'_{qi})/T'_{doi} \tag{3}$$

$$\dot{E}_{fdi} = (K_{Ai}(v_{refi} - v_i + u_i) - E_{fdi})/T_{Ai} \tag{4}$$

$$T_{ei} = E'_{qi} i_{qi} - (x_{qi} - x'_{di}) i_{di}\, i_{qi} \tag{5}$$

Where, i_d and i_q are d-q components of armature current. E_{fd}, E'_d and E'_q are voltage proportional to field voltage, damper winding flux and field flux, respectively. Also, T'_{d0} and T'_{q0} are d-axis and q-axis transient time constant, respectively. In this paper, the results obtained with a relatively large power system which is the New England 10 machine 39 bus power system.

A. PID Stabilizer

The operating function of a PID is to produce a proper torque on the rotor of the machine involved in such a way that the phase lag between the exciter input and the machine electrical torque is compensated. The supplementary stabilizing signal considered is one proportional to speed. A widely speed based used PID is considered throughout the study [6]. The transfer function of the ith PID is:

$$U_i = \frac{ST_w}{1+ST_w}.(K_P + \frac{K_I}{S} + \frac{K_D}{1+T_D S})\Delta\omega_i(s) \tag{6}$$

Where $\Delta\omega_i$ is the deviation in speed from the synchronous speed. The value of the time constant, T_w is usually not critical and it can range from 0.5 to 20 s. The stabilizer itself mainly consists of two lead-lag filters as shown in Fig. 1. The parameters of the damping controllers for the purpose of simultaneous coordinated design are obtained using the multi objective HBMO algorithm. Many input signals have been proposed for the FACTS to damp the inter-area mode for this system. Signals which carry invaluable information about the inter-area mode can be considered as the input signals.

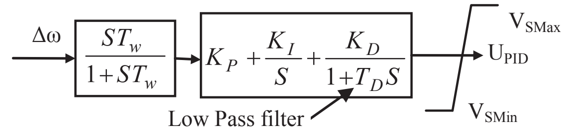


Figure 1. Structure of PID stabilizer

B. TCSC Modeling

The series connection scheme allows the power flow to be influenced through changing the effective admittance linking two buses, and is a method of improving transient stability limits and increasing transfer capabilities [13]. The transfer function pattern of a TCSC controller [14] has been given in Fig. 2.

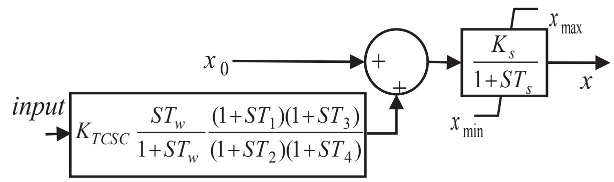


Figure 2. structure of TCSC based controller

This block may be considered as a lead-lag compensator. It comprises gain block, signal-washout block and two stages of lead-lag compensator. Where, X_0 is the impedence reference of TCSC. The X is the output reactance of TCSC. Time T_1 is a measurement time constant and T_w is the washout time constant.

C. SVC Modeling

Figure 3 shows the structure of an SVC model with a lead–lag compensator. The susceptance of the SVC, B, can be defined by:

$$\rho B = \frac{1}{T_s}(K_s(B_{ref} - u_{SVC}) - B) \tag{7}$$

Where, B_{ref}, K_s and T_s are the reference susceptance, gain and time constant for SVC device. As given in Fig. 3, a lead–lag controller is considered in the feedback loop to create the SVC stabilizing signal u_{SVC}.

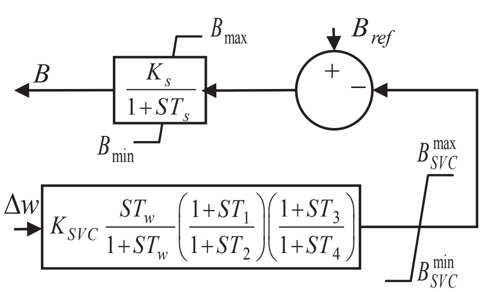


Figure 3. structure of SVC based controller

III. Multi Objective Honey Bee Mating Optimization

The honey bee is a social insect that can survive only as a member of a community, or colony. This means that they tend to live in colonies while all the individuals are the same family. In the more highly organized societies there is a division of labor in which individuals carry out particular duties. In fact, a colony consists of a queen and several hundred drones, 30,000 to 80,000 workers and broods in the active season. Each bee undertakes sequences of actions which unfold according to genetic, ecological and social condition of the colony [15]. The queen is the most important member of the hive because she is the one that keeps the hive going by producing new queen and worker bees and any colony maybe contain one or much queen in it life′s. Drones' role is to mate with the queen. In the marriage process, the queen(s) mate during their mating flights far from the nest [16]. In each mating, sperm reaches the spermatheca and accumulates there to form the genetic pool of the colony. The queen’s size of spermatheca number equals to the maximum number of mating of the queen in a single mating flight is determined. When the mate be successful, the genotype of the drone is stored. In start the flight, the queen is initialized with some energy content and returns to her nest when her energy is within some threshold from zero or when her spermatheca is full. A drone's mate probabilistically is [17]:

$$P_{rob}(Q,D) = e^{-(\Delta f)/(S(t))} \tag{8}$$

Where,

Prob (Q, D) = The probability of adding the sperm of drone *D* to the spermatheca of queen *Q*

$\Delta(f)$ = The absolute difference between the fitness of *D* and the fitness of *Q (i.e., f (Q))*

S(t) = The speed of the queen at time *t*

After each transition in space, the queen’s speed, and energy, decay using the following equations:

$$S(t+1) = \alpha \times S(t)(2), \quad \alpha \in [0,1] \tag{9}$$
$$E(t+1) = E(t) - \gamma$$

γ = The amount of energy reduction after each transition. The flowchart of Classic HBMO is presented in “Fig. 4”, [14].

Thus, HBMO algorithm may be constructed with the following five main stages [13]:

- The algorithm starts with the mating–flight, where a queen (best solution) selects drones probabilistically to form the spermatheca (list of drones). A drone is then selected from the list at random for the creation of broods.
- Creation of new broods by crossoverring the drones’ genotypes with the queen’s.
- Use of workers (heuristics) to conduct local search on broods (trial solutions).
- Adaptation of workers’ fitness based on the amount of improvement achieved on broods.
- Replacement of weaker queens by fitter broods.

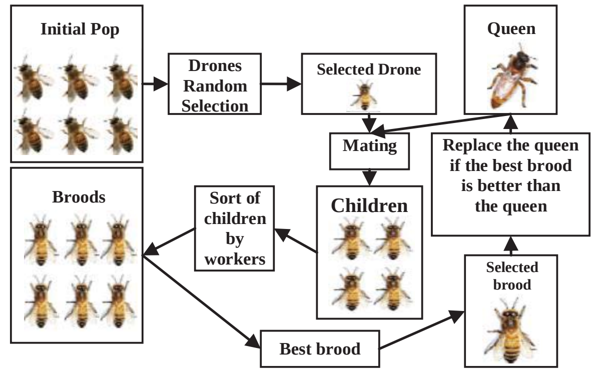


Figure 4. The Classic HBMO technique

A. Fuzzy Decision in Multi Objective HBMO

Usually, a membership function for each of the objective functions is defined by the experiences and intuitive knowledge of the decision maker. In this work, a simple linear membership function was considered for each of the objective functions. The membership function is defined as:

$$FDM_i = \begin{cases} 0 & , \mu_i \le 0 \\ \dfrac{f_i^{\max} - f_i}{f_i^{\max} - f_i^{\min}} & , 0 < \mu_i < 1 \Rightarrow \mu_i = \dfrac{f_i^{\max} - f_i}{f_i^{\max} - f_i^{\min}} \\ 1 & , \mu_i \ge 1 \end{cases} \tag{10}$$

Where f_i^{min} and f_i^{max} are the maximum and minimum values of the i^{th} objective function, respectively. For each non-dominated solution k, the normalized membership function FDM^k is calculated as:

$$FDM^k = \left(\sum_{i=1}^{N_{obj}} FDM_i^k\right) \Bigg/ \left(\sum_{j=1}^{M}\sum_{i=1}^{N_{obj}} FDM_i^j\right) \tag{11}$$

Where M is the number of non-dominated solutions, and N_{obj} is the number of objective functions.

IV. Numerical Results

A multi objective problem is formulated to optimize a composite set of objective functions comprising the damping factor, and the damping ratio of the lightly damped electromechanical modes, and the effectiveness of the suggested technique is confirmed through eigenvalue analysis and nonlinear simulation results. The simulation operated with multi objective HBMO algorithm and the objective functions for optimization as follow:

$$J_1 = \sum_{j=1}^{N_p} \sum_{i=1}^{N_g} \int_0^{t_{sim}} t.(|\Delta\omega_{ij}|).dt \qquad (12)$$

$$J_2 = \sum_{j=1}^{N_p} \sum_{i=1}^{N_g} \max_{i,j}[\mathrm{Re}(\lambda_{i,j}) - \min\{-\zeta\,|\,\mathrm{Im}(\lambda_{i,j})\,|, \alpha\}] \qquad (13)$$

Where, N_P, N_g, t_{sim}, λ and ζ are number of operating condition, number of generators, the time of simulation, the i^{th} eigenvalue of the system at an operating point and the desired minimum damping, respectively. The optimal location and tuning parameters problem can be formulated as the following constrained optimization problem, where the constraints are the PID, TCSC and SVC parameters bounds. The optimization Problem can be stated as:

$$\begin{aligned} &\text{Minimize } J \text{ Subject to :} \\ &K^{\min} \le K_{PID/TCSC/SVC} \le K^{\max} \\ &T_i^{\min} \le T_{i(PID/TCSC/SVC)} \le T_i^{\max}, i = 1,...,4 \end{aligned} \qquad (14)$$

Typical ranges of the optimized parameters are [0.01-20] for $K_{PID/TCSC/SVC}$ and [0.01-1] for T_1 to T_4. Different operating conditions are analyzed for the New England system, as given in Table 1.

TABLE I. OPERATING CONDITIONS.

Conditions	Characteristics
1	Base case (normal operation)
2	Lines out: 1-2
3	Line out: 8-9
4	Increase 20% load to bus 17
5	Lines out: 46-49, Load increase 25% : 20, 21 generation increase 20%: G_9

It should be noted that proposed algorithm is run several times. The initial colony is produced randomly for each drone and is kept within a typical range. Figure 5 shows the trend evaluating process. The optimum parameters are given in Table 2. To demonstrate performance robustness of the proposed method, two performance indices: the Integral of the Time multiplied Absolute value of the Error (ITAE) and Figure of Demerit (FD) based on the system performance characteristics are defined as

$$ITAE = 100 \times \sum_{i=1}^{N_G} \int_0^{t_{sim}} t.(|\Delta\omega_i|).dt \qquad (15)$$

$$FD = \frac{1}{N_G} \sum_{i=1}^{N_G} ((600 \times OS_i)^2 + (8000 \times US_i)^2 + 0.01 \times T_{s,i}^2) \qquad (16)$$

Where, Overshoot (OS), Undershoot (US) and settling time of rotor angle deviation of machine is considered for evaluation of the FD. It is worth mentioning that the lower value of these indices is, the better the system response in terms of time domain characteristics.

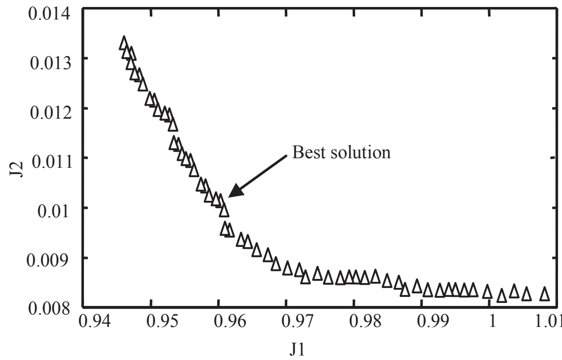


Figure 5. Fitness convergence with proposed algorithm.

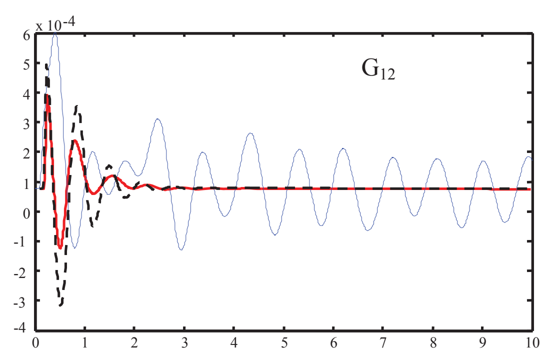
TABLE II. OPTIMAL VALUE FOR SVC, TCSC AND PID.

Type	Loc	K	T_1	T_2	T_3	T_4	
SVC	25	19.12	0.79	0.09	0.78	0.08	
TCSC	26#27	17.43	0.54	0.26	0.48	0.21	
PID	Loc	K_P	K_I	K_D	Loc	K_P	K_I	K_D
	1	13.23	11.43	5.43	9	13.43	12.43	6.54
	3	13.54	14.31	3.22	10	18.34	8.98	3.22
	5	18.32	12.74	3.90	12	13.52	9.54	1.22
	6	18.45	8.33	3.21	13	11.24	11.23	3.23
	7	12.32	13.54	2.12	15	17.87	12.43	1.43
	8	17.33	13.12	3.11	16	19.23	10.32	3.44

The results of the proposed multi objective based designed PID, SVC and TCSC under transient conditions is verified by applying disturbance and fault clearing sequence under different operating conditions based tuned them with mentioned objective functions. The following types of disturbances have been considered.

- *Scenario 1:* the three lines (16#17, 1#2 and 25#26) are out of service, assuming also that the nonlinear time domain simulations were carried out for a three phase-fault, with duration of 100 ms on the line 25#60. The speed deviations of generators under the proposed fault are shown in Fig. 6.

By considering to fig. 6, it can be said that the proposed method could provide low overshoot, undershoot as well as settling time in comparison with other techniques.



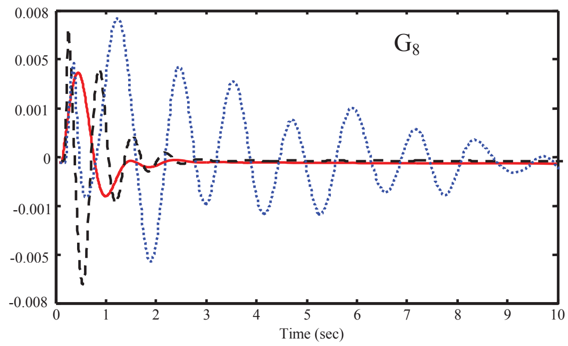


Figure 6. Speed variations of G8 and G12 under scenario I; solid (PID/SVC/TCSC), dashed (only with PID), dotted (with TCSC and SVC)

- *Scenario 2:* the two lines (16#17 and 25#26) are out of service and three-phase fault is applied at the same above mentioned location in scenario 1, assuming also that the variations of +30% in all load levels were used. The speed deviations of generators under the proposed fault are shown in Fig. 7.

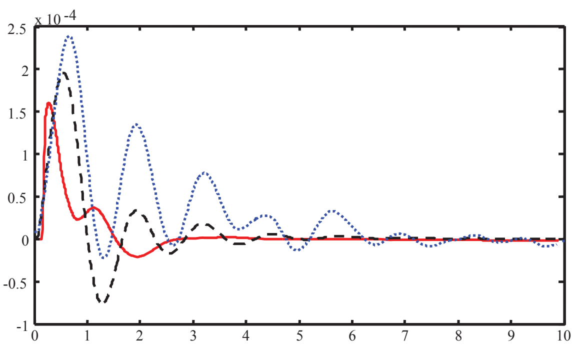


Figure 7. Speed variations of G_{15} under scenario II; solid (PID/SVC/TCSC), dashed (only with PID), dotted (with TCSC and SVC).

Numerical results of the system performance for different loading conditions are shown in Fig 8. It is worth mentioning that the lower the value of these indexes is, the better the system answer in terms of time domain characteristics. It is clear that the values of the power system performances with the proposed strategy are smaller compared when only PID or TCSC/SVC is installed. This shows that the OS, US, settling time and speed deviations of all generators are greatly reduced by applying the proposed multi objective HBMO algorithm based tuned PID, SVC and TCSC. Moreover, the nature of critical (Table 3) eigenvalue and time response analysis reveal that the proposed controller is more superior than the uncoordinated TCSC or SVC damping controller and PID stabilizers to improve the small signal oscillation problem even during critical loading. Also, the convergence of proposed method has been presented in Fig. 9.

TABLE III. CRITICALSWING MODES

SVC and TCSC		PID, TCSC and SVC	
Swing modes	Damping ratio	Swing modes	Damping ratio
Line outage (#13-14)			
-0.645±6.534i	0.982	-0.956±4.736i	0.1978
Load increase (20% more than nominal value)			
-0.756±6.032i	0.124	-0.847±4.021i	0.206

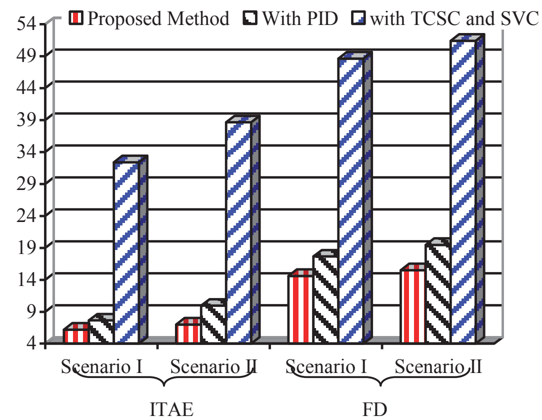


Figure 8. Values of performance indexes.

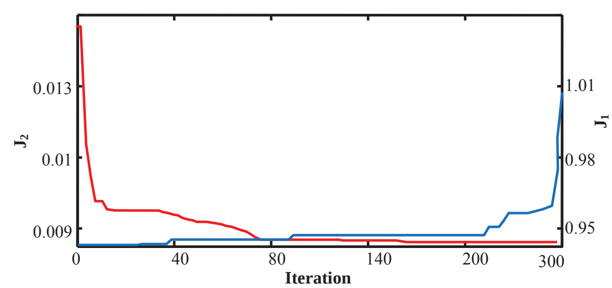


Figure 9. Convergence of objective functions

V. Conclusions

In this paper, the multi objective HBMO is implemented over an optimization problem for finding the best location and the parameters of coordinated PID stabilizers, SVC and TCSC controller simultaneously. Also, fuzzy decision making approach is proposed to obtain the best Pareto optimal location and settings of the FACTS controller among the Pareto optimal solutions. The proposed method has been applied over 10-machine 39 bus power system in different load conditions. Also, to demonstrate the validity of proposed method simulation results compared with only PID and only TCSC/SVC controller. Obtained results proofs the superiority of proposed method.

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