Optimal Placement and Tuning of SVC, TCSC Controller and PID Stabilizers in Multi Machine Using Multi Objective IABC

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Abstract—This study aims to simultaneously select 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 Interactive Artificial Bee Colony (IABC) to damp small signal oscillations in a multi machine power system. Though classical controller associated with generators are obligatory necessities for damping of oscillations in the multi machine power system, its efficiency still gets affected by changes in network models, load deviations, etc. For this reason, installations of Flexible AC Transmission (FACT) devices have been introduced in this study to achieve noticeable damping of small signal oscillations. Nevertheless, the performance of FACT devices highly depends upon its parameters and suitable position in the power network. In this study the multi objective IABC is used to consider this problem in order to improve the low frequency oscillation. To demonstrate the validity of the proposed scheme, simulations are carried out in 16-machine 68-bus as a large scale power system. The results of simulation have been represented employing eigenvalue as well as time domain response. It has been seen that the coordinated design is more effective than the uncoordinated of TCSC or SVC POD controller or PID stabilizers even during higher loading in mitigating the small signal stability problem.

Keywords—Multi objective, IABC, FACTs devices, PID, Small signal stability.

I. INTRODUCTION

Low frequency oscillations are detrimental to the goals of maximum power transfer and optimal power system security. Three different oscillations have been observed in large interconnected power systems: Inter-unit Oscillations (1-3Hz), Local Mode Oscillations (0.7-2Hz), and Inter-area Oscillations (0.5-1Hz). These low frequency oscillations may result in serious consequences such as tripping the generator from the grid, or even participating to major system blackouts. 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. These stabilizers have previously tuned both single and multiple operation points of the power system using various methods. The approaches used to the problem of PSS parameters tuning range from modern control theory, to the more recent one using many random heuristic methods, such as FGSA [1], GSA [3], DE [5], Hybrid ABC [3] and etc, for achieving high efficiency and search global optimal solution in the problem space.

Despite the potential of the modern control techniques with different structure, Proportional Integral Derivative (PID) type controller is still widely used for industrial applications such as power systems control [6]-[7]. This is because it performs well for a wide class of process. Also, they give robust performance for a wide range of operating conditions and easy to implement. PID has been widely used to damp low frequency oscillation and enhance power system stability [7].

Generally, in large scale power systems, using only conventional PID may not present adequate damping for inter-area oscillations. Besides PID, FACTs devices are too employed to enhance small signal stability [8]-[10]. FACTs devices are based on high-voltage and high-speed power electronics devices. They increase the controllability of power flows and voltages enhancing the utilization and stability of existing systems. In these cases, FACTS Power Oscillation Damping (POD) controllers are effective solutions.

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 IABC to investigate the small signal stability problem have not been discussed in existing literature. In this paper, this fact has been taken into consideration as well as a multi objective IABC based technique is proposed to place and the coordinated SVC, PID and TCSC controllers design separately in a multi machine system in order to damp the small signal oscillations. The IABC method may also be considered as a typical evolution and swarm based approach for optimization, in which the search algorithm is inspired by the heuristic foraging behavior of a honeybee swarm process for finding source foods. The behavior of honeybees is the
interaction of their genetic potentiality, ecological and physiological environments, and the social conditions of the colony, as well as various prior and ongoing interactions between these three parameters. Simulations are carried out on a typical multi-machine electric power systems; 16-machine 68-bus. The simulation results clearly confirm that the proposed method enhances the small signal stability of the power system, particularly when the operating point changes.

II. MULTI MACHINE FORMULATION

A. Non-Linear Machine model

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) [1].

\[ \delta_i = \omega_i (\omega_i - 1) \]  
\[ \dot{\omega}_i = (P_{mi} - P_{ei} - D_i (\omega_i - 1))/M_i \]  
\[ E_{qi}^i = (E_{fqi} - (x_{di} - x_{dqi}^i) i_{di} - E_{dqi}^i)/T_{daqi} \]  
\[ E_{fqi} = (K_{m1} v_{sref} + u_7) - E_{fqi}^i )/T_{Aqi} \]  
\[ T_{ei} = E_{qi}^i i_{qi} - (x_{qi} - x_{dqi}^i) i_{di} i_{qi} \]  

Where, \( i_d \) and \( i_q \) are d-q components of armature current. \( E_{dqi}, E_{qi} \) and \( E_{fqi} \) are voltage proportional to field voltage, damper winding flux and field flux, respectively. Also, \( T_{daqi} \) and \( T_{dqi} \) 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/New York interconnected system (16-machine, 68-bus), Fig. 1, are presented.

B. 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:

\[ U_i = \frac{ST_w}{1+ST_w} \left( K_s + \frac{K_f}{S} + \frac{K_d}{1+T_d S} \right) \Delta \omega_i (s) \]  

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. 2. The parameters of the damping controllers for the purpose of simultaneous coordinated design are obtained using the multi objective IABC 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.

\[ \Delta \omega = \frac{ST_w}{1+ST_w} K_p + \frac{K_f}{S} + \frac{K_d}{1+T_d S} \]  

Low Pass filter

Fig. 2. Structure of PID stabilizer

C. 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 [10]. The transfer function pattern of a TCSC controller [11] has been given in Fig. 3.

Fig. 3. 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 impedance 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.

D. SVC Modeling

Figure 4 shows the structure of an SVC model with a lead-lag compensator. The susceptance of the SVC, \( B \), can be defined by:

\[ \rho B = \frac{1}{T_f} (K_s (B_{sref} - u_{SVC}) - B) \]  

Where, \( B_{sref}, K_s \) and \( T_f \) are the reference susceptance, gain and time constant for SVC device. As given in Fig. 4, a lead-lag controller is considered in the feedback loop to create the SVC stabilizing signal \( u_{SVC} \).
III. MULTI OBJECTIVE INTERACTIVE ARTIFICIAL BEE COLONY

A. Standard ABC

In this subsection, the standard ABC briefly reviewed, for complete illustration see Ref. [26]. In the original ABC, the number of employed bees is equal to the number of food sources which is also equal to the number of onlooker bees [27]. The process of the ABC algorithm is presented as follows:

- **Step 1. Initialization:** Generate random population and calculate their fitness values. This population and fitness values called employed bees and nectar amounts, respectively.
- **Step 2. Move the Onlookers:** An onlooker bee evaluates the nectar information taken from all employed bees and chooses a food source with a probability related to its nectar amount by “Eq. (11)”, this method, known as roulette wheel selection method. The movement of the onlookers follows the equation.

\[ p_i = \text{fit}_i / \left( \sum_{i=1}^{SN} \text{fit}_i \right) \]  

Where, \( P_i \) and \( SN \) are probability of selecting the \( i^{th} \) employed bee and number of employed bees, and \( \text{fit}_i \) is the fitness value of the solution.

\[ X_{ij}^{(t+1)} = \theta_{ij} + \phi_k (\theta_{ij}^{(t)} - \theta_{ij}^{(t)}) \]  

Where, \( k \in \{1,2,...,BN\} \) and \( j \in \{1,2,...,D\} \) are randomly chosen indexes and \( x, t, \theta_k \) and \( \phi(t) \) are the position of the \( i^{th} \) onlooker bee, the iteration number, the randomly selected employed bee and random variable between (-1,1), respectively, \( D \) is the number of dimension of optimization problem.

- **Step 3. Move the Scouts:** When selected a food source, all the employed bees associated with it abandon the food source, and become scout. The scouts are moved by:

\[ \theta_{ij} = \theta_{ij, \min} + r(\theta_{ij, \max} - \theta_{ij, \min}) \]  

Where, \( r \) shows a random factor and \( \in [0,1] \).

- **Step 4. Update the Best Food Source Found So Far:** Memorize the best food source found so far.

- **Step 5. Termination Checking:** checking termination criteria satisfied, if it is satisfied then stop algorithm otherwise go to step 2.

B. Interactive Artificial Bee Colony

Notwithstanding, the supposed algorithm is prosperous for finding best answer in optimization problem, but only considers the relation of employed bee and selected by the roulette wheel selection [13]. The factor of this mathematics formulation generate randomly. Therefore, it cannot use full exploitation capacity. In order to surmount this shortage, the Newtonian law of universal gravitation is used. In the Interactive Artificial Bee Colony (IABC) algorithm the Eq. (11) is considered which shows the universal gravitations between the selected employed bees are exploited by the roulette wheel selection and the onlooker bee.

\[ F_{ij} = G \frac{m_1 m_2}{r_{ij}^2} \]  

\[ r_{ij} = \frac{r_i - r_j}{|r_i - r_j|} \]  

Where, \( m_1, m_2, r_{ij}, r_{ij} \) and \( G \) are masses of the objects, the separation between the objects, the unit vector and \( G \) is considered universal gravitation constant, respectively. In the proposed method, the mass \( m_1 \) and \( m_2 \) replaced by parameters: \( F(\theta_j) \) and \( F(\theta_i) \), they are fitness value of the employed bee that picked by applying the roulette wheel selection and the randomly selected employed bee, respectively. We can drive similar formulation for universal gravitation. Thus, we have:

\[ F_{ij} = \frac{G \theta_j - \theta_i}{(\theta_j - \theta_i)^2} \]  

\[ x_j^{(t+1)} = \theta_j^{(t)} + \sum_{k=1}^{n} \tilde{F}_{ik} [\theta_j^{(t)} - \theta_i^{(t)}] \]  

Where, \( F_{ik} \) considered universal gravitation between the employed bee, which is hand-picked by the onlooker bee, and more than one employed bees. \( F_{ik} \) plays factor controlling in the roulette wheel selection. By developing and considering the gravitation between the picked employed bee and \( n \) selected employed bees, the results can be expressed as:

\[ x_j^{(t+1)} = \theta_j^{(t)} + \sum_{k=1}^{n} \tilde{F}_{ik} [\theta_j^{(t)} - \theta_i^{(t)}] \]  

Where, \( \tilde{F}_{ik} \) is the normalized gravitation force.

C. Multi Objective IABC

The multi objective optimization problem contains of several objectives to be optimized simultaneously and is associated with a many of inequality, equality and binary constraints. For multi objective coordinated design of SVC, TCSC and PID in power system, any two solutions \( x_1\) and \( x_2\), can have one of two possibilities: one dominates the other or none dominates the other (see [14]). In the proposed problem,
functions. The membership function is defined as:

\[ f_i(x_j) = \begin{cases} 0, & \mu_i \leq 0 \\ \frac{f_{j_{\text{min}}}^i - f_{i_{\text{min}}}^j}{f_{j_{\text{max}}}^i - f_{i_{\text{min}}}^j}, & 0 < \mu_i < 1 \\ \mu_i, & \mu_i \geq 1 \end{cases} \]

\[ FDM_k = \frac{1}{M} \sum_{i=1}^{N_{\text{obj}}} FDM_i \]

If any of the mentioned cases is violated, \( x_j \) does not dominate \( x_k \). Also, if \( x_k \) dominates \( x_j \) then \( x_k \) is named the non-dominated solution. The solutions those are non-dominated inside the entire search space are denoted as Pareto-optimal and constitute the Pareto-optimal set. The entire group of Pareto-optimal solutions forms a Pareto-optimal set, and the curve they form when being joined is called the Pareto-optimal front.

D. Fuzzy Decision in Multi Objective ABC

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:

\[ FDM_k = \frac{1}{M} \sum_{i=1}^{N_{\text{obj}}} FDM_i \]

Where \( FDM_i \) is the normalized membership function \( FDM_k \) is calculated as:

\[ FDM = \frac{1}{M} \sum_{i=1}^{N_{\text{obj}}} \left( \frac{1}{N_{\text{obj}}} \sum_{j=1}^{N_{\text{obj}}} FDM_i \right) \]

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

E. Archiving

Pareto-dominance concept is used to evaluate the fitness of each solution and thus determine which solution must be chosen to reserve in the archive of non-dominated answers. The archive absorbs superior current non-dominated solutions and eliminates inferior solutions in the archive through interacting with the generational population in every generation. A candidate answer can be added to the archive if it satisfies any of the following terms:

- The archive is full but the candidate solution is non-dominated and it is in a less crowded region than at least one solution.
- The archive is not full and the candidate solution is not dominated by any solution in the archive.
- The candidate solution dominates any existing solution in the archive.
- The archive is empty.

F. The Computational Flow

In this paper, the basic multi objective ABC has been investigated in order to make it suitable for solving real-world nonlinear constrained optimization problems. The following adjustments have been incorporated in the basic multi objective ABC method.

- A procedure is imposed to check the feasibility of the initial population individuals and the generated children through ABC operations. This ensures the feasibility of Pareto-optimal non-dominated solutions.
- A procedure for updating the Pareto-optimal set is developed. In every generation, the non-dominated solutions in the first front are combined with the existing Pareto optimal set. The augmented set is processed to extract the non-dominated solutions that represent the updated Pareto-optimal set.
- A fuzzy-based mechanism is employed to extract the best compromise solution over the trade-off curve and assist the decision maker to adjust the generation levels efficiently.

The computational flow chart of the proposed method is shown in Fig. 5:

G. Settings of the Proposed Approach

The method used in this paper was developed and implemented on 2.53-GHz PC using MATLAB language. On all optimization runs, the population size and the maximum number of generations were selected as 120 and 300, respectively. The maximum size of the Pareto-optimal set was chosen as 20 solutions. If the number of non-dominated Pareto optimal solutions exceeds this bound, the clustering technique is used. The colony size and limit value are chosen as 50, 40 and 10 to different studies system, respectively for ABC in all optimization runs.

H. Constraints handling

Since ABC is essentially an unconstrained optimization algorithm, the constraints handling scheme needs to be incorporated into it in order to deal with the constrained power dispatch problem. Here a straightforward constraint checking procedure called rejecting strategy is added. When any two
individuals are compared, their constraints are examined first. If both satisfy the constraints, the concept of Pareto-dominance is then applied to determine which one is the survivor. If one is feasible and the other is not, the feasible candidate dominates. Though this constraint satisfaction checking scheme is simple, it turns out to be very effective in guaranteeing the feasibility of the non-dominated solutions.

IV. APPLY MULTI OBJECTIVE IABC FOR PROPOSED PROBLEM

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 factor, and the damping ratio of the lightly damped composite set of objective functions comprising the damping of PID, TCSC and SVC parameters as shown with:

\[ J_1 = \sum_{j=1}^{N_P} \sum_{i,j} \max_{i,j} [\text{Re}(\lambda_{i,j}) - \min \{-\zeta \mid \text{Im}(\lambda_{i,j}), \alpha_i\}] \]  

Where, \( N_P, N_e, t_{sim}, \lambda, \zeta, \) and \( \alpha_i \) are number of operating condition, number of generators, the time of simulation, the 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:

\[
\text{Minimize } J \text{ Subject to: } \\
K_{\text{min}} \leq K_{\text{PID/TCSC/SVC}} \leq K_{\text{max}} \\
T_i^{\text{min}} \leq T_i(\text{PID/TCSC/SVC}) \leq T_i^{\text{max}}, i = 1, ..., 4
\]  

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

**TABLE I. OPERATING CONDITIONS.**

<table>
<thead>
<tr>
<th>Conditions</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Base case (normal operation)</td>
</tr>
<tr>
<td>2</td>
<td>Lines out: 1-2</td>
</tr>
<tr>
<td>3</td>
<td>Line out: 8-9</td>
</tr>
<tr>
<td>4</td>
<td>Increase 20% load to bus 17</td>
</tr>
<tr>
<td>5</td>
<td>Lines out: 46-49, Load increase 25%: 20, 21 generation increase 20%: G_o</td>
</tr>
</tbody>
</table>

Where, \( K \) and \( T \) stand for the respective gains and time compensator of PID, SVC and the TCSC controller. The initial colony is produced randomly for each drone and is kept within a typical range. The colony pattern corresponding to the PID, SVC and TCSC controller is shown in Fig. 6. Figure 7 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 Merit (FM) based on the system performance characteristics are defined as

\[
\text{ITAE} = 100 \times \sum_{i=1}^{N_G} \int_{0}^{t_{\text{sim}}} t_i |\Delta \omega_i| \, dt
\]

\[
\text{FD} = \frac{1}{N_G} \sum_{i=1}^{N_G} \left( 600 \times OS_i^2 + (8000 \times US_i)^2 + 0.01 \times T_{s,i}^{-2} \right)
\]

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.

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

<table>
<thead>
<tr>
<th>Type</th>
<th>Loc</th>
<th>( K_I )</th>
<th>( K_P )</th>
<th>( K_D )</th>
<th>( K_{\text{TCSC}} )</th>
<th>( K_{\text{SVC}} )</th>
<th>( K_{\text{PID}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>SVC</td>
<td>25</td>
<td>19.63</td>
<td>0.82</td>
<td>0.09</td>
<td>0.75</td>
<td>0.07</td>
<td>0.07</td>
</tr>
<tr>
<td>TCSC</td>
<td>26/27</td>
<td>18.64</td>
<td>0.65</td>
<td>0.20</td>
<td>0.45</td>
<td>0.19</td>
<td>0.19</td>
</tr>
<tr>
<td>PID</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>12.78</td>
<td>12.55</td>
<td>4.53</td>
<td>9</td>
<td>13.11</td>
<td>13.17</td>
</tr>
<tr>
<td></td>
<td></td>
<td>15.46</td>
<td>13.71</td>
<td>1.15</td>
<td>10</td>
<td>19.23</td>
<td>8.99</td>
</tr>
<tr>
<td></td>
<td></td>
<td>19.57</td>
<td>11.59</td>
<td>2.38</td>
<td>12</td>
<td>14.30</td>
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<td>19.64</td>
<td>7.25</td>
<td>1.23</td>
<td>13</td>
<td>11.84</td>
<td>15.08</td>
</tr>
<tr>
<td></td>
<td></td>
<td>11.57</td>
<td>12.94</td>
<td>1.48</td>
<td>15</td>
<td>19.04</td>
<td>14.13</td>
</tr>
<tr>
<td></td>
<td></td>
<td>19.70</td>
<td>13.53</td>
<td>5.11</td>
<td>16</td>
<td>19.79</td>
<td>9.25</td>
</tr>
</tbody>
</table>
V. RESULTS AND SIMULATION

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. 8.

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. 9.

Numerical results of the system performance for different loading conditions are shown in Fig 10. 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 IABC algorithm based tuned PID, SVC and TCSC. Furthermore, it is obvious from eigenvalues shown in Fig.11 that the electromechanical mode eigenvalues have been shifted to the left in s-plane and the system damping with the proposed method is greatly improved and enhanced.

The voltages on buses 1 is shown in Fig. 12. It can be observed from mentioned figure that under the three-phase grounding short-circuit fault, the bus voltage at the short-circuit point fall down to zero, and finally the system can’t find the stability. When the 12 kinds of PID and a TCSC and SVC are simultaneously installed, the system tends to stabilize at around 2s. The closed loop frequency response for the compensated test system is shown in Fig. 13. From the simulation results it is clear that the performance indices associated with the frequency response are generally accepted values and the system is highly stable if the above outlined PID, TCSC and SVC is mounted on the power system. Unlike the other heuristic methods, the proposed Multi Objective IABC based approach does not rely on the initial solution. Starting anywhere in the search space, IABC algorithm ensures the convergence to the optimal solution. Scenario I is reconsidered to demonstrate this point. In this case, the main target is to shift the dominant eigenvalues as far as possible to the left of the s-plane. Different initial solutions are considered by changing the seed of the random number generator that generates the initial solution. The convergence of the objective functions with different initial solutions is shown in Fig. 14.
The results emphasize that the proposed IABC based approach finally leads to the optimal solution regardless of the initial one.

![PID/TCSC/SVC vs Without controller](image)

**Fig. 12.** The voltage on bus 1 under a three-phase grounding short-circuit fault with and without of PID respectively installed.

![Closed loop frequency response of NETS with Proposed Method](image)

**Fig. 13.** Closed loop frequency response of NETS with Proposed Method.

![Convergence of objective functions with different initializations](image)

**Fig. 14.** Convergence of objective functions with different initializations.

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VI. CONCLUSION

In this paper, the multi objective Interactive Artificial Bee Colony (IABC) has been used to search the best location and the parameters of coordinated PID stabilizers, SVC and TCSC controller simultaneously. The application is extended to study the small signal oscillation problem in case of a multi machine power system considering all network bus dynamics. The 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 eigenvalue analysis reveals the effectiveness of the proposed strategy to damp out local as well as inter-area modes of oscillations. The nonlinear time simulation results show that the proposed method can work effectively over a wide range of loading conditions and system configurations. 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.

**TABLE III. CRITICAL SWING MODES**

<table>
<thead>
<tr>
<th>Swing modes</th>
<th>Damping ratio</th>
<th>PID, TCSC and SVC Damping ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>SVC and TCSC</td>
<td>Line outage (#13-14)</td>
<td>0.645±6.334i 0.982</td>
</tr>
<tr>
<td>PID, TCSC and SVC</td>
<td>Load increase (20% more than nominal value)</td>
<td>0.756±6.032i 0.124</td>
</tr>
</tbody>
</table>

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REFERENCES


