Hierarchical VBA based TCSC Robust damping control system design

Laiq Khan, Ilkram Ullah and K.L. Lo

Department of Electrical Engineering, COMSATS Institute of Information Technology Abbottabad Pakistan

Department of Electrical and Electronic Engineering, University of Strathclyde Glasgow UK

Abstract: A novel Hierarchical virtual bee’s algorithm (HVBA) based design method for robust control of Thyristor controlled series compensator (TCSC) is presented in this paper. The design problem of controller is first formulated as an optimization problem. Then HVBA is employed to simultaneously select an appropriate structure of controller and its optimal parameters by minimizing the multi-objective function of supplementary damping control system. The effectiveness of the proposed technique is evaluated and compared with no control and conventional control design. The performance and robustness of the proposed technique is validated through small and large signal simulations in multi-machine power system.

Key words: Electromechanical oscillations, VBA, Power system stability, TCSC, Multi-machine power system.

INTRODUCTION

Electricity supply industry is undergoing a profound variation worldwide day by day. Market deregulation, scarcity of natural resources and ever increasing power demand are some of the factors creating unprecedented changes in power systems. The trend of large interconnected power systems has been resulting in poorly damped electro-mechanical low frequency inter-area oscillations (0.1~0.6 Hz). Many power utilities facing a variety of environmental, land-use and regulatory problems. Thus prevent them to build new transmission lines and establishing new generating power plants. The analysis of the options available for maximizing the existing transmission assets, with high level of reliability and stability, has pointed in the direction of power electronics. The new technologies based on high power electronics equipment such as Flexible AC Transmission Systems (FACTS) devices and their techniques are potential substitute of the conventional solutions. This can improve the operation and control of power system in transmission line based control strategies that have slow response times and high maintenance costs (Aboul-Ela et al., 1996). Damping of power system is not the only reason of using FACTS controllers for enhancing power system but a variety of benefits can be taken from FACTS controller for enhancing power system stability. The uses of these controllers give the grid planner and operator a great flexibility regarding the type of control actions that can be taken at any given time. Additionally, it can improve transfer capability, enhancing continuous control over the voltage profile and minimizing losses etc (Chow et al., 2000). However when these devices are installed supplementary control laws can be employed to improve damping as well as satisfy the primary requirements of the device. Thyristor controlled series compensator (TCSC) belongs to the family of FACTS devices in particular have been studied and practically shown to significantly enhance the system stability (Hingorani, 1991).

In the dynamic application of TCSC, various control techniques and designs have been proposed for damping power system oscillations to improve system dynamic response, whereas for steady state control, the main interest of users and researchers has been the use of this controller for power flow control in transmission lines, usually considering optimal scheduling strategies e.g. damping torque analysis (Pilotto et al., 2003), optimal control theory (Lin and Xu, 2005) and linear programming (Padiyar and Varma, 1991). A controller design for certain operating conditions may not be accepted for other operating conditions. In order to develop a closed loop control system which is stable and fulfills the performance objectives related to plant uncertainty and parameter variations (Chen and Anderson, 1995),a lot of has been done based on the robust control techniques to power systems. Heuristic search approaches like Genetic algorithm, self tuning controllers (STC) (Pourbeik, 1997; Taranto and Falcao, 1998) and model adaptive reference system (MRAS), tabu search
A novel population based biological inspired algorithm called the Virtual Bees Algorithm (VBA) Abido, (2002) is introduced as evolutionary computational technique. Engineering problems with multi objective functions are hard and time consuming in optimization. The nature of biological inspired algorithm in combination with the conventional optimization methods has been very successful in the few decades in many applications Laq Khan, (2008).

The VB algorithm is inspired by the natural foraging behavior of honey bees to find the food source. The algorithm performs a kind of neighborhood search combined with random search and can be used for both combinatorial and functional optimization. The optimization functions can have discrete, continuous or even mixed parameters without any priori assumptions about continuity and differentiability. VBA is characterized by simple in concept, easy to implement and efficient in computation. Thus, it is suitable for parameter search in optimization problem as compared to other evolutionary algorithm. In this paper, a novel advanced optimization technique HVBA is employed in designing TCSC supplementary damping control system. HVBA algorithm is employed to optimize the design problem by simultaneously selecting an appropriate structure of multi level lead/lag controller and optimal parameters Yang et al., (2005). The design problem is transformed into optimization problem with constraints and two different eigenvalues based objective functions. Eigenvalue analysis and nonlinear simulation results show the effectiveness and robustness of the proposed design under different disturbances and loading conditions.

The structure of the paper is as follows: Section II describes a brief overview of natural inspired virtual bees algorithm VBA. The design of the proposed hierarchical VBA based TCSC controller in selection of appropriate structure and optimal parameters are discussed in section III. In section IV, the test system model of multi-machines power is described, together with brief description of the analysis, simulation tools and results of the proposed TCSC controller design. Finally, section V gives the conclusion

**Virtual Bees Algorithm:**

**A. Overview:**

Virtual Bees Algorithm is also a type of Swarm Intelligent methods inspired by the natural foraging behavior of honey bees to find the optimal solution. The VBA is simpler than other nature inspired algorithms like PSO etc. due to less parameter setting and simple in implementation. It is based on social insects like bees and begins to show its power and effectiveness in many applications. A swarm is a group of mobile agents such as bees that are liable to interact or communicate in a direct or indirect manner in their local environment. For example, when a bee finds a food source and successfully brings some nectar back to the hive, it communicates by performing the so-called ‘waggle dance’ so as to recruit more other bees to go to the food source. The neighboring bees seem to learn the distance and direction from the dance. As more and more bees forage the same source, it becomes the favorite path. The VBA scheme starts with a troop of virtual bees, each bee randomly wonders in the n-dimensional search space

VBA has the following advantages over other search algorithms

- **VBA** is a population based search algorithm so it is less susceptible in getting trapped on local minima.
- **VBA** is based on objective function information to search the parameters in the problem space so it can also deal non-differential multi-objective functions.
- **VBA** can search complicated and uncertain area and, therefore, it is more flexible and robust than conventional methods, because, it is a type of stochastic optimization algorithm based on probabilistic transition rules.
- **VBA** is more efficient than GA and other heuristic algorithms, due to parallelism of multiple independent bees.
- **VBA** is simple in implementation as compared to other natural inspired algorithms like PSO due to less parameter setting.

**B. VBA as Optimization Algorithm:**

The elements of the VBA are stated briefly as follows:

**Position S(t):**

It is an individual solution called virtual bee represented by a k-dimensional real-valued vector, where k is the number of optimized parameters. At time t, the ith bee can be described as
\[ S_i^j(t) = [s_i^j(t), s_i^2(t), s_i^3(t), ..., s_i^k(t)] \] where \( s_i^j(t) \) is the value of \( j \text{th} \) parameter in \( k \) dimensions search space i.e. the \( j \text{th} \) parameter of \( i \text{th} \) bee.

No of Virtual Bees (\( n \)):
It is the size of virtual bees population in time \( t \) i.e., and \( S(t) = [S_1(t) , S_2(t) , ..., S_n(t)] \) \( S_i(t) \) is the position vector of \( i \text{th} \) virtual bee among \( n \) virtual bees.

Time Steps:
It is the number of iterations for which the objective function is to be optimized or the objective function reaches its optimized value which is the stopping criteria.

Randomness Amplitude of fly Bees (\( \alpha \)):
It is the constant value specified for the randomness in order to avoid the convergence at local minima used in population updating i.e., \( \alpha = \alpha^\ast (\text{Rand}(i) - 0.5) \)

Speed of Convergence (\( \beta \)):
It is also a constant value specified for the fast convergence towards the best position among all virtual bees of the population.

Best Position \( S_{\text{best}} \):
The position of virtual bee for which the objective function value is minimum among all others virtual bees of the population.

The parameter values used in this study are given in Table. 1.

The main steps of the virtual bees' algorithm for function optimizations are described as:

1) Generation of Initial Position of Scout Bees:
An initial random position of \( n \) scout bees is generated, at counter \( t=0 \) i.e., \( S_i(0), i = 0, 1, 2, ..., n \) where \( S_i(0) = [s_i^1(0), s_i^2(0), s_i^3(0), ..., s_i^k(0)] \) is a randomly generated value of \( j \text{th} \) optimized parameter in \( k \) set of parameters search space \([s_{\text{min}}^j, s_{\text{max}}^j] \) of initial population of virtual bees.

2) Encoding of the Objective/ Optimization Functions:
Each bee of initial population is evaluated through objective function. The minimum value of the objective function is evaluated as \( J_{\text{min}} = \min(J) \) and the best parameter values are associated with the minimum value of the objective function i.e., \( S_{\text{best}} = S(J = J_{\text{min}}) \) and \( S_{\text{best}} = [s_{\text{best}}^1, s_{\text{best}}^2, ..., s_{\text{best}}^k] \) is the row matrix of the all \( k \) parameter best values.

3) Criteria for Communication:
The minimum objective function value among the virtual bees is selected as the criteria for communicating the direction and distance with other virtual bees.

4) Marching or Updating the Population:
While stopping criteria not met the counter is updated as \( t=t+1 \) and all bees are updated as

\[
S_i(t+1) = S_i(t) + S_{\text{best}} + S_{\text{rand}}
\]
After certain time of evolution, the highest modes in the number of virtual bees or intensity/frequency of visiting bees correspond to the best estimates i.e., . \( J = \text{max}(J,t=0,1,\ldots,\text{time steps}) \)

(6) Optimized Parameters:

The parameters of the global minimum objective function value are the optimal parameters. In VBA, each bee moves in the search space with respect to its initial position, previous best position and a random position as shown in Fig. 1. The balance between these components determines the performance of a VBA algorithm.

![Fig. 1: Concept of modification of searching position by VBA](image)

### III. Hierarchical VBA based TCSC controller design:

#### A. Power System Model:

The complete nonlinear dynamic model of power system is given in the Appendix. In the design of TCSC, the linearized incremental model of power system around an equilibrium points can be described in state space form of \( n \) state variables, \( p \) TCSC devices and \( q \) outputs as follows:

\[
\begin{align*}
\dot{\Delta \mathbf{X}} &= \mathbf{A} \Delta \mathbf{X} + \mathbf{B} \Delta \mathbf{U}_{\text{TCSC}} \\
\Delta \mathbf{Y} &= \mathbf{C} \Delta \mathbf{X} + \mathbf{D} \Delta \mathbf{U}_{\text{TCSC}}
\end{align*}
\]

(3) (4)

Where \( \Delta \mathbf{X} \) is the state vector and \( \Delta \mathbf{X} = [\Delta \delta, \Delta \omega, \Delta E_q, \Delta E_a, \Delta E_q^*, \Delta E_a^*, \Delta B_{\text{TCSC}}] \). \( \mathbf{A} \) is the System real constant matrix of size \( n \times n \), \( \mathbf{B} \) is the Control real constant matrix of size \( n \times p \), \( \mathbf{C} \) is the Output real constant matrix and of size \( q \times n \), \( \mathbf{D} \) is the feed forward real constant matrix of size \( q \times p \), \( \Delta \mathbf{Y} \) is the output signal of the controller, \( \Delta \mathbf{U}_{\text{TCSC}} \) is the input signal of TCSC controller which will provide supplementary damping by moving modes to the left which can be described as

\[
\Delta \mathbf{U}_{\text{TCSC}} = K_{\text{TCSC}} \Delta \mathbf{Y}
\]

(5)

Here \( K_{\text{TCSC}} \) is the transfer function given as

#### B. Structure of TCSC damping Controller:

The structure of TCSC based damping controller, to modulate the susceptance offered by the TCSC is...

hierarchically selected. The input and output signals of the proposed controller is the bus voltage and TCSC susceptance respectively.

$$\Delta U_{TCSC} = K_T \left( \frac{\varepsilon T_o}{1 + T_o} \right) \prod_{i=1,2,3} \left( \frac{1 + \varepsilon T_i}{1 + \varepsilon T_j} \right) \Delta Y$$

(6)

The structure consists of gain block with gain $K_{v}$, a signal washout block and multi-stage phase compensation blocks. The signal washout block serves as high pass filter, with time constant $T_w$ high enough to allow signals associated with oscillation in input signal to pass unchanged. The multi-stage phase compensation blocks and their respective parameters values are being hierarchically selected through optimization algorithm. The damping controller model in state space form can be described as

$$\Delta \dot{X}_k = A_k \Delta X_k + B_k K_{TCSC} \Delta Y$$

$$\Delta Y = C_k \Delta X_k$$

(7) (8)

Where $D=0$ in eqn. 8. Combining Equations 7 and 8 a closed loop system given as

$$\Delta \dot{X}_c = (A_k + B_k K_{TCSC} C_k') \Delta X_c$$

(9)

Where $\Delta X_c = [\Delta X \ \Delta X_q]$ and $A_k + B_k K_{TCSC} C_k = A_c$

Fig. 2: Block diagram of H-VBA based TCSC closed loop controller

C. Objective Function:

In order to pull the critical eigenvalues to left hand side i.e., inside the D shaped (least damping ratio) as well as to restrict the non-critical eigenvalues on the left side. While there is coupling between critical and non-critical eigenvalues, i.e., by moving the critical eigenvalues to the left the non-critical eigenvalues will also move toward the right. So it is to incorporate both eigenvalues in designing the TCSC controller to minimize the power system oscillations. By considering the above specifications the objective function is defined as

$$\Psi(\sigma) = [\Psi_1(\sigma) + \Psi_2(\sigma)]$$

(10)

It is the design objective to be minimized,

where $\sigma_j = [\sigma_{1j}, \sigma_{2j}, ..., \sigma_{mj}, \sigma_{1j}, \sigma_{2j}, ..., \sigma_{nj}, \sigma_{2j}, ..., \sigma_{nj}]$
\[ \psi_1(\sigma) = \sum_{i=1}^{l} \sum_{j=1}^{n} (\sigma_j - \sigma_k^i)^2, \quad \psi_2(\sigma) = \sum_{i=1}^{l} \sum_{j=1}^{n} (\sigma_j - \sigma_k^n)^2 \quad \forall \left[ \sigma_j^i \geq \sigma_k^i, \quad \sigma_j^i \geq \sigma_k^n \right] \]

\(i\) denotes the operating condition, \(j\) denotes the index for critical and non-critical oscillatory modes, \(l\) is the total number of operating points considered in the design process, \(m\) is the total number of critical eigenvalues and \(n\) is the total number of non-critical oscillatory modes. \(\sigma_j^i\) denotes the real part of \(j\)th eigenvalue at the \(i\)th operating point, \(\sigma_k^i\) denotes the real part of critical eigenvalues for \(i\)th operating point, while the \(\sigma_k^i\) denotes the threshold value of real part of non-critical modes eigenvalues.

The above stated design problem is solved by the optimization algorithm as:

\[ \downarrow \min_{\Omega \in \mathbb{R}} \psi(\sigma) \]  

(11)

Where \(\Omega\) defines the set of free variables.

Subject to:

\[ 0 < \frac{K_{mk}^i}{T_i} < K_{mk}^i \leq K_{mk} \]


<table>
<thead>
<tr>
<th>Parameter</th>
<th>Min</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>(T_{ij,1,3,7})</td>
<td>0.1</td>
<td>1</td>
</tr>
<tr>
<td>(T_{ij,2,4,8})</td>
<td>0.07</td>
<td>0.15</td>
</tr>
<tr>
<td>(K_{ij})</td>
<td>1</td>
<td>100</td>
</tr>
</tbody>
</table>

The supplementary damping control strategy selects multi-stage lead-lag structure and also tunes the parameters of each stage. A hierarchical VBA is used for selecting the structure and the optimal parameters of controller.

**D. H-VBA Evolution**

The hierarchical swarm is the population of bees containing parametric bees as well as control bees. Control bees select multiple stages in a hierarchical manner. The selection of the particular group of parametric bees is being done through the value of the respective control bee, i.e., multiple groups of parametric bees are governed by their respective control bees. The control bee of value one activates the associated parametric bees while deactivates the respective block on zero value in the multi-stage structure. The HVBA can simultaneously optimize the structure as well as the parameters of the multi-stage lead-lag supplementary damping controller for robust damping controller design as shown in Fig. 2. In this design approach, three operating points are selected, one is nominal case and the other two are extreme loading conditions, which represent different power flow directions along the transmission line i.e., OP-2 is opposite to OP-1 and OP-3 in direction of power flow. A linearised system model is used for each of the three operating points. Then, the eigenvalues of each closed-loop system at each operating point are computed and the objective function is evaluated.

**RESULTS AND DISCUSSIONS**

**Test system:**

The two area four machine system is used in this study as shown in Fig. 4. The system consists of two identical areas. Each area includes two 900 MVA with fast acting exciters. Two generators \(G_1\) and \(G_2\) are located in area 1 while area 2 consists of \(G_3\) and \(G_4\). According to modal analysis the system is stable, but
the inter-area mode has a damping ratio less than the permissible value of 0.005. The TCSC is inserted between busses 101 and 102 providing a line of 40% compensation at steady state. The TCSC gain ($K_{TCSC}$) is 1 and time constant ($T_{TCSC}$) is 0.005 sec. $B_{max}$ and $B_{min}$ are set to ±3 (p.u) on the system base, which is equivalent to ±10% compensation. The input signal to TCSC damping control systems is chosen as line voltage. The operating points are given in Table III.

**B. Optimization Results:**

The results obtained from the proposed algorithm shows that single square block is selected based on the control bees values. The parametric bees values associated with selected block are final optimal controller parameters given in Table IV. The convergence of objective functions is shown in Fig. 5. It can be noted that the optimization process reaches the optimal solution in about 80 iterations, after which the objective function value became steady over the remaining search process. The root loci of HVBA based design is given in Fig. 6.

![Fig. 3: Flowchart of H-VBA](image)

![Fig. 4: Test power system](image)
Fig. 5: Convergence of objective function using H-VBA

Table 3: Operating points

<table>
<thead>
<tr>
<th>Operating Points</th>
<th>Bus no.</th>
<th>P</th>
<th>Q</th>
<th>Tie line power flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>OP-1</td>
<td>4</td>
<td>11.76</td>
<td>1.00</td>
<td>1.865</td>
</tr>
<tr>
<td></td>
<td>14</td>
<td>15.17</td>
<td>1.00</td>
<td></td>
</tr>
<tr>
<td>OP-2</td>
<td>4</td>
<td>16.76</td>
<td>1.00</td>
<td>-3.069</td>
</tr>
<tr>
<td></td>
<td>14</td>
<td>10.17</td>
<td>1.00</td>
<td></td>
</tr>
<tr>
<td>OP-3</td>
<td>4</td>
<td>9.76</td>
<td>1.00</td>
<td>4.010</td>
</tr>
<tr>
<td></td>
<td>14</td>
<td>17.17</td>
<td>1.00</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 6: Root loci of HVBA based design

C. Eigenvalue Analysis and Simulation Results:

The design objective of moving all eigenvalues (critical and non-critical) to the left of least of damping ratio line is achieved. The eigenvalues of the open loop system at three operating points are shown in Fig. 7 and the closed loop eigenvalues are given in Fig. 8. The least damped eigenvalue is in the range of 0.6-0.7 Hz which belongs to inter-area mode. The other eigenvalues in 1 Hz range are electromechanical ones in each area. It is observed that the HVBA based TCSC controller design has successfully damped the critical modes. The eigenvalues of both without TCSC controller and with H-VBA based TCSC controller are given in Tables V-VII. By comparing the least damped electromechanical modes for three operating points i.e., improved from 0.0116 to almost 0.052 for OP-1 while for OP-2 from 0.06244 to 0.1588 and for OP-3, the damping ratios are improved from 0.0093 to 0.0636. The TCSC step responses for no damping control, conventional control and VBA-based control are shown in Figs. 9-11 for three operating points. It can be seen that the TCSC controlled
by the proposed damping control strategies exhibits lesser overshoot and lesser settling time. The proposed control systems present excellent performance for all the three operating conditions. The effectiveness of the proposed HVBA based TCSC controller is shown through non-linear simulations over a range of operating condition. At time $t = 0.1s$, a three phase line to ground fault is applied on line 13-15. The fault is cleared at time $t = 0.2s$. The inter-plant machine speed deviations of machine-2 relative to machine-1, for three operating points are given in Figs. 12-14. While the relative inter-area machines speed deviations of machine-3 with respect to machine 1 for three operating points are shown in Figs. 15-17. The HVBA based TCSC damping controller has shown comparatively better performance for all three operating points. Although the conventional control has better performed for only the designed operating point i.e. OP-1, but it hasn’t performed well for other operating condition. So it is proved that HVBA based TCSC damping control system has less settling time and provides superior damping as shown in Figs. 18-20. The susceptance of TCSC is given in Fig. 21-23. Thus HVBA based TCSC controller has shown robust performance under varying conditions described by non-linear simulations.

### Table 4: Open and closed loop eigenvalues of OP-1

<table>
<thead>
<tr>
<th>Open-loop eigenvalues</th>
<th>H-VBA based</th>
<th>Closed loop eigenvalues</th>
<th>H-VBA based</th>
</tr>
</thead>
<tbody>
<tr>
<td>-0.5047 ± 6.8669i</td>
<td>0.0733</td>
<td>-0.5095 ± 7.0013i</td>
<td>0.0726</td>
</tr>
<tr>
<td>-0.4870 ± 6.9207i</td>
<td>0.0702</td>
<td>-0.5058 ± 6.8384i</td>
<td>0.0738</td>
</tr>
<tr>
<td>-0.0396 ± 3.3875i</td>
<td>0.0116</td>
<td>-0.1869 ± 3.5920i</td>
<td>0.0520</td>
</tr>
<tr>
<td>-0.6155 ± 2.0957i</td>
<td>0.2818</td>
<td>-0.4859 ± 2.0402i</td>
<td>0.2317</td>
</tr>
</tbody>
</table>

### Table 5: Open and closed loop eigenvalues of OP-2

<table>
<thead>
<tr>
<th>Open-loop eigenvalues</th>
<th>H-VBA based</th>
<th>Closed loop eigenvalues</th>
<th>H-VBA based</th>
</tr>
</thead>
<tbody>
<tr>
<td>-0.5439 ± 6.8350i</td>
<td>0.07932</td>
<td>-0.3829 ± 6.9079i</td>
<td>0.0553</td>
</tr>
<tr>
<td>-0.4563 ± 6.9314i</td>
<td>0.06569</td>
<td>-0.6777 ± 6.7373i</td>
<td>0.1001</td>
</tr>
<tr>
<td>-0.1921 ± 3.0703i</td>
<td>0.06244</td>
<td>-0.3085 ± 1.9173i</td>
<td>0.1588</td>
</tr>
<tr>
<td>-0.4134 ± 2.3827i</td>
<td>0.17095</td>
<td>-0.9752 ± 1.8023i</td>
<td>0.4759</td>
</tr>
</tbody>
</table>

### Table 6: Open and closed loop eigenvalues of OP-3

<table>
<thead>
<tr>
<th>Open-loop eigenvalues</th>
<th>H-VBA based</th>
<th>Closed loop eigenvalues</th>
<th>H-VBA based</th>
</tr>
</thead>
<tbody>
<tr>
<td>-0.5186 ± 6.8821i</td>
<td>0.07514</td>
<td>-0.5336 ± 6.9980i</td>
<td>0.0760</td>
</tr>
<tr>
<td>-0.5114 ± 6.8404i</td>
<td>0.07455</td>
<td>-0.5145 ± 6.8152i</td>
<td>0.0753</td>
</tr>
<tr>
<td>-0.0286 ± 3.0860i</td>
<td>0.00926</td>
<td>-0.2695 ± 4.2287i</td>
<td>0.0636</td>
</tr>
<tr>
<td>-0.6109 ± 2.0368i</td>
<td>0.28729</td>
<td>-0.9188 ± 1.9045i</td>
<td>0.4345</td>
</tr>
</tbody>
</table>

Fig. 7: Open loop eigenvalues
Fig. 8: H-VBA based closed loop eigenvalue

Fig. 9: Step Response for OP-1

Fig. 10: Step Response plots for OP-2
Fig. 11: Step Response plots for OP-3

Fig. 12: Machine speed deviation for OP-1

Fig. 13: Machine speed deviation for OP-2
Fig. 14: Machine speed deviation for OP-3

Fig. 15: Inter area speed deviation for OP-1

Fig. 16: Inter area speed deviation for OP-2
Fig. 17: Inter area speed deviation for OP-3

Fig. 18: Fault bus voltage for OP-1

Fig. 19: Fault bus voltage for OP-2
Fig. 20: Fault bus voltage for OP-3

Fig. 21: Susceptance at OP-1

Fig. 22: Susceptance at OP-2
Conclusion:

A novel hierarchical VBA is implemented in designing supplementary damping controller for TCSC in this paper. The structure of the controller and the respective parameters is hierarchically selected from multi stage lead/lag structure through optimization process. The design problem is formulated as an optimization problem and then HVBA algorithm as been used to optimize the problem for different operating conditions. The proposed design strategy is validated through eigenvalue analysis and time domain simulations for different loading conditions. Furthermore, nonlinear simulation results are compared with no damping control and conventional control. The HVBA based damping control system for TCSC has shown more improved performance than the conventional damping control system in oscillation damping, lesser overshoot, lesser settling time and lesser steady state error for various operating conditions.

Appendix A:

Dynamic Model of Power System:

Power system can be modeled as dynamic devices with their controllers and FACTS devices i.e. TCSC, so each dynamic device is treated as a subsystem coupled with transmission system. The complete model of each subsystem is being illustrated. The generator is represented by fifth order model consist of electromechanical swing equation of the \( i \)th generator given as

\[
\frac{d\delta_i}{dt} = \omega_1 - \omega_0
\]  
\[
\frac{d\omega_1}{dt} = \frac{1}{M} (P\omega_1 + K_d\omega_1 - Pe_i)
\]  

\( Pe_i \) is the electrical output of \( i \)th generator

\[
Pe_i = E_q^2\alpha_q + \sum_{j=1,j\neq i}^{n} E_j E_j \chi_j \cos(\beta_j - \delta_j)
\]  

And the dynamic behaviour of \( i \)th generator can be described as set of differential equations which used to deal the changes in rotor flux linkages due to changes in synchronous generators or network operations:
Dynamic model of TCSC:

TCSC compensate the impedance of the line and is installed in series with ac transmission system to provide smooth control of series reactance. The $i$th dynamic model with supplementary damping control loop can be expressed by the following differential equations

\[
\frac{dB^i_q}{dt} = \frac{1}{T_{qc}} (-B^i_q + (x^i_q - x^q) i^q) \quad (A-4)
\]

\[
\frac{dB^i_a}{dt} = \frac{1}{T_{dc}} (E^i_a - E^i_q + (x^i_a - x^q) i^a) \quad (A-5)
\]

\[
\frac{d\Delta E^a_{gs}}{dt} = \frac{1}{T_A} \left[ K_A (V^g_a - V^g) - \Delta E^a_{gs} \right] \quad (A-6)
\]

\[
\frac{dB^a_q}{dt} = \frac{1}{T_{qc}} (E^a_q + (x^a_q - x^q) i^q - B^a_q) \quad (A-7)
\]

\[
\frac{dB^a_a}{dt} = \frac{1}{T_{dc}} (E^a_a + (x^a_a - x^a) i^a - B^a_a) \quad (A-8)
\]

\[
\frac{d}{dt} (\nu_1(t)) = \frac{d}{dt} (K_T y) - \frac{1}{T_o} \nu_1(t) \quad (A-9)
\]

\[
\frac{d}{dt} (\nu_2) = \frac{1}{T_2} \left[ T_1 \frac{d}{dt} (K_T y) + \left( 1 - \frac{T_1}{T_o} \right) \nu_1 - \nu_2 \right] \quad (A-10)
\]

\[
\frac{d}{dt} (u_T) = \frac{1}{T_4} \left[ \frac{T_2}{T_3} (T_3 - T_2) \nu_2 + \frac{T_3}{T_2} (T_3 - T_1) \nu_1 + \frac{T_3}{T_2} \frac{d}{dt} (K_T y) - u_T \right] \quad (A-11)
\]

\[
\frac{d}{dt} (B_T) = \frac{1}{T_{TSC}} \left[ K_{TSC} \left( B_T - \Delta u_T \right) - B_T \right] \quad (A-12)
\]

REFERENCES


Lin, Y.F., Z. Xu, Y. Huang, 2005. Power Oscillation Damping Controller Design for TCSC Based on The Test Signal Method, Project Supported by National Science Foundation of China, IEEE.


