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Virtual Bees Algorithm Based Design of Damping Control System for TCSC

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Abstract: Due to the deregulation in the electrical market, difficulties in building new transmission lines, and the continuous increase in power demand the maintenance of power system stability becomes difficult and a very challenging problem. In large, interconnected power system damping is often reduced, leading to lightly damped electromechanical modes of low frequency oscillations (0.1~0.6Hz). In this paper, supplementary damping control system design for Thyristor controlled series compensator (TCSC) based on natural inspired Virtual Bees Algorithm (VBA) is presented. The controller design problem is formulated as an optimization problem and VBA is employed to search optimal set of controller parameters by minimizing the eigenvalues based multi-objective function. The linear and non-linear simulation results of various small and large disturbances show the effectiveness and robustness of the proposed controller design and its ability to provide efficient damping of low frequency oscillations.

Key words: Inter-area oscillations, Virtual Bees Algorithm, Power system stability, TCSC, Multi-machine power system.

INTRODUCTION

Modern power systems may be thought of large interconnected non-linear systems covering large geographic areas. These power systems having a large number of load buses and generators with many lightly damped electromechanical modes of oscillation. If the damping of these modes becomes too small or even positive, it can impose severe constraints on the system's operation. It is thus important to determine the nature of those modes, their stability limits and to control instability due to these modes. The poorly damped low frequency electromechanical oscillations occur due to long weak tie lines and inadequate damping torque in some generators, causing both local-mode oscillations (1 Hz to 2 Hz) and inter-area oscillations (0.1 Hz to 1 Hz) (Sadikovic, R., 2006). The traditional approach employs power system stabilizers (PSS) on generator excitation control systems in order to damp those oscillations. PSSs are effective but they are usually designed for damping local modes and in large power systems they may not provide enough damping for inter-area modes. In large power systems the number of inter-area modes is usually larger than the number of control devices available (Aboul-Ela, M.E., A.A. Salam, 1996). To meet the load and electric market demands, new lines should be added to the system, but due to environmental reasons, the installation of electric power transmission lines must often be restricted. Hence, the utilities are forced to rely on already existing infrastructure instead of building new transmission lines. In order to maximize the efficiency of generation, transmission and distribution of electric power, the transmission networks are often pushed to their physical limits, where outage of lines or other equipments could result in the rapid failure of the entire system.

With such increasing stress on the existing transmission lines the use of Flexible AC Transmission Systems (FACTS) devices becomes an important and effective option. Hence, in order to improve damping of these modes, it is of interest to use FACTS based controllers. Generally, damping of power system oscillations is not the primary reason of placing FACTS devices in the power system, but rather power flow control, transfer capability, enhancing continuous control over the voltage profile and minimizing losses etc (Chow, J., J. Sanchez-Gasca, 2000). However, when installed, supplementary control laws can be applied to existing devices to improve damping as well as satisfy the primary requirements of the device. Implementation of new equipment consisting high power electronics based technologies such as (FACTS) and proper controller design

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can improve the operation and control of power system (Hingorani, N.G., 1991; Pilotto, L.A.S., A. Bianco, 2003) in transmission line-based control strategies. Thyristor controlled series compensator (TCSC) can be utilized to improve the damping of the system for its fast controllability on its impedance as a result the apparent impedance of corresponding transmission line could be changed (Lin, Y.F., Z. Xu, 2005). Therefore, a TCSC can change the power flow of the network. So in order to vary the impedance of the TCSC, power might flow according to the desire.

Various FACTS damping control techniques have been employed to enhance power system dynamic performance. The conventional damping control designs consider a single operating condition of the system e.g., damping torque analysis (Padiyar, K.R. and R.K. Varma, 1991), optimal control theory (Chen, H. and G. Anderson, 1995), linear programming (Pourbeik, P., 1997) and decentralized control (Taranto, G.N. and D.M. Falcao, 1998). The controller is simple, but works often only within a limited operating range. In case of contingencies, changed operating conditions can cause poorly damped or even unstable oscillations since the controller parameters yielding satisfactory damping for one operating condition may no longer provide sufficient damping for others. In order to address this issue, researchers over the years have proposed different approaches for adaptive control structures for PSSs as well as FACTS devices e.g., heuristic search approach like Genetic algorithms, self-tuning controllers (STC) (Hasanovic, A. and A. Felachi, 2002; Magid, A., Y.L., 2003) and model adaptive reference systems (MRAS), tabu search algorithm (Abido, M.A., 1999) and simulated annealing (Abido, M.A., 2002). The primary idea is to overcome the problems that might be encountered by conventionally tuned controllers with the changing of operating conditions. A more sophisticated controller which can maintain good damping over a wide range of operating conditions is, therefore, needed. Another evolutionary computation technique, called particle swarm optimization (PSO) has been applied to the design of PSS by Abido (Abido, M.A., 2001; Abido, M.A., 2002). Recently, it was used to design robust damping control for TCSC (Laiq Khan, Tariq Saeed, 2008). The obtained results proved effective utilization using different measurements for optimal controller design.

A new population-based search algorithm called the Virtual Bees Algorithm (VBA) is recently developed (Yang, X.S., *et al*, 2005). Engineering problems with optimization objectives are often difficult and time consuming and the applications of nature or biological inspired algorithms have been very successful in the last several decades. The algorithm mimics the food foraging behavior of swarms of honey bees. In its basic version, the algorithm performs a kind of neighborhood search combined with random search and can be used for both combinatorial optimization and functional optimization. Biological-derived algorithms can be applicable to a wide variety of optimization problems. For example, the optimization functions can have discrete, continuous or even mixed parameters without any priori assumptions about their continuity and differentiability. Thus, the evolutionary algorithms are particularly suitable for parameter search and optimization problems.

In this paper, a new advanced optimization technique VBA is employed in designing FACTS supplementary damping control system. A conventional lead/lag control structure is tuned via optimization scheme for different operating conditions. In this study, the design problem of TCSC controller to damp low frequency inter area oscillations problem is transformed into an eigen value based multi objective optimization problem. VBA approach is employed to search for the optimal TCSC controller parameters. Objective function is defined in terms of the critical modes and non-critical modes for different loading conditions. The simulation results have been carried out to demonstrate the effectiveness and robustness of the proposed approach to enhance the power system stability.

The paper is organized as: In Section II Power system modeling is discussed, Section III describes the problem formulation and controller structure design, VBA algorithm is presented in Section IV. Section V presents the VBA based TCSC controller design and in Section VI results and discussion about the case study of two-area four-machine power system is given. Time domain simulations are performed to justify the proposed approach. In Section VII the final conclusions are given.

II. Power System Modeling:

The non-linear model of power system is described as a set of differential equations (Ishimaru, M., 2000; Zhang, P., 1999)

$$\dot{x} = f(x, u) \tag{1}$$

The detailed mathematical model of synchronous generators with AVR dynamics and TCSC dynamics model are given in the appendix.

The n-dimensional LTI power system dynamic model linearized at particular operating points can be expressed in the state space form as:

$$\Delta\dot{x} = A_{n\times n}\Delta x + B_{n\times p}\Delta u_{TCSC} \tag{2}$$

$$\Delta y = C_{q\times n}\Delta x + D_{q\times p}\Delta u_{TCSC} \tag{3}$$

Here Δx is the state vector and $\Delta x = [\Delta\delta, \Delta\omega, \Delta E'_q, \Delta E'_d, \Delta E''_q, \Delta E''_d, \Delta E_{fd}, ---, \Delta B_{TCSC}]$, **A** (System), **B** (Control) and C (Output) D (Feed forward) are the real constant matrices. Δy is the bus voltage used as the control signal and Δu_{TCSC} is the input of TCSC controller signal which will provide supplementary damping by moving modes to the left. The feedback compensator can be described as

$$\Delta u_{TCSC} = K\Delta y \tag{4}$$

Where K is the gain matrix of order $p \times q$. The damping controller LTI model in state space form can be described by

$$\Delta\dot{x}_k = A_k\Delta x_k + B_k K\Delta y \tag{5}$$

$$\Delta y = C_k\Delta x_k \tag{6}$$

Where D=0 in eqn. 6. Combining eqns. 5 and 6 a closed loop system given as

$$\Delta\dot{x} = (A_1 + B_1 KC_1)\Delta x \tag{7}$$

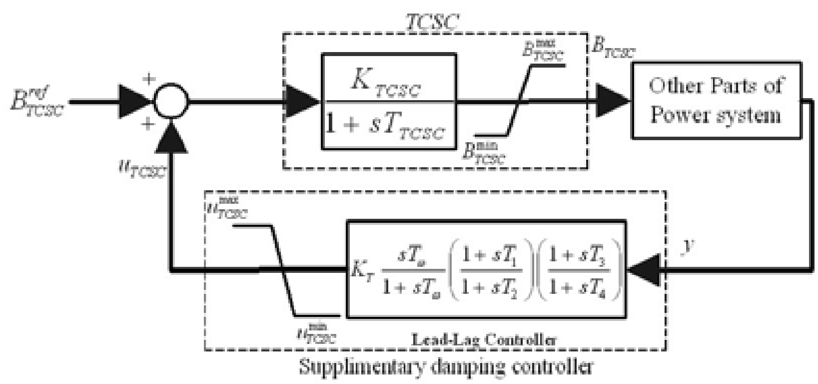

Fig. 1: Block diagram of Control system

III. Problem Formulation and Controller Structure Design:

In this section, a procedure for tuning multiple power system damping controllers over a range of operating conditions is described. For every operating condition a linearized model is obtained. The problem of selecting the parameters of the controllers that would ensure maximum damping performance over the considered set of operating points is solved using VBA optimization procedure with an eigenvalues based performance index. A convent ional lead/lag controller is installed in the feedback loop to generate the TCSC stabilizing signal Δu_{TCSC} as shown in Fig. 1. T_ω value is not critical so it is fixed to unity during the optimization process. y is the input signal to TCSC damping controller, two similar lead/lag compensators are assumed as T_1=T_3 and

$T_2=T_4$. The controller gain K_T and time constants T_1 and T_2 are the damping controller parameters to be tuned for achieving robustness.

$$u_{TCSC} = K_T\left(\frac{sT_\omega}{1+T_\omega}\right)\left(\frac{1+sT_1}{1+sT_2}\right)\left(\frac{1+sT_3}{1+sT_4}\right)y \tag{8}$$

The critical'●' and non-critical'○' modes of oscillation are shown in Fig. 2. In this particular case study, the non-critical eigenvalues are all inside the D-shape area. These eigenvalues are restricted not to move towards the right hand side but are kept inside the specified region by the proposed design scheme. At the same time, the critical eigenvalues are pulled towards the left hand side and are placed inside the D-shape area. But the critical eigenvalues should not be moved towards the left hand side at the cost of moving the non-critical eigenvalues towards the right. Hence, the proposed design scheme takes care of mobility of both the eigenvalues. Due to the coupling between critical and non-critical eigenvalues, the non-critical eigenvalues could not be discarded from the optimization process. As the critical eigenvalues are moved towards the left, the non-critical eigenvalues move towards the right. Therefore, the proposed scheme incorporates both critical and non-critical eigenvalues. The proposed design scheme allows the critical eigenvalues to move towards the left but at the same time does not allow the non-critical eigenvalues to move towards the right.

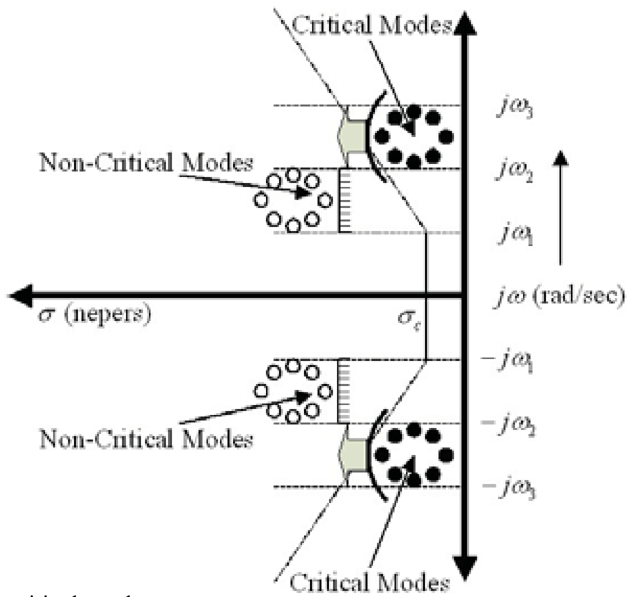

Fig. 2: Critical and non critical modes

A. Objective Function:

It is required to design the TCSC controller in order to minimize the power system oscillations after a disturbance so as to improve the stability. The objective function can be defined as

$$J = \sum_{i=1}^{l}\sum_{j=1}^{m}\left(\sigma_j^i - \sigma_c^i\right)^2 + \sum_{i=1}^{l}\sum_{j=1}^{n}\left(\sigma_j^i - \sigma_{nc}^i\right)^2 \qquad \forall\begin{cases}\sigma_j^i \geq \sigma_{nc}^i, & \omega:[\omega_1\omega_2]\\ \sigma_j^i \geq \sigma_c^i, & \omega:[\omega_2\omega_3]\end{cases} \tag{9}$$

Where 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. σ_j^i denotes the real part of *jth* eigenvalue at the *ith* operating point. σ_c^i denotes the real part of critical eigenvalue for *i*th operating point, while the σ_{nc}^{i} denotes the threshold value of real part of non-critical modes eigenvalues

B. Optimization Problem:

In this study, minimization of the objective function J is used. The constraints are the TCSC controller parameters bounds.

Minimize J

$$T_1^{\min} \leq T_1 \leq T_1^{\max}$$
$$T_2^{\min} \leq T_2 \leq T_2^{\max}$$
$$K^{\min} \leq K \leq K^{\max}$$

The proposed design is optimized through Virtual Bees algorithm to search the optimal set of TCSC controller parameters

IV. Virtual Bees Algorithm:

The Virtual Bees Algorithm is an optimization algorithm inspired by the natural foraging behavior of honey bees to find the optimal solution. Natural inspired algorithms have some similarity with genetic algorithms, but it has multi agents that work independently and thus it is much more efficient than the genetic algorithms due to the parallelism of the multiple independent bees. The VBA is simpler than other natural inspired algorithms like PSO etc; due to less parameters setting. VBA based on social insects and swarm intelligence begins to show their 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 neighbouring bees seem to learn the distance and direction from the dance (Von Frisch, K., 1967; Gordon, D.M., 1996). 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. The main steps of the virtual bee algorithm for function optimizations are: (1) Creating a population of virtual bees, each bee is associated with a memory bank with several strings (2) encoding of the objectives/ optimization functions and converting into the virtual food (3) defining a criterion for communicating the direction and distance (4) marching or updating a population of individuals to new positions for virtual food searching, marking food and the direction with virtual '*waggle dance'* according to eqn. 10 (5) after certain time of evolution, the highest mode in the number of virtual bees or intensity/ frequency of visiting bees correspond to the best estimates (6) decoding the results to obtain the solution to the problem. The modified position of each bee can be calculated using

$$\begin{aligned} \mathbf{x}_{\mathbf{k}}^{\mathbf{i+1}} &= \mathbf{x}_{\mathbf{k}}^{\mathbf{i}} * (1-\beta) + \mathbf{x}_{\mathbf{best}} * \beta + \alpha * (\mathbf{Rand(i)} - 0.5) \\ \mathbf{y}_{\mathbf{k}}^{\mathbf{i+1}} &= \mathbf{y}_{\mathbf{k}}^{\mathbf{i}} * (1-\beta) + \mathbf{y}_{\mathbf{best}} * \beta + \alpha * (\mathbf{Rand(i)} - 0.5) \end{aligned} \quad (10)$$

Where α and β are two positive constants called randomness amplitude and speed of convergence respectively and $\mathbf{x}_{\mathbf{best}}$ and $\mathbf{y}_{\mathbf{best}}$ are best parameters in *ith* iteration. Rand (i) is a random number in [0 1]. Different values of the VBA parameters are given in Table I. The *ith* bee in the swarm is represented by a k dimensional vector $\boldsymbol{X}_k = (x_1, x_2 ... x_k)$ and also the other coordinate is $\boldsymbol{Y}_k = (y_1, y_2 ... y_k)$. The current position (searching point in the solution space) can be modified by

$$s_k^{i+1} = s_k^i + s_{best} + s_{rand} \quad (11)$$

Where $s_k^{i+1} = (x_k^{i+1}, y_k^{i+1}), s_k^i = (x_k^i, y_k^i), s_{best} = (x_{best}, y_{best})$

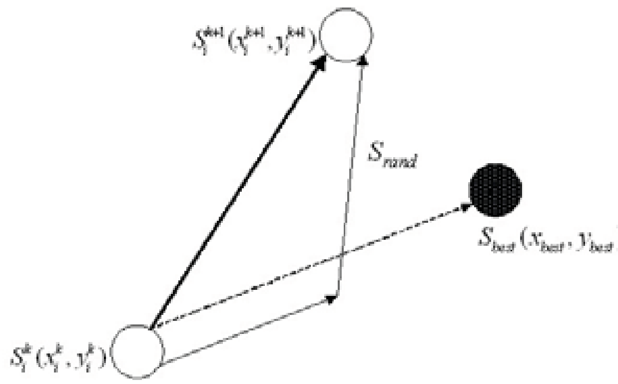

Fig. 3: Concept of modification of searching position by VBA

In VBA, each particle moves in the search space according to its own previous best solution as shown in Fig. 3. The balance between these parts determines the performance of a VBA algorithm. In the above equations, superscripts denote the iteration. The general flowchart of VBA is shown in Fig. 4

V. VBA based TCSC Controller Design:

The proposed design approach is divided in two phases. In the first phase, the parameters T_1, T_2 and K_T of TCSC controller are formed by optimizing eigenvalue based objective function using VBA. Then in the next phase the non linear simulations of multi machines power system results have been carried out to assess the robustness and effectiveness of the proposed controller design under different disturbances, loading conditions and system configurations.

The search procedure of VBA is as under:

1. Initialize population with random solutions of three controller's parameters and the boundaries of the parameters are specified.
2. Every initial bee of the Population is being tested for closed loop system stability, if it satisfies the stability criteria.
3. Then the objective function value of each bee of the population is evaluated.
4. The minimum objective function value among the bees is selected for waggle dance to communicate with others.
5. Evolution of virtual bees with time is according to the set of eqns. 10 and these are set according to the boundaries given in Table II.
6. While (Stopping criteria not met) March/ Update all virtual bees to new positions.
7. If maximum iterations are achieved then go to 8 otherwise go to 2.
8. The parameters of repeated minimum objective function that are generated are the optimal controller parameters

Table I: Parameters of VBA

Parameter	Value
Timesteps (no of iterations)	100
n (no of bees)	20
α (randomness amplitude of fly bees)	0.2
β (Speed of convergence) 0 » 1)=(slow » fast)	0.1

Table II: Boundaries of the parameters to be tuned

Parameter	Max	Min
T_1	0.1	1
T_2	0.07	0.15
K	1	100

The VBA based controller design approach is given in flow chart as in Fig. 5.

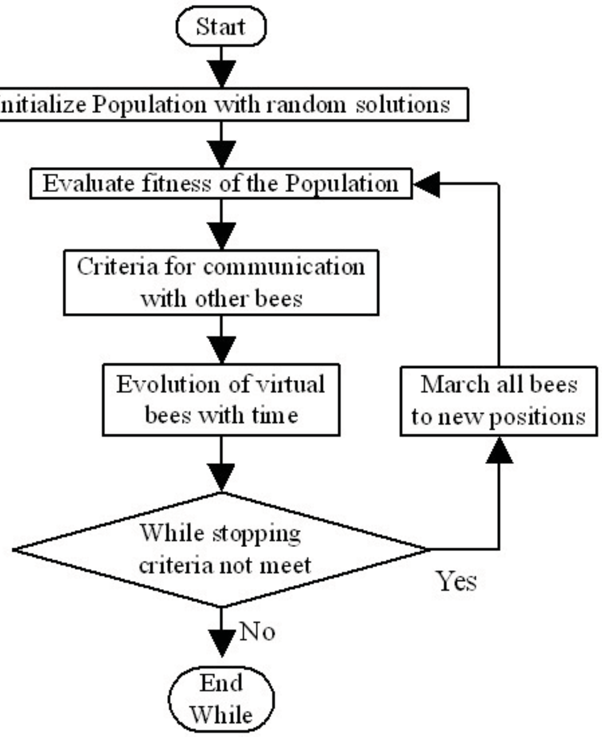

Fig. 4: Flowchart of VBA

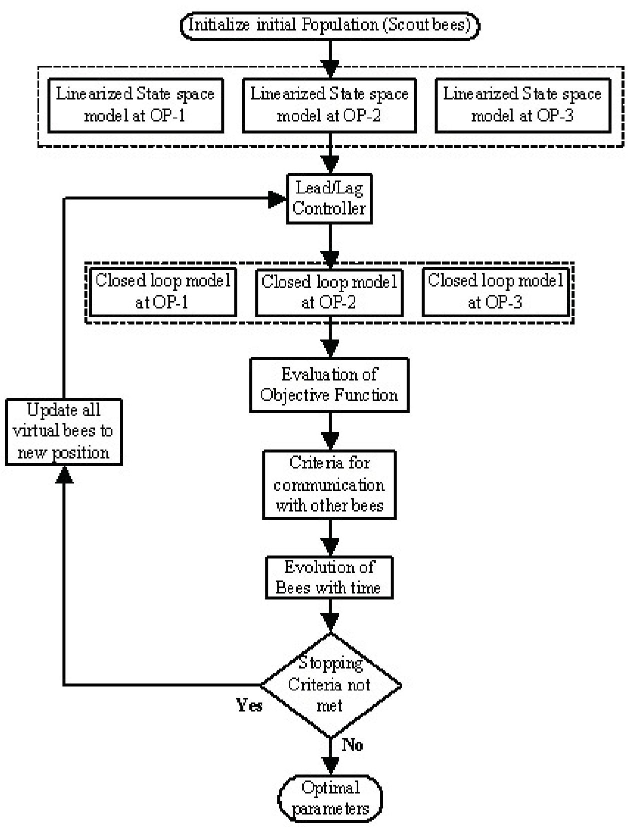

Fig. 5: Flowchart of design methodology

RESULTS AND DISCUSSION

In order to show the advantages of designing TCSC controller dynamics and tuning of its parameters in this study, a case study of four-generator two-area interconnected power system is taken.

A. Case Study:

The system is of two identical areas of 900MVA with fast acting exciters. The bus voltage magnitude is selected for the input signal to the TCSC damping controller. The test system consists of four synchronous machines (G1, G2, G3 and G4) equipped with fast acting exciters of which two generators G1 and G2 are located in one area while other two G3 and G4 are located in the second area as shown in Fig. 6. TCSC is inserted between bus 101 and 102, providing a line of 40 percent compensation at steady-state. The TCSC gain (K_{TCSC}) is 1 and time constant (T_{TCSC}) is 0.005 s, B_{max} and B_{min} are set to ±3 (p.u) on the system base, which is equivalent to ±10 compensation. In the proposed design approach, three operating points are selected one is nominal case and 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 linearized system model is used for each three operating points. Then, the eigenvalues of each closed-loop system at each operating point are computed and the objective function is evaluated. The operating points are given in Table III.

Table III: Operating points

Operating Points	Bus no	P	Q	Tie line power flow
OP-1	4	1	1	1.865
	14	1	1	
OP-2	4	1	1	-3.069
	14	1	1	
OP-3	4	9	1	4.01
	14	1	1	

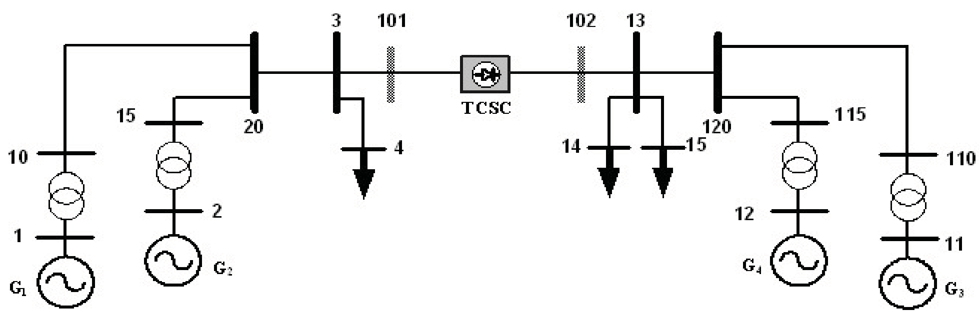

Fig. 6: Test power system

B. Eigenvalue Analysis:

The system eigenvalues without and with TCSC controller for the three operating points considered, are summarized in Tables IV, V and VI. The eigenvalues of the open loop system at three operating points are shown in Fig. 7. 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. The closed loop eigenvalues of the system at three operating points are shown in Fig. 8 which shows that the critical modes have been successfully damped by the designed VBA-based TCSC controller. For OP-1, the least damped electromechanical mode has its damping ratio increased from 0.0117 to almost 0.053 while for OP-3, the damping ratio has increased from 0.0093 to 0.0705.

Table IV: Open and closed loop eigenvalues of OP-1

Open-loop eigenvalues	ξ (open-loop)	Closed loop eigenvalues	ξ (closed-loop)
-0.5047 ± 6.8669i	0.0733	-0.5111 ± 6.9991i	0.0728
-0.4870 ± 6.9207i	0.0702	-0.5052 ± 6.8386i	0.0737
-0.0396 ± 3.3875i	0.0116	-0.1884 ± 3.5774i	0.0526
-0.6155 ± 2.0957i	0.2818	-0.4905 ± 2.0481i	0.2329

Table V: Open and closed loop eigenvalues of OP-2

Open-loop eigenvalues	ξ (open-loop)	Closed loop eigenvalues	ξ (closed loop)
-0.5439 ± 6.8350i	0.0793	-0.3857 ± 6.9082i	0.0557
-0.4563 ± 6.9314i	0.0656	-0.6737 ± 6.7472i	0.0994
-0.1921 ± 3.0703i	0.0624	-0.2974 ± 1.9312i	0.1522
-0.4134 ± 2.3827i	0.1709	-0.9757 ± 1.8023i	0.4761

Table VI: Open and closed loop eigenvalues of OP-3

Open-loop eigenvalues	ξ (open-loop)	Closed loop eigenvalues	ξ (closed loop)
-0.5186 ± 6.8821i	0.0751	-0.5354 ± 6.9975i	0.0763
-0.5114 ± 6.8404i	0.0745	-0.5143 ± 6.8152i	0.0753
-0.0286 ± 3.0860i	0.0092	-0.2984 ± 4.2212i	0.0705
-0.6109 ± 2.0368i	0.2872	-0.9171 ± 1.9089i	0.4331

C. Simulation Results:

The optimized controller parameter values of the VBA-based TCSC controller are given in Table VII and the minimum damping ratios achieved for the three operating points with VBA-TCSC are shown in Table VIII.

Table VII: Optimal parameters values

VBA-based TCSC Controller parameters	T_1	T_2	K
Values	0.4120	0.0700	79.67

Table VIII: Minimum damping ratios values for three operating points

Operating Points	ξ
OP-1	0
OP-2	0
OP-3	0

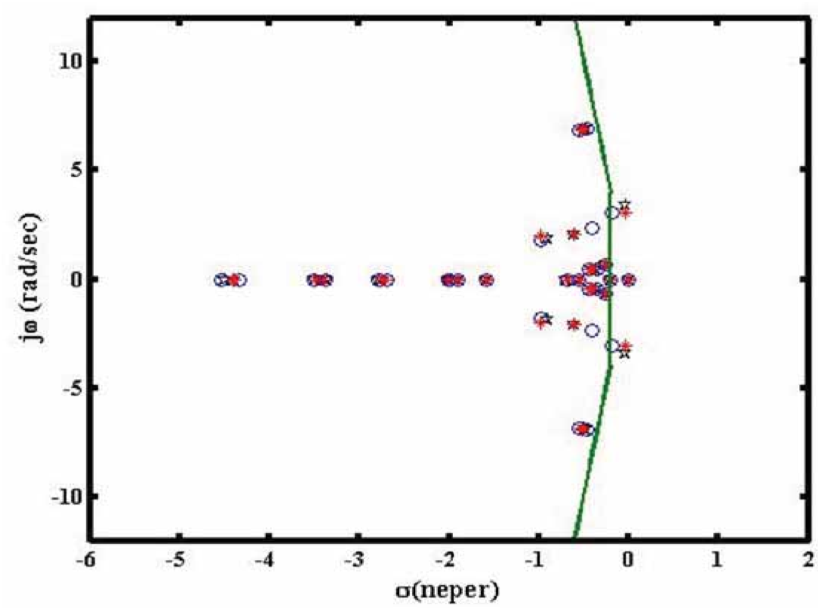

Fig. 7: Open loop eigenvalues for three operating points

The objective function convergence is shown in Fig. 9. It can be noted that the process reaches the optimum solution in about 30 iterations, after which the objective function reaches a value that remains steady over the remaining search process. Time domain simulations were performed to confirm the results of the control system design based on linearized power system. The TCSC step responses for no damping control, conventional control and VBA-based control are shown in Figs. 10-12 for OP-1, OP-2 and OP-3 respectively. It can be seen that the TCSC controlled by the proposed damping control strategy exhibits lesser overshoot and lesser settling time. The proposed control presents excellent performance for all the three operating conditions.

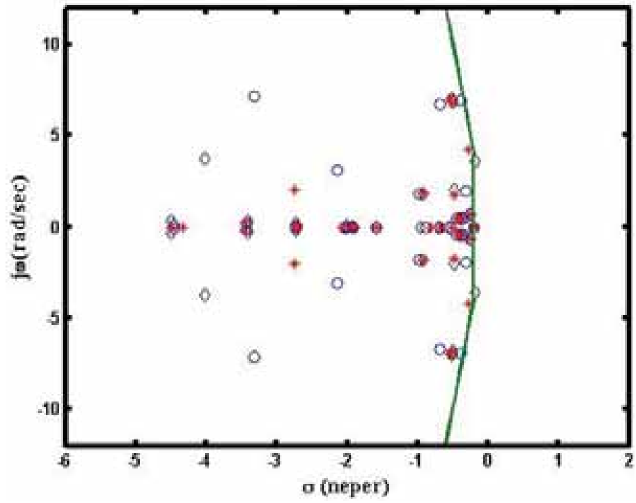

Fig. 8: Closed loop eigenvalues for three operating points

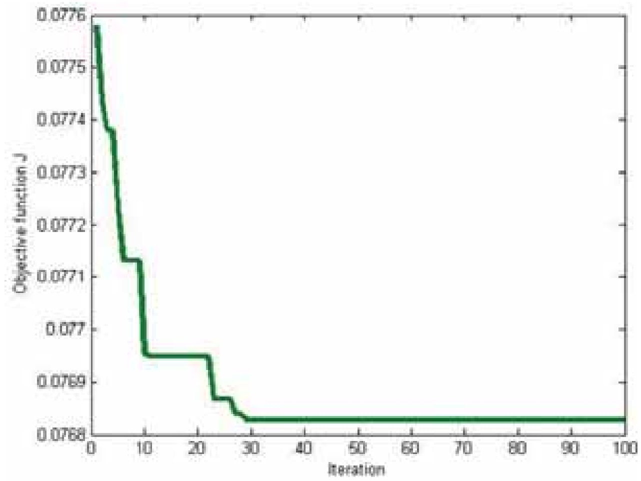

Fig. 9: Convergence of objective function

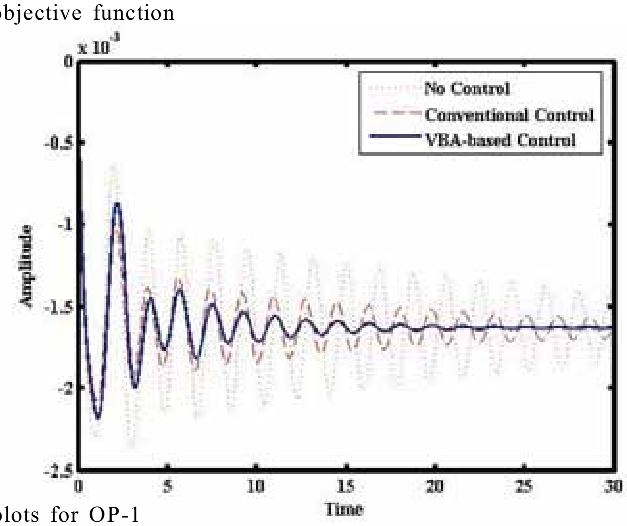

Fig. 10: Step Response plots for OP-1

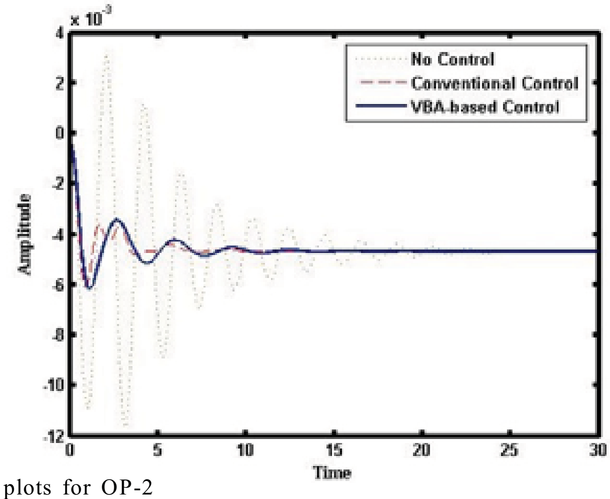

Fig. 11: Step Response plots for OP-2

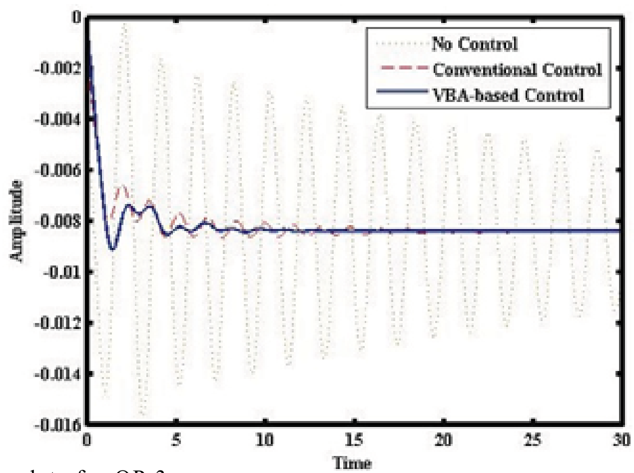

Fig. 12: Step Response plots for OP-3

D. Non-linear Time-domain Simulations:

The effectiveness of the proposed VBA-TCSC controller is shown through non-linear simulations over a range of operating conditions. At time t = 0.1 s, a three phase line to ground fault is applied on line 13-15. The fault is cleared at time t = 0.2 s. Figs. 13-15 show relative inter-plant machine speed deviations of machine-2 with respect to machine-1, for the systems operating at OP-1, OP-2 and OP-3, respectively. Figs. 16-18 show relative inter-area machine speed deviations of machine-3 with respect to machine-1, for the systems operating at OP-1, OP-2 and OP-3 respectively. It can be easily noted that the designed VBA-TCSC controller has excellent performance for three operating conditions. It can also be observed that conventional control has better performance only for its designed operating point, i.e., OP-1, but its performance is not so good for other operating conditions. It is clear that the system response with the VBA-TCSC controller settles faster and provides superior damping. This indicates that the time domain specifications are simultaneously met. Figs. 19-21 show the fault bus voltage magnitude for the system at OP-1, OP-2 and OP-3 respectively. Figs. 22-24 show susceptance of TCSC. It is seen that the fault disturbance is recovered by the designed VBA-TCSC controller in reasonable time. Thus, the non-linear simulations reveal that the designed VBA-TCSC controller has robust performance under varying conditions.

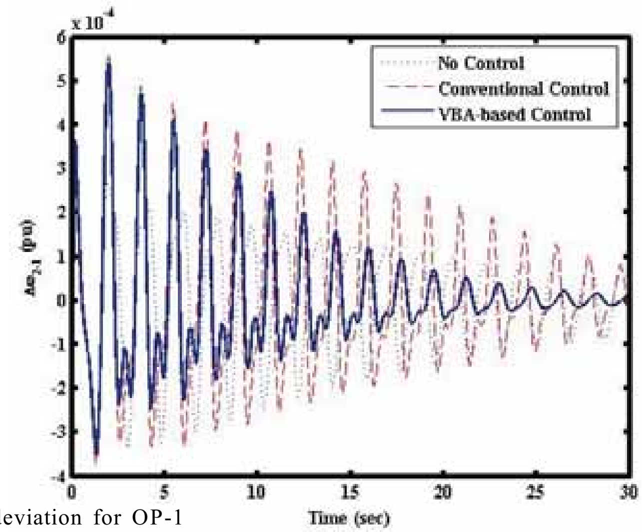

Fig. 13: Machine speed deviation for OP-1

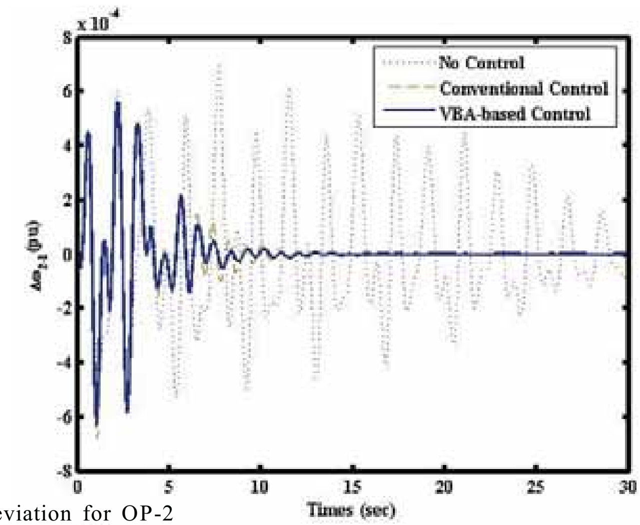

Fig. 14: Machine speed deviation for OP-2

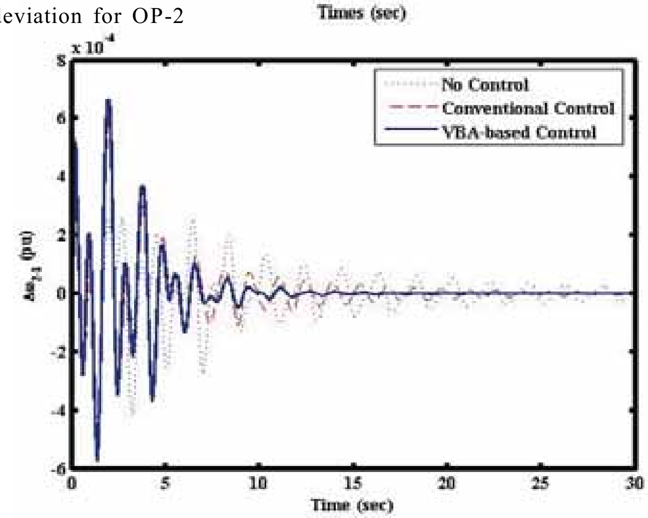

Fig. 15: Machine speed deviation for OP-3

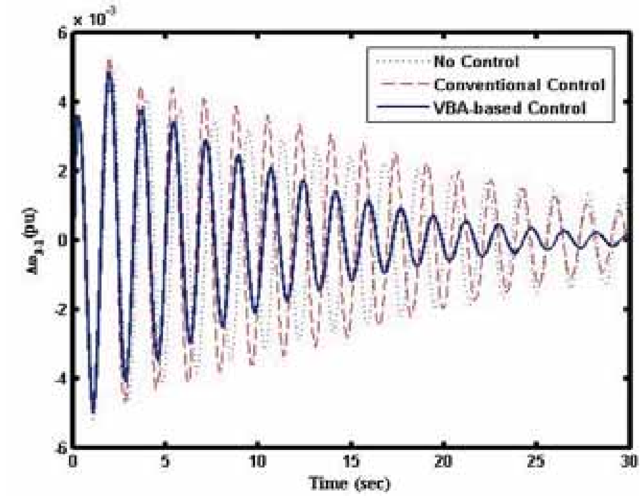

Fig. 16: Inter area speed deviation for OP-1

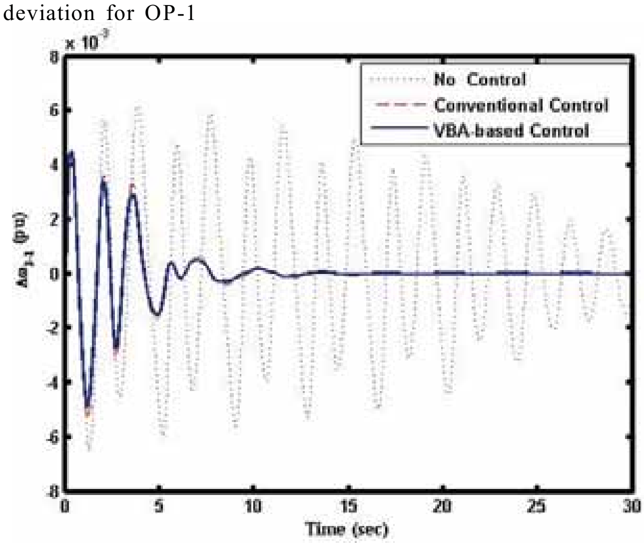

Fig. 17: Inter area speed deviation for OP-2

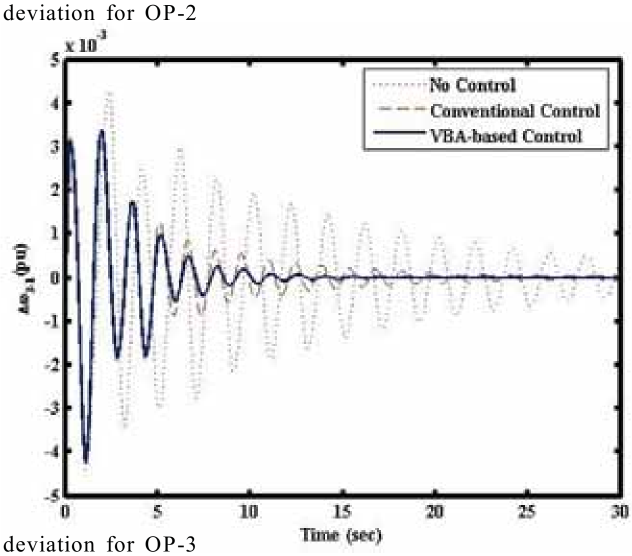

Fig. 18: Inter area speed deviation for OP-3

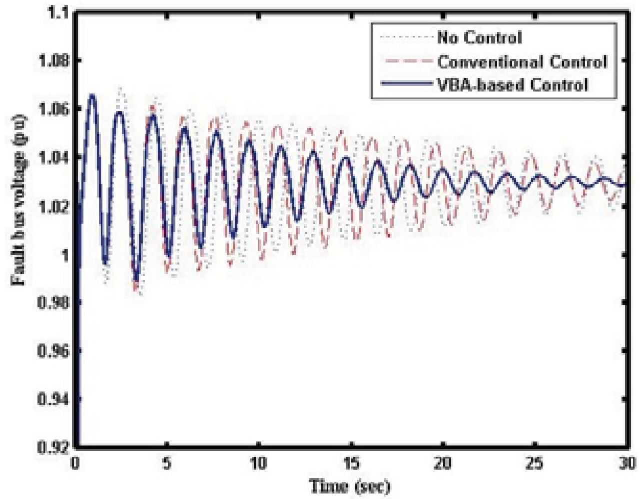

Fig. 19: Fault bus voltage for OP-1

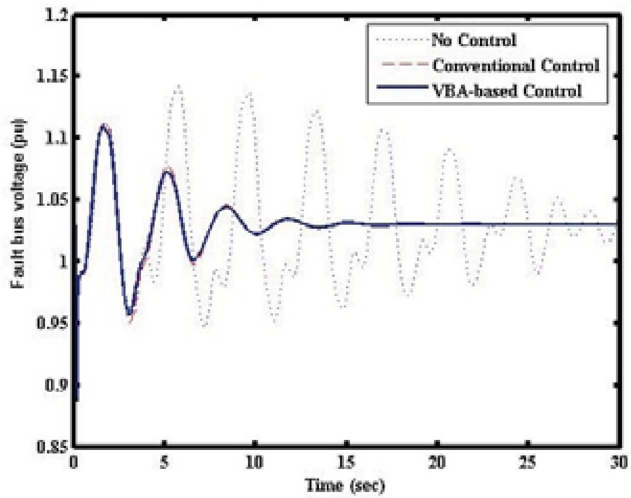

Fig. 20: Fault bus voltage for OP-2

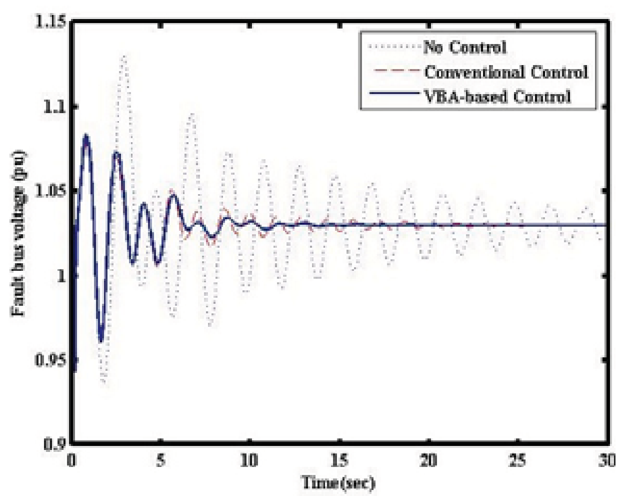

Fig. 21: Fault bus voltage for OP-3

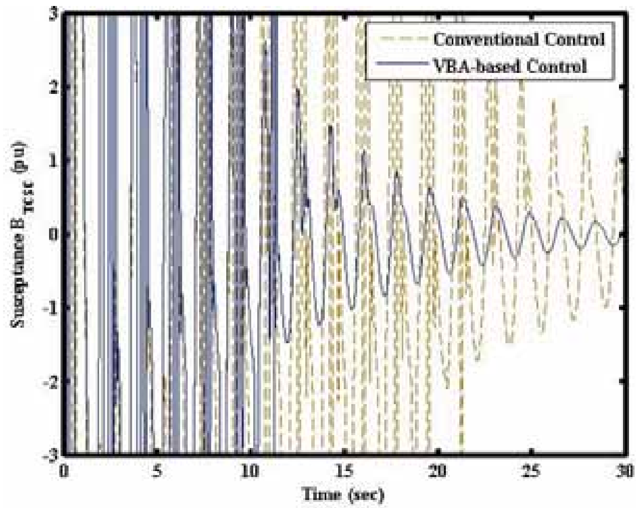

Fig. 22: Susceptance of TCSC at OP-1

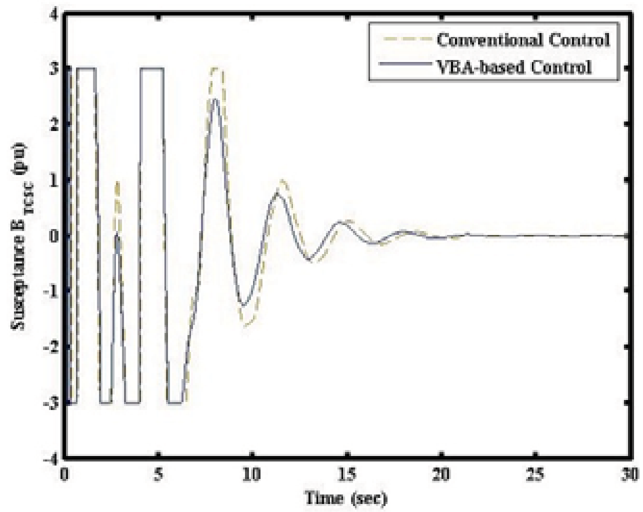

Fig. 23: Susceptance of TCSC at OP-2

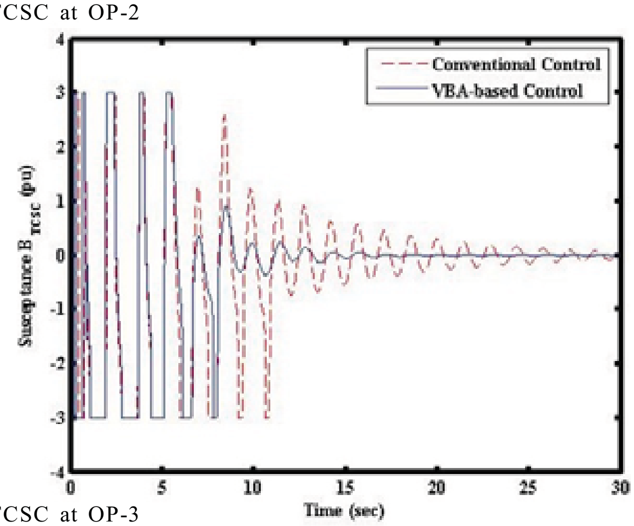

Fig. 24: Susceptance of TCSC at OP-3

VII. Conclusions:

In this paper, a new natural inspired VBA implementation in designing supplementary damping controller for TCSC is presented. Controller structure was same as conventionally used lead/lag structure. At first, the problem is formulated as an optimization problem for different operating conditions and then VBA algorithm has been used to optimize the problem. The proposed design is tested for different loading conditions through eigenvalue analysis and time domain simulations. Simulations are compared with no damping control and conventional control. The VBA-based damping control system has been tested both in small signal as well as non-linear time domain simulations. The proposed designed damping control system for TCSC has shown improved performance than conventional damping control system in terms of better oscillations damping, lesser overshoot, lesser settling time and lesser steady state error for all the operating conditions.

Appendix

A. Power system

The synchronous machines are simulated by 6th order differential eqns given below:

$$\frac{d\delta_i}{dt} = \omega_i - \omega_o$$

$$\frac{d\omega_i}{dt} = \frac{1}{M}(Pm_i + K_d\,\omega_i - Pe_i)$$

$$\frac{dE'_{di}}{dt} = \frac{1}{T'_{qo}}(-E'_{di} + (x'_{qi} - x_{qi}).i_{qi})$$

$$\frac{dE'_{qi}}{dt} = \frac{1}{T'_{do}}(E_{fi,oi} - E'_{qi} + (x_{di} - x'_{di}).i_{di})$$

$$\frac{dE''_{di}}{dt} = \frac{1}{T''_{qo}}(E'_{di} + (x'_{qi} - x''_{qi}).i_{qi} - E''_{di})$$

$$\frac{dE''_{qi}}{dt} = \frac{1}{T''_{do}}(E'_{qi} + (x'_{di} - x''_{di}).i_{di} - E''_{qi})$$

$$\frac{d\Delta E_{fdi}}{dt} = \frac{1}{T_A}\left\{K_A(V_{ri} - V_{ti}) - \Delta E_{fdi}\right\}$$

The system algeblaic equations are given as follows:

$$i_{di} = G_{ii}E''_{di} + B_{ii}E''_{qi} + \sum_{\substack{k=1\\k\neq i}}^{n}\begin{cases}E''_{dk}(G_{ik}\cos\delta_{ik} + B_{ik}\sin\delta_{ik})\\E''_{qk}(B_{ik}\cos\delta_{ik} - G_{ik}\sin\delta_{ik})\end{cases}$$

$$i_{qi} = G_{ii}E''_{di} - B_{ii}E''_{qi} + \sum_{\substack{k=1\\k\neq i}}^{n}\begin{cases}E''_{qk}(G_{ik}\cos\delta_{ik} + B_{ik}\sin\delta_{ik})\\E''_{dk}(B_{ik}\cos\delta_{ik} - G_{ik}\sin\delta_{ik})\end{cases}$$

$$V_{di} = E''_{di} - r_i i_{di} - x''_{qi} . i_{qi}$$
$$V_{qi} = E''_{qi} - r_i i_{qi} - x''_{qi} . i_{di}$$

$$V_i = \sqrt{V_{di}^2 + V_{qi}^2}$$
$$P_{ei} = E''_{di} i_{di} + E''_{qi} i_{qi} + (x''_{di} - x''_{qi}) i_{di} i_{qi}$$

B. TCSC Dynamic Model:

$$\frac{d}{dt}(v_1) = \frac{d}{dt}(K_T y) - \frac{1}{T_\omega} v_1$$

$$\frac{d}{dt}(v_2) = \frac{1}{T_2}\left\{T_1 \frac{d}{dt}(K_T y) + (1 - \frac{T_1}{T_\omega}) v_1 - v_2\right\}$$

$$\frac{d}{dt}(u_{TCSC}) = \frac{1}{T_4}\left\{\frac{T_2 - T_3}{T_2} v_2 + \frac{T_3}{T_2}(\frac{T_\omega - T_1}{T_\omega}) v_1 + \frac{T_1 T_3}{T_2} \frac{d}{dt}(K_T y) - u_{TCSC}\right\}$$

$$\frac{d}{dt}(B_{TCSC}) = \frac{1}{T_{TCSC}}\left[K_{TCSC}\left(B_{TCSC}^{ref} + \Delta u_{TCSC}\right) - B_{TCSC}\right]$$

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