Optimal Placement and Tuning of TCSC for Damping Oscillations

Maryam Mohiti, Mahtab Khalilifar, Ahmad Salehi, Rahim Zeinali
Power System Research center
Monenco Iran Consultant Engineers Tehran, Iran
maryammohiti@gmail.com,khalilifar.mahtab@monenco.com,salehi.Ahmad@monenco.com,zeinali.Rahim@monenco.com

Abstract— **This paper presents a Genetic Algorithm (GA) based Method for the allocation and tuning of TCSC to improve poorly damped oscillations. The method only uses Eigen-values of systems oscillatory modes, thus system transfer function isn't needed. This feature makes the method applicable in large systems which all of the system data aren't available. The method is implemented in DIgSILENT software which contains a powerful programming language called DPL. The effectiveness of the method has been tested on IEEE 9-bus system.**

Keywords- TCSC;oscillation damping; damping ratio; genetic algorithm.

I. INTRODUCTION

Recently, the deregulated energy market and the increasing demand of electricity have led to the enlargement of power systems. Damping of oscillations between interconnected synchronous generators is essential for secure system operation. These oscillations are categorized into two groups; local modes and inter area modes.

While local oscillations, involving one or more generators swinging against the rest of the system are mainly influenced by a restricted number of local system parameter the behavior of low frequency inter-area oscillations is generally determined by global parameters of the power system. Power System Stabilizers (PSSs) applied on generators Automatic Voltage Regulators (AVR) can damp local oscillation modes effectively, but have a minor influence on inter-area modes. A solution for damping these modes is use of Flexible AC Transmission Systems (FACTS) devices installed on the path of inter-area oscillations. These devices provide dynamic control of the power transfer parameters such as transmission voltage, line impedance and phase angle. Applying a supplementary controller (POD) on FACTS increases the damping of the inter-area oscillations. FACTS devices are more effective in damping oscillations if their Power Oscillation Dampers controllers use a global signal as an input. Since system oscillations are heavily influenced by line impedance, TCSC can be very effective in providing additional damping.

FACTS can improve both dynamic and static performance of the system. Optimal location of FACTS has been investigated in many researches. Static indexes such as system cost, system loadability and voltage deviation have been optimized in many papers. In [1] the optimal location, type and values are determined to improve loadability of the system. [2] optimizes the location of FACTs to minimize the overall system cost, which compromises of generation cost and investment cost. [3] uses a multi objective of total fuel cost, power losses and system loadability. In these research optimal location of FACTS devices are determined to improve only static criteria. Allocating FACTS to improve dynamic indexes haven't been wholly considered, yet.

In [4, 5] a residue method is used to find the optimal location of FACTS devices for damping oscillations but the POD controller tuning is not investigated. [6] selects a suitable feedback signals for FACTS POD controller to improve damping. In [7, 8] FACTS are allocated to improve power system oscillations. In [3] the three issues –economic, congestion and damping are dealt with by a multi objective approach.

In [9] a residue method is used to tune the POD controller parameters but in large power systems residue factors may not be available, thus in the proposed technique TCSC placement and POD controller parameters are optimized with the use of only the Eigen-values of the transfer function of the power system. The method is implemented in DIgSILENT software which contains a powerful programming language called DPL. Large power system can be simulated in DIgSILENT which provides the implementation of the proposed method for real networks.

This paper presents a method in which the POD controller and the TCSC steady state parameters are tuned and the optimal location of the TCSC(s) is determined to improve the damping of the weakly damped inter-area modes. Since this problem has a large search space Genetic Algorithm (GA) is applied.

This paper is organized as follows: Section II introduces the TCSC model used in the study; Section III briefly discusses power system dynamic behavior. The implementation of the problem by Genetic algorithm is presented in section V. Simulation results and discussions of the results are presented in section VI.

II. TCSC MODELING

978-1-4673-3059-6/13/$31.00 ©2013 IEEE

System oscillations are heavily influenced by line impedance, thus TCSC can be very effective in providing additional damping. A further benefit is that it is among the cheapest FACTS on the market. Figure 1 shows the main circuit of a TCSC.

TCSC can be controlled to work either in the capacitive or the inductive zone.

where:

$$X_{TCSC}(\alpha) = \frac{X_C X_l(\alpha)}{X_L(\alpha) - X_C} \tag{1}$$

$$X_L(\alpha) = X_L \frac{\pi}{\pi - 2\alpha - \sin\alpha} \tag{2}$$

α is the firing angle, X_L is the reactance of the inductor and X_l is the effective reactance of the inductor at firing angle.

Inter-area oscillations are damped by adding an additional damping signal generated by a POD. The selection of appropriate feedback signal for FACTS controllers and tuning them properly is an important consideration. According to [4], [10] the most suitable supplementary input signals are transmission current or active power, therefore these two signals are used as the controllers input (Fig.2). The POD controller structure is depicted in Fig.3. It consists of an amplification block, a wash-out and low-pass filters and two stages of lead-lag blocks. Firing delay is modeled by a time constant T_m and T_w is the washout time constant.

T_{lead} and T_{lag} are the lead and lag time constants respectively. T_m and T_w are not expected to significantly effect the inter-area modes damping, hence they are considered constant. Fig.5 depicts the TCSC model and control loop in DIgSILENT.

III. POWER SYSTEM DYNAMIC BEHAVIOR

The power system small signal dynamic behavior can be described by linearized power system –algebraic equations [11]. Equation (3) describes the power system in state space.

$$\begin{bmatrix} \Delta\dot{x} \\ 0 \end{bmatrix} = A_{sys} \begin{bmatrix} \Delta x_1 \\ \Delta x_1 \end{bmatrix} + B[\Delta y] = A_{sys}\Delta x + \Delta u \tag{3}$$

where A_{sys} is the complete system matrix, B is the control matrix, Δx state variable matrix and Δu the vector of inputs.

The eigenvalues which characterize oscillation modes of the system are computed by (4) [1]:

$$\det(A - \lambda I) = 0 \tag{4}$$

where I is an identity matrix and λ eigen-values of the system.

Damping ratios of the system oscillations modes are calculated as:

$$\xi_i = \frac{-\sigma}{\sigma^2 + \omega^2} \tag{5}$$

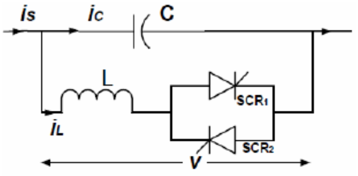

Fig. 1 configuration of TCSC

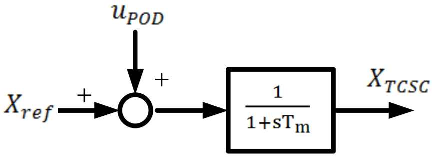

Fig. 2 TCSC Controller

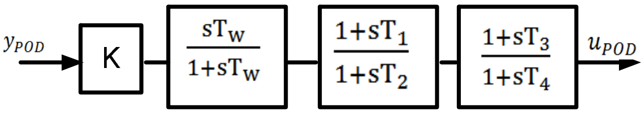

Fig. 3 POD Structure

which σ is the real part and ω the imaginary part of the eigenvalues. The oscillatory modes with damping ratios less than 3-5% [11] are critical and negative damping ratio corresponds to an unstable system.

In the GA approach proposed POD parameters (k , T_{1-4}) are tuned to increase the minimum damping ratio of the system oscillatory modes. The washout time constant doesn't have a major influence on the system oscillatory modes and as the previous research it is set constant [12].

IV. OPTIMIZATION PROBLEM

The formulation of the optimal location and setting of TCSC can be expressed as follows. The objectivez function is to tune the controller parameters and locate the TCSC in the optimal location by maximizing the damping ratio of the worst damped mode of the system that is given by (6):

$$max\ \xi_{min} = min\ \xi_i \qquad i \in modes \tag{6}$$

The Genetic algorithm objective function is set as equation (6).

V. GENETIC ALGORITHM IMPLEMENTATION

GA is a search algorithm based on the mechanism of natural selection and natural genetics; it can search several possible solutions simultaneously. In GA, individuals are simplified to a chromosome that codes for the variables of the problem. The GAs start with random generation of initial population and then selection, crossover and mutation are produced until the best population is found. It can search a large space and therefore, it is a suitable method for searching the optimal solution in a complex problem.

A. Variable encoding

The configuration of FACTS devices is obtained by three parameters: the location of the TCSC , steady state values and POD controller values. These variables are codes as follows.

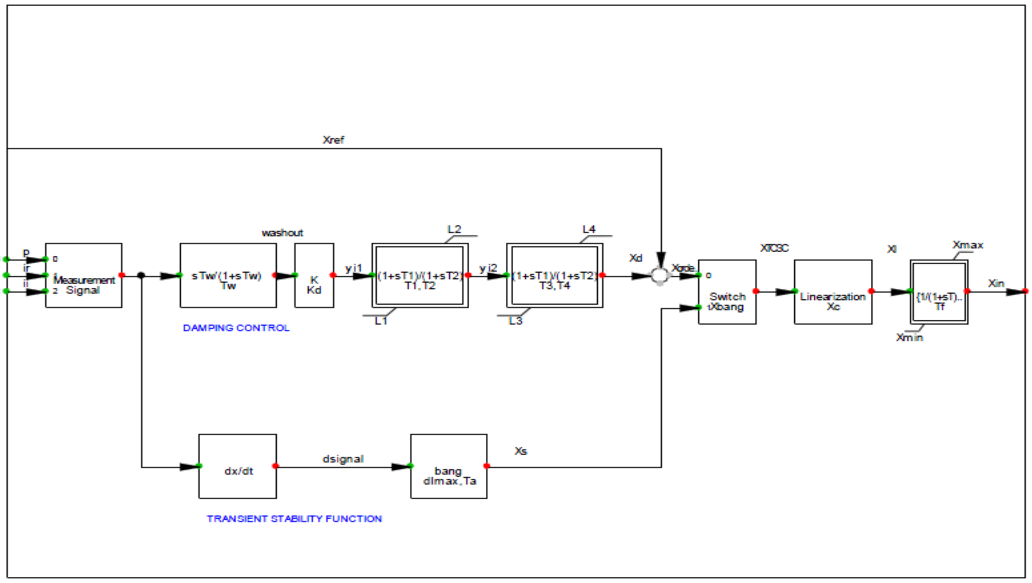

Fig. 4 TCSC Controller Structure in DIgSILENT

1) TCSC location

Location of TCSC is modeled through a vector of binary variables v_{loc} which defines whether a line is selected for the FACTS placement or not.

$$V_{loc} = \begin{array}{|c|c|c|c|}\hline \mathbf{1} & \mathbf{0} & \dots & \mathbf{1} \\ \hline\end{array} \tag{7}$$

where if v_{loc}=1 a TCSC is installed on line k (kϵ N_{line}) anN_{line} is the number of transmission lines.

2) TCSC steady-state parameters

Real values are used to represent the steady-state parameters (X_c, X_l) of the TCSC.

$$V_{TCSC} = \begin{array}{|c|c|c|c|c|}\hline X_{c1} & X_{l1} & \dots & X_{cN_{line}} & X_{lN_{line}} \\ \hline\end{array} \tag{8}$$

where X_c and X_l are in the working range of the TCSC. As stated in [12] the ratio of X_{lmax} *to* X_{cmax} is assumed 0.3.

3) TCSC POD parameters

As explained in section II the POD is characterized by five independent variables: k and T_{1-4}. Therefore five real variables are employed to represent the POD ratings. A wide range is used for the gain and time constants to cover all of the space. This range can be changed due to the available TCSC ratings.

B. GA Operators

The employed GA procedure is implemented in the DPL environment. The following operators are used.

1) Selection:

Selection is a process where the individual is selected to move to a new generation according to their fitness. The Roulette Wheel selection is employed. In Roulette Wheel selection the chromosome with the higher fitness has the higher probability to be selected.

2) Crossover:

The main task of crossover is to reorganize the information of two different individuals and produce a new one. This is done to make the members of the society more variant and preserve the GA method to find a local optimum solution. A two-point crossover is applied in this paper.

3) Mutation:

Mutation is used to introduce some sort of artificial to avoid premature convergence to local optimum. In this paper binary and real mutation are both used.

4) Migration:

Migration is used to generate new random chromosomes to expand the search space. The chromosomes generated in migration are completely random and may increase the convergence time.

In the proposed optimization strategy 10% of every generation are the best chromosomes of the previous generation, 5% are produced by migration and 80% are chromosomes produced by GA operators (selection, crossover and mutation).

VI. CASE STUDY AND RESULTS

The modified IEEE 9 bus test system is used to verify the proposed algorithm which line and load data can be found in [13]. The one-line diagram of the system is shown in Fig.5.

In order to study the effectiveness of the proposed GA method different operating conditions are considered as study cases and optimal location, steady-state and POD controller parameters of the TCSC are determined. Minimum damping ratio of the systems oscillatory modes, setting and location of TCSC are shown in table 1. The local modes are well damped

TABLE I. RESULTs OF TCSC SETTING AND OPTIMAL LOCATION

Case number	*TCSC Location*	*Steady state parameters*		*POD parameters*					ξ_{min}
		X_c	X_l	K	T_1	T_2	T_3	T_4	
1	-	*	*	*	*	*	*	*	0.094
2	-	*	*	*	*	*	*	*	0.04
3	Line 4-5	111.2	44.8	72.6	4.3	1.62	4.76	2.66	0.069
4	Line 4-6	156.97	52.58	36.28	2.83	3.12	1.12	2.67	-1
5	Line 4-5	101.7	34.6	63.1	3.06	2.29	3.74	1.23	0.068
6	Line 4-6	101.7	32.2	45.8	3.2	2.18	1.3	2.5	0.1

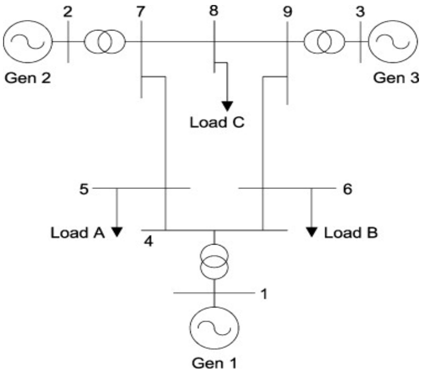

Fig. 5 IEEE 9 bus single line view

TABLE I GA SETTINGS

Pop size	350
Generations	120
Selection	Roulette Wheel
Crossover	Two-point
Mutation	Real

by PSS and it is expected that the POD controller will not influence them [9]. With this assumption the minimum damping ratio is due to inter-area modes. As mentioned in section II transmission active power and current are the most suitable signals for the POD controller. In the following case studies transmission active power is used as the reference signal for the POD controller.

If the transfer function of the system has poles in the right s-plane the system is unstable. Instability corresponds to negative damping ratio. Damping ratios which are less than 3-5% are critical and need further attention.

A. Case 1. Normal operation without TCSC

In this case the system is operating normally and no contingencies are applied in the power system. No TCSCs are installed in the network either.

B. Case 2. Outage of line 4-5 and no TCSC installed in the system

In this case line 4-5 is out and no TCSCs are installed. A critical mode ($\xi = 0.04$) is observed but all poles are in the left S-plane and the system is stable.

C. Case3. Outage of line 45 and TCSC tuned by the proposed GA

Line 4-5 is out. The optimal location, setting of the TCSC and its POD controller are obtained by the results of the GA-method proposed in section V. Table 2 shows the settings of the implemented GA. Minimum damping ratio equals to 0.069 as a result no critical and unstable modes are observed.

D. Case 4. Outage of line 4-5 with a TCSC tuned randomly

This case is similar to case 3 except than the POD controller parameters are tuned randomly and not with the GA-based method. With the untuned parameters the system becomes unstable ($\xi_{\min} = -1$).

E. Case 5. Increasing line 4-5 length.

Line 4-5 length is increased from 1Km to 16 Km (scaled lengths) and the location and parameters are chosen by the GA-method. Increasing line 4-5 length conduce to system instability ($\xi < 0$). By setting the POD parameters and the location of the TCSC optimally the damping ratio increases to 0.068 and the system becomes stable.

F. Case 6. Load B is increased

The loading at bus 6 is increased 60 MW (from 90 to 150 MW). By applying the Proposed GA $\xi_{\min}$ grows from 0.03 to 0.1.

Cases 2, 3 and 4 show a TCSC which is located and tuned optimallay can improve the damping of system oscillations. As case 4 points out although TCSC is installed in the system but since it isn't tuned properly it makes the system instable; hence the parameters of the POD directly influence the damping ratio and need to be tuned precisely. Cases 5 and 6 show that the TCSC can improve the damping ratio during contingencies such as increasing line length and loading, significantly.

VII. Conclusion

In this paper a GA-based method which solves damping inter-area oscillations issue by optimizing the location, setting of TCSC and its POD controller is presented. The method only uses Eigen-values of systems oscillatory modes, thus the system transfer function isn't needed. This feature makes the method applicable in large systems which all of the system data aren't available. The minimum damping ratio ($\xi_{\min}$) of the oscillatory modes has been selected as the objective function. The results of the simulation show optimal placement and setting of TCSC and appropriate tuning of POD controller can significantly improve system performance in damping oscillations.

As future developments of the present work other FACTS devices and other objective functions can be considered.

ACKNOWLEDGMENT

The authors gratefully acknowledge the contributions of Monenco Iran Consultant Engineers, Tehran, Iran.

REFERENCES

[1] Stéphane Gerbex, Rachid Cherkaoui, and Alain J. Germond, “Optimal Location of Multi-Type FACTS Devices in a Power System by Means of Genetic Algorithms”, IEEE Trans.on Power Systems, vol. 16, no. 3, Aug. 2001.

[2] Prashant Kumar Tiwari, Yog Raj Sood, “Optimal Location of FACTS Devices in Power System Using Genetic Algorithm” 2009 World Congress on Nature & Biologically Inspired Computing ,India, Dec. 2009.

[3] A. Lashkar Ara, , A. Kazemi, and S. A. Nabavi Niaki, “Multiobjective Optimal Location of FACTS Shunt-Series Controllers for Power System Operation Planning”, Trans. on Power delivery, vol. 27, no. 2, April 2012.

[4] V. Ilea, A. Berizzi, M. Eremia, “Damping inter-area oscillations by FACTS devices”, UPEC 2009, Glasgow, Scotland, September, 2009.

[5] Kundur, P., Power system stability and control, New York, USA: The EPRI Power System Engineering Series McGraw-Hill, 1994.

[6] M.E. Aboul-Elea, A.A. Sallam, J.D. McCalley, A.A. Fouad, "Damping controller design for power system oscillation using global signals" IEEE Trans. on Power Systems, vol. II , no. 2, pp. 767-773, May 1996.

[7] Alberto Berizzi, Cristian Bovo, Valentin Il, “Optimal placement of FACTS to mitigate congestions and inter-area oscillations” , IEEE Trondheim PowerTech , 2011.

[8] Nuraddeen Magaji, , M.W. Mustafa, “Optimal Location of FACTS devices for damping oscillations using Residue Factor”, Power and Energy conference, IEEE , Dec. 2008.

[9] Alberto Berizzi, Member, IEEE, Cristian Bovo, Member, IEEE, Valentin Ilea “Optimal placement of FACTS to mitigate congestions and inter-area oscillations”, IEEE 2011, PowerTech, Trondheim, 2011.

[10] V. Ilea, “Improvement of small-disturbance stability by FACTS devices”, PhD.dissertation Dept. Power Systems, Univ. “Politehnica” of Bucharest,2010.

[11] L. Cai and I. Erlich, “Optimal choice and allocation of FACTS devices using genetic alghoritms”, ISAP, Intelligent Systems Application to power Systems, Lemnos, Greece, Aug., 31 – Sept., 3, 2003.

[12] S. Gerbex, R. Cherkaoui, and A. J. Germond, “Optimal Location of FACTS Devices to Enhance Power System Security”, Power Tech conference , IEEE , Bolgano , 2003 .

[13] Mustafa, M. W.; Magaji, N., "Optimal Location of Static Var Compensator Device for Damping Oscillations", American J. of Engineering and Applied Sciences, vol.4, no.3, pp. 353-359, May. 2009.

[14] L.J. Cai,and I. Erlich, Member IEEE, “Optimal Choice and Allocation of FACTS Devices using Genetic Algorithms”, Power Systems Conference and Exposition, IEEE PES Oct. 2004

[15] N.G. Hingorani, L. Gyugyi, “Understanding FACTS: Concepts and Technology of Flexible AC Transmission System”, IEEE Power Engineering Society, IEEE press, Delhi 2001.

[16] Panda and N. Prasad Padhy, “Power system with PSSs and FACTS controller: modeling, simulation and simultaneous tuning employing genetic algorithm”, International Journal of Electrical, Computer and System Engineering, vol. 1, No.1, pp. 9-18, 2007.

[17] D. E. Goldberg, Genetic Algorithms in Search Optimization and Machine Learning: Addison-Wesley Publishing Company, Inc., 1989.

[18] Sadikovic, R.; Korba, P.; Andersson, G., "Self-tuning Controller for Damping of Power System Oscillations with FACTS Devices", Power Engineering Society General Meeting, IEEE, pp. 1-6, Oct. 2006.

[19] Abouzar Samimi, Peyman Naderi, “ New Method for Optimal Placement of TCSC Based on Sensitivity Analysis for Congestion Management”, Smart Grid and Renewable Energy Journal, feb. , 2012.

[20] R. K. Pandey and N. K. Singh “An Approach for Optimal Power Oscillation Damping with UPFC” Power and Energy Society General Meeting -, 2008 IEEE ,July 2008

[21] S . Gerbex, R. Cherkaoui, and A. J. Germond, Member, “Optimal Location of FACTS Devices to Enhance Power System Security 2003 IEEE Bologna PowerTech Conference, June 23-26, Bologna, Italy.