Effective Location Of Facts Controllers To Enhance Small Signal Stability Of The Power System

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Abstract

The problem of small signal instability is usually due to insufficient damping of system oscillations. The use of power system stabilizers to control generator excitation systems is one of the effective methods of enhancing small signal stability of power system. However with change in operating state of the power system, the parameters of PSS require retuning. The power electronic based FACTS controllers are effective for system voltage control and power flow control. They can also be used for damping electromechanical oscillations.

This presents a systematic method of developing the mathematical model for small signal stability analysis of power system using FACTS based damping controllers (SVC and TCSC) and the effective location of these FACTS based damping controllers using residue factor method. These FACTS controllers are modeled as current injections in the network. In this, the two axis model of the synchronous machine is used for developing the small signal model of the multi-machine power system with FACTS controllers. Case studies are carried out on the standard WSCC 3 Machine, 9-Bus system and 10 machine, 39 bus New England system.

***Keywords:* -** Small Signal Stability, FACTS, Residue Factor.

I. INTRODUCTION

As power systems became interconnected, areas of generation were found to be prone to electromechanical oscillations. These oscillations have been observed in many power systems worldwide. With increased loading conditions and interconnections the transmission system became weak and inadequate, also load characteristics added to the problem causing spontaneous oscillations. These oscillations may be local to a single generator or a generator plant (local oscillations, 0.8 – 2 Hz), or they may involve different groups of generators widely separated geographically (interarea oscillations, 0.2 –0.8 Hz).These uncontrolled electro mechanical oscillation may lead to total or partial power interruption [1].

The recent advances in power electronics technology have led to the development of FACTS controllers which are effective candidates for providing secure loading, power flow control and voltage control in transmission systems. These controllers when placed effectively with supplementary stabilizing loops are found to be effective for damping out power system oscillations was discussed in [2].

Ref. [3] presents the basic Static Var Compensator (SVC) control strategies for enhancing the dynamic and transient stabilities in a simple two machine system and Ref. [4] presents the Modeling of SVC and TCSC power system dynamic simulation.

The dynamic behavior of voltage source converter based FACTS devices for simulation studies was discussed in ref. [6].These devices were modeled as current injections for dynamic analysis.

This proposes a Residue factor to find the location of SVC and TCSC in multi-machine system. The proposed residue factor was based on the relative participation of the parameters of SVC controller to the critical mode was discussed in ref. [2] and TCSC was discussed in ref. [4]. The electrical circuit dynamics of the synchronous machines are modeled using the standard two axis model [7]. The following section presents the mathematical modeling details of the FACTS devices enhancement of dynamic stability, Small signal stability enhancement and Material & Methods.

II. MATHEMATICAL MODELING OF SYNCHRONOUS MACHINE

The linearized state equations in p.u form are given below. [7]

$$\Delta \dot{E}'_{di} = \frac{1}{\tau'_{qoi}}\left(-\Delta E'_{di} - \left(x_{qi} - x'_{qi}\right)\Delta I_{qi}\right)$$

$$\Delta \dot{E}'_{qi} = \frac{1}{\tau'_{doi}}\left(\Delta E_{FDi} - \Delta E'_{qi} + \left(x_{di} - x'_{di}\right)\Delta I_{di}\right)$$

$$\Delta \dot{\omega}_i = \frac{1}{\tau_{ji}}\{\Delta T_{mi} - D\Delta\omega_i - \Delta T_{ei})$$

--- (1)

$$\Delta \dot{\delta}_i = \Delta\omega_i$$

$$i = 1, 2 - - n$$

A. Modeling of shunt FACTS controller:

For the purpose of developing the small signal stability program all the series connected FACTS devices are represented as current injections in two nodes of the network [6]. However, if the device is a shunt connected device then the injections are confined only to one node. The shunt connected FACTS devices are replaced with an equivalent current injection as shown in the figure 1.

The change in bus voltage (ΔV_S) due to shunt connected FACTS device in the network is expressed in terms of the state variables from the last row of the matrix equation given by

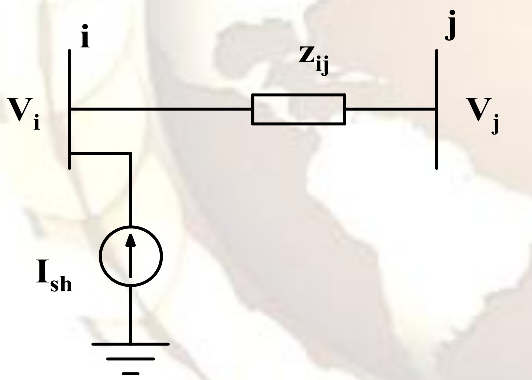

Fig.1 Shunt Connected FACTS –current Injection Model

$$\begin{bmatrix} \Delta\bar{I}_1 \\ \Delta\bar{I}_2 \\ \Delta\bar{I}_{sh} \end{bmatrix} = \begin{pmatrix} Y_{11}e^{j\theta_{11}} & Y_{12}e^{j(\theta_{12}-\delta_{120})} & Y_{13}e^{j(\theta_{13}-\delta_{130})} \\ Y_{21}e^{j(\theta_{21}-\delta_{210})} & Y_{22}e^{j\theta_{22}} & Y_{23}e^{j(\theta_{23}-\delta_{230})} \\ Y_{31}e^{j(\theta_{31}-\delta_{310})} & Y_{32}e^{j(\theta_{32}-\delta_{320})} & Y_{33}e^{j\theta_{33}} \end{pmatrix} \begin{bmatrix} \Delta\bar{E}_1 \\ \Delta\bar{E}_2 \\ \Delta\bar{V}_s \end{bmatrix}$$

$$-j\sum_{k=1}^{n} \begin{bmatrix} \bar{V}_{k0} Y_{1k} e^{j(\theta_{1k}-\delta_{1k0})}\Delta\delta_{1k} \\ \bar{V}_{k0} Y_{2k} e^{j(\theta_{2k}-\delta_{2k0})}\Delta\delta_{2k} \\ \bar{V}_{k0} Y_{3k} e^{j(\theta_{3k}-\delta_{3k0})}\Delta\delta_{3k} \end{bmatrix}$$

--- (2)

B. SVC Modeling:

The SVC dynamic model used for linear analysis is shown in Fig. 2. With an additional stabilizing signal, supplementary control superimposed on the voltage control loop of an SVC can provide damping of system oscillations [3].

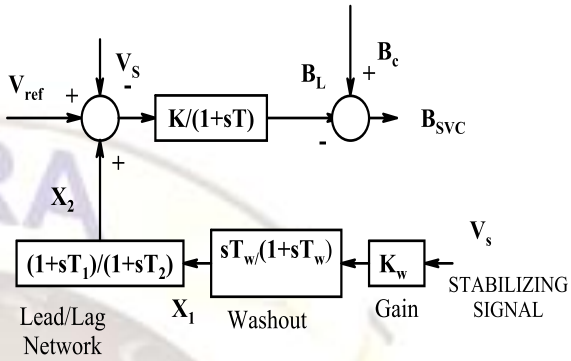

Fig. 2 Dynamic Model of SVC

From the matrix equation (2), the change in network current with the introduction of SVC in the d-q reference frame is given below.[8]

The linearized state equations of the SVC for small signal analysis is given below

$$\begin{aligned} \Delta I_{qi} &= G_{ii}\Delta E'_{qi} - B_{ii}\Delta E'_{di} \\ &+ \sum_{k\neq i,j}[(G_{ki}\cos\delta_{kio} - B_{ki}\sin\delta_{kio})\Delta E'_{qk} \\ &-(B_{ki}\cos\delta_{kio} + G_{ki}\sin\delta_{kio})\Delta E'_{dk} \\ &-(G_{ki}\sin\delta_{kio} + B_{ki}\cos\delta_{kio})\Delta\delta_{ki}E'_{qko} \\ &+(B_{ki}\sin\delta_{kio} - G_{ki}\cos\delta_{kio})\Delta\delta_{ki}E'_{dko}] \\ &+\sum_{j} \begin{matrix} [(G_{ji}\cos\delta_{jio} - B_{ji}\sin\delta_{jio})\Delta V_{srj} \\ -(B_{ji}\cos\delta_{jio} + G_{ji}\sin\delta_{jio})\Delta V_{smj} \end{matrix} \\ &-(G_{ji}\sin\delta_{jio} + B_{ji}\cos\delta_{jio})\Delta\delta_{ji}V_{srjo} \\ &+(B_{ji}\sin\delta_{jio} - G_{ji}\cos\delta_{jio})\Delta\delta_{ji}V_{smjo}] \end{aligned}$$

--- (3)

$$\Delta I_{di} = B_{ii}\Delta E'_{qi} + G_{ii}\Delta E'_{di}$$
$$+\sum_{k\neq i,j}[(G_{ki}\sin\delta_{kio} + B_{ki}\cos\delta_{kio})\Delta E'_{qk}$$
$$+(G_{ki}\cos\delta_{kio} - B_{ki}\sin\delta_{kio})\Delta E'_{dk}$$
$$+(G_{ki}\cos\delta_{kio} - B_{ki}\sin\delta_{kio})\Delta\delta_{ki}E'_{qko}$$
$$-(B_{ki}\cos\delta_{kio} + G_{ki}\sin\delta_{kio})\Delta\delta_{ki}E'_{dko}]$$
$$+\sum_{j}\begin{matrix}[(G_{ji}\sin\delta_{jio} + B_{ji}\cos\delta_{jio})\Delta V_{srj} \\ +(G_{ji}\cos\delta_{jio} - B_{ji}\sin\delta_{jio})\Delta V_{smj}\end{matrix}$$
$$+(G_{ji}\cos\delta_{jio} - B_{ji}\sin\delta_{jio})\Delta\delta_{ji}V_{srjo}$$
$$-(B_{ji}\cos\delta_{jio} + G_{ji}\sin\delta_{jio})\Delta\delta_{ji}V_{smjo}]$$

$$\Delta\dot{B}_L = \frac{K}{T}\Delta X_L + \frac{K}{T}\left[\left(\frac{T_1}{T_2}\right)K_W - 1\right]\Delta V_S - \frac{\Delta B_L}{T} - \frac{K}{T}\left(\frac{T_1}{T_2}\right)\Delta X_W \quad (5)$$

The differential equations connected with the washout and lead lag filter are [8]

$$\Delta\dot{X}_W = \frac{K_W}{T_W}\Delta V_S - \frac{\Delta X_W}{T_W} \quad \text{--- (6)}$$

$$\Delta\dot{X}_L = \frac{1}{T_2}\left(1 - \frac{T_1}{T_2}\right)(K_W\Delta V_S - \Delta X_W) - \frac{\Delta X_L}{T_2} \quad \text{--- (7)}$$

Substituting (3) and (4) in the differential of the synchronous machine (1) and SVC dynamic equations (5-7) yields the system state space matrix.

The complete set of state variables describing the dynamics of the synchronous machine with the (4) inclusion of the SVC in the network is as follows.

$$x^T = [E'_d, E'_q, \omega, \delta, B_L, X_W, X_L] \text{ --- (8)}$$

C. *Algorithm for Small Signal Stability Enhancement:*

The critical steps for the small signal stability evaluation in multi-machine power systems with FACTS devices are listed below.

- Step 1:

Get the transmission line data, bus data and generator data for the given system and form the bus admittance matrix from the given transmission line data

- Step 2:

Eliminate all the nodes except for the internal generator nodes and FACTS connected nodes. For shunt connected devices, there is only one node whereas for series connected devices, there are two nodes.

- Step 3:

Obtain the Y_{red} matrix from the reduced network,

$Y_{red}=Y_{nn}-(Y_{nr}*inv(Y_{rr})*Y_{rn})$

- Step 4:

For the formation of state space model, the initial conditions are computed in advance. ($E`_{qo}$, $E`_{do}$, $I`_{qo}$, $I`_{do}$)

- Step 5:

Formulate the differential equations for pE'_q, pE'_d, $p\delta$, $p\omega$ with additional state variables due to FACTS devices as $\dot{\underline{x}} = [\underline{A}]\,\underline{x}$ after eliminating the algebraic equations.

- Step 6:

From the state space matrix, the Eigen values are to be calculated and damping ratio are calculated for the electromechanical modes as

ζ=-Re (eigenvalue)/(|eigenvalue|)

- Step 7:

Compute the participation matrix from the right and left Eigen vectors of the A-matrix.

D. TCSC Modeling:

The TCSC is an important component of FACTS. With the firing control of the thyristors, it can change its apparent reactance smoothly and rapidly.The TCSC is able to directly schedule the real power flow through a typically selected line and allow the system to operate closer to the line limits. More importantly because of its rapid and flexible regulation ability, it can improve transient stability and dynamic performance of the power systems.

The structure and the mathematical model of the TCSC aregiven in Fig. 4 and Fig. 5 respectively.

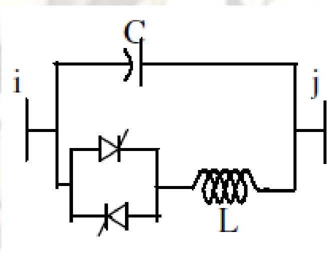

Fig.4 TCSC Structure

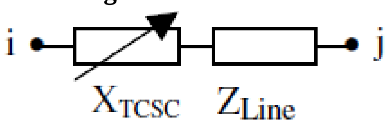

Fig.5 Modeling of TCSC

III SMALL SIGNAL STABILITY ENHANCEMENT

The test system considered for small signal stability investigation is the 3 Machine 9 Bus system [7] (Fig 3) . The 3 machine test system is operating with the load at bus 5 carrying 125 MW, bus 6 carrying 90 MW and bus 8 supplying 100 MW. The real power generations are 71.3, 163 and 85 in generators 1, 2 and 3 respectively.

Table 1: Eigen value analysis for 3 machine 9 bus system

Eigen values	**Damping Ratio**	**Associated States**
-0.002664094411874 ± 0.034642495926657i	0.07345	δ_{13}, ω_3
-0.000621367513248 ± 0.022977648680621i	0.02654	δ_{12}, ω_2

Eigen value analysis results of the 3 Machine 9 Bus system around the operating state mentioned above is displayed in Table 1.For verification of results Machine 1 is considered as classical model & Machines 2, 3 as two axis models.

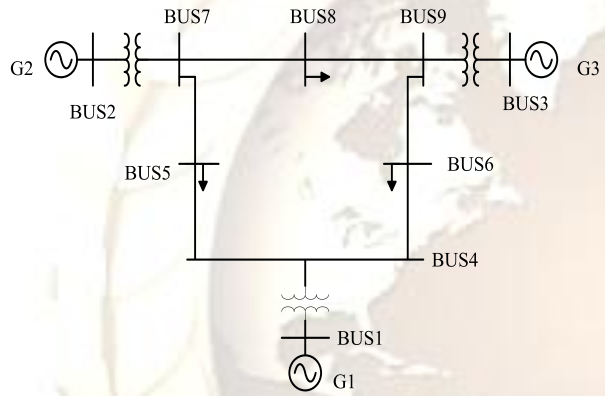

Fig.3 3-Machine 9 Bus System

It can be observed that damping ratio of the swing modes (local modes) are poor (0.07345 and 0.02654). The Eigen values calculations match with the results given in the Ref. [7].

Table2: Eigen value Analysis –Effect of FACTS stabilizers

Without Damping Controller	With SVC (at bus-5)	With SVC (at bus-6)	With SVC (at bus-8)
-0.00243 ± 0.03444i ζ = 0.07345	-0.00232 ± 0.02456i ζ = 0.09432	-0.00229 ± 0.02244i ζ = 0.10188	-0.00167 ± 0.01548i ζ = 0.10751
-0.00053 ± 0.02281i ζ = 0.02654	-0.00060 ± 0.01058i ζ = 0.05754	-0.00063 ± 0.01197i ζ = 0.05315	-0.00099 ± 0.01155i ζ = 0.08549

Table 2 displays the effect of FACTS stabilizer on the dynamic stability of the 3 machine 9 bus system. For this analysis all the machines are modeled using the two axis model, to accurately model the small signal behavior of the system. The shunt connected FACTS device (SVC) is located at load buses. The data for the FACTS stabilizers are listed in the appendix.

From the table it can be observed that with SVC in the network the damping ratio of the modes improve when it is located at bus-8.

Table 3 displays the effect of FACTS stabilizer on the dynamic stability of the 3 machine 9 bus system. For this analysis all the machines are modeled using the two axis model, to accurately model the small signal behavior of the system. The series connected FACTS device (TCSC) is located at load buses. The data for the FACTS stabilizers are listed in the appendix.

Table3: Eigen value Analysis –Effect of FACTS stabilizers

With TCSC (at bus-5)	With TCSC (at bus-6)	With TCSC (at bus-8)
-0.0043615 ± 0.03328218i ζ = 0.12993	-0.00409785 ± 0.03345801i ζ = 0.12156	-0.00358704 ± 0.03295447i ζ = 0.10820
-0.0015801 ± 0.02154983i ζ = 0.07312	-0.00167405 ± 0.02142238i ζ = 0.07790	-0.00096379 ± 0.01991587i ζ = 0.04833

From the table 2 & 3 it can be observed that with SVC and TCSC in the network the damping ratio of the modes improve when it is located at bus-8.

IV. MATERIALS AND METHODS

Residue: Let us start from the mathematical model a dynamic system expressed in terms of a system of nonlinear differential equations:

$$\dot{x} = F(x,t) \qquad \text{--- (9)}$$

If this system of non-linear differential equations is linearized around an operating point of interest x = x_0, it results in:

--- (10)

,,

Assume that an input u(t) and an output y(t) of the linear dynamic system (10) have defined:

$$\dot{x}(t) = Ax(t) + Bu(t)$$
$$y(t) = Cx(t) \quad \text{--- (11)}$$

Considering (11) with Single Input and Single Output (SISO) and assuming D = 0, the open loop transfer function of the system can be obtained by:

$$G(s) = \frac{y(s)}{u(s)}$$
$$= C(sI - A)^{-1}B \quad \text{--- (12)}$$

The transfer function G(s) can be expanded in partial fractions of the Laplace transform of y in terms of C and B matrices and the right and left eigenvectors as:

$$G(s) = \sum_{i=1}^{N} \frac{C\phi_i \psi_i B}{(s - \lambda_i)}$$
$$= \sum_{i=1}^{N} \frac{R_{ijk}}{(s - \lambda_i)} \quad \text{--- (13)}$$

Where, Rijk is the residue associated with ith mode, jth output and kth input. Rijk can be expressed as:

$$R_{ijk} = C_j v_i w_i B_k \quad \text{--- (14)}$$

Where, vi and wi denote the right and left eigenvectors, respectively associated with the ith Eigen value.
This can be expressed in terms of mode controllability and observability. The controllability of mode i from the kth input is given by:

$$CI_{ik} = |w_i B_k| \quad \text{--- (15)}$$

The measure of mode observability of mode *i* from output j is given by:

$$Obsv_{ij} = |C_j v_i| \quad \text{--- (16)}$$

It is clear that:

$$|R_{ijk}| = |C_j v_i w_i B|_k = obsv_{ij} * cont_{ik} \quad (17)$$

Each term in the denominator, Rijk, of the summation is a scalar called residue. The residue Rijk of a particular mode i give the measure of that mode's sensitivity to a feedback between the output y and the input u; it is the product of the mode's observability and controllability.
For the mode of the interest, residues at all locations have to be calculated. The largest residue then indicates the most effective location of FACTS device.

V. RESULTS

The effectiveness of the proposed method was tested on WSCC 3 machine, 9bus system. The results for the system are presented as follows:

The system consists of 3generators, three consumers and 6 branches with generator 1 taken as reference generator. The equivalent power system of south Malaysian peninsular is depicted in Fig. 3.

Table 4: Placement of SVC using residue factor at different load buses

Bus	Residue Factor of SVC	Residue Factor of TCSC
5	0.02394	4.02632e+002
6	0.03143	2.26273e+002
8	0.08916	1.20044e+002

Placement: The Residue Factor at load buses are computed for SVC and TCSC are given in Table 4.
It is observed from Table 4 that bus 8 has the maximum residue factor value. Thus, bus 8 is the best location for placement of SVC and TCSC device

VI. CONCLUSION

This paper presented the location and development methodology of the small signal stability program with FACTS devices in a multi-machine power system. Much of the earlier work relevant to small signal stability enhancement using FACTS stabilizers has used the classical model of the synchronous machine neglecting the effect of electrical circuit dynamics. This paper has presented a systematic and generalized approach for small signal modeling and a method called 'Location index' for the location of FACTS device. It should be noted that this paper makes use of local feedbacks as stabilizing signals for the location of FACTS based damping controllers.

APPENDIX

The data for FACTS devices are given below in p.u

R	:	0	X	:	0.025
R_C	:	0.077	C	:	0.2592
K	:	10	T_1	:	1.1
K_d	:	10	T_2	:	0.05
K_{Mac}	:	1	T_{Mac}	:	0.01
K_p	:	10	K_I	:	1

REFERENCES

[1]. P. Kundur, "Power System Control and Stability", New York McGraw-Hill, 1994.
[2]. Haque, M.H., 2000. Optimal location of shunt FACTS devices in long transmission lines. Proceedings on Generation Transmission and Distribution, July 2000, IEEE Xplore Press, USA., pp: 218-222. DOI: 10.1049/ip-gtd:20000412.
[3]. A.E.Hammad, "Analysis of Power System Stability Enhancement by Static Var Compensators", IEEE Trans.Power Syst., Vol. PWRS-1, No.4, pp.222-228, Nov 1986.

[4]. K.Keerthivasan, V.Sharmila Deve, Jovitha Jerome and R.Ramanujam, "Modeling of SVC and TCSC for power system dynamic simulation", IEEE Seventh International Conf. Power Engineering, pp.696-700, 2005.

[5]. M.W. Mustafa and N. Magaji, "Optimal Location of Static Var Compensator Device for Damping Oscillations", American J. of Engineering and Applied Sciences 2 (2): 353-359, 2009.

[6]. W.Freitas and A.Morelato, "A generalized current injection approach for modeling of FACTS in power system dynamic simulation", IEEE Seventh International Conf.AC-DC Power Transmission, pp.175-180, 2001.

[7]. P.M.Anderson and A.A.Fouad, "Power System Control and Stability". John Wiley & Sons, Inc., Publication, 2003.

[8]. R.Ramanujam, "Power System Dynamics-Analysis and Simulation", PHI Learning Private Limited, 2009.