OPTIMAL LOCATION OF TCSC DEVICE FOR DAMPING OSCILLATIONS

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ABSTRACT

This paper proposes a residue factor method to obtain the optimal location of the Thyristor Controlled Series Capacitor (TCSC) device to damp out the inter-area mode of oscillations. The residue method is base on the facts that it is the product of the mode's Observability and controllability index of TCSC controllers to the critical mode. The placements of TCSC controllers have been obtained for the base case and for the dynamic critical contingences. Eigen value analyses are used to assess the most appropriate input signals (stabilizing signal) for supplementary damping control of TCSC. The Right-Half Plane zeros (RHP-zeros) and Hankel Singular Value (HSV) is used as tools to select the most receptive signal to a mode of the Interarea oscillation. The effectiveness of the proposed method of placement is demonstrated on practical network of 25 bus south Malaysian Power system.

Keywords: TCSC, power system oscillations, linear models, eigenvalues, HSV, RHP-zeros and residue factors.

INTRODUCTION

Damping of electromechanical oscillations between interconnected synchronous generators is necessary for a secure system operation. Power system stabilizers (PSSs) are effective for controlling system oscillations but are usually designed for damping local electromechanical oscillations. The behaviour of low frequency inter-area oscillations is generally determined by global parameters of larger parts of the power system. The limited influence on inter-area modes, however, leads us to the fact that they may not be considered as the only solution to damp inter-area oscillations. Flexible AC Transmission Systems are being increasingly used to improve the utilization capacity of the existing transmission systems.

Flexible AC Transmission System (FACTS) is a technology based solution to help the utility industry deal with changes in the power delivery business. A major thrust of FACTS technology is the development of power electric based systems that provide dynamic control of the power transfer parameters transmission voltage, line impedance and phase angle (A. Kazemi and Andami April 2004).

The Thyristor Controlled Series Capacitor (TCSC), which is a series device, provides dynamically variable series impedance to regulate the power at a line where it is connected (A. Kazemi and Andami April 2004; A. R Messina and M. 1999). Application of TCSC device for evaluating system damping using various techniques are reported in the literature (A.B. Leirbukt *et al*., 1999; Bamasak 2005; Chaudhuri and Pal 2004; E.V. Larsen *et al*., 1995; Haque 2006; J.H. Chow and 1987; L. Fan and Feliachi 2001), and the usefulness of damping the oscillations depend on the location of TCSC controllers. Several methods have been proposed for the placement of FACTS (TCSC) controllers. The proposed method by authors (K.S.Verma *et al*., 2001; M.H.Haque 2000; S.N Singh and David. 2000; Singh and David 2000.) considered only static criterion base on improving power transfer, available transfer capability (ATC) and loss minimizations and did not took into account any dynamic criteria for the placement of the TCSC controllers.

Kalyan Kumar and Singh (B. Kalyan Kumar *et al*., 2007) used modal controllability index, for effective damping, to find suitable location for damping inter-area mode of oscillations. This method, however, considers the model of the system with and without FACTS device to determine the maximum value of the controllability index corresponding to the most critical mode which considers only the input of the FACTS devices without knowing what is happening in the output of the FACTS devices through observability index.

The selection of appropriate feedback signal to FACTS controllers and effective tuning for improving the damping controls is an important consideration. According to (A.B. Leirbukt *et al*., 1999; Bikash Pal and Chaudhuri 2005. N.Mithulananthan 2003.) the most suitable supplementary input signals are locally measured transmission line-current magnitude or locally measured active power. In (S. Lee and C.C. Liu 1994.; Zhou 1993) used generator angular speed as a supplementary input signal.

Farsangi et al (Farsangi *et al*., June 2005, 2004) proposed a method for selecting suitable feedback signal to FACTS controllers for improving the damping. She used the Minimum Singular Values (MSV), the Right-Half Plane zeros (RHP-zeros), the Relative Gain Array (RGA) and the Hankel Singular Values (HSV) as indicators to find stabilizing signals in the single-input single-output (SISO) and multi-input- multi-output (MIMO) systems. But she did not suggest any criterion for placing FACTS controllers.

Sadikovic and Anderson (R. Sadikovic 2005) used residue, called location index for effective damping, to find suitable location for damping inter-area mode of oscillations. The authors used only UPFC placement based on only single operating condition.

In this paper, a residue has been proposed for optimal placement of TCSC controllers. These residues have been calculated for the base case and for appropriate operating condition. In addition, the best selection of the input signals for FACTS device proposed by (Farsangi *et al.* June 2005, 2004) has also been applied in this paper and extended to practical system that is TNB 25 bus system.

RESIDUE FACTOR

Let us start from the mathematical model of a dynamic system expressed in terms of a system of non-linear differential equations:

$$\dot{x} = F(x,t) \tag{1}$$

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

$$\Delta\dot{x} = A\Delta x(t) \tag{2}$$

Assume that an input u (t) and an output y (t) of the linear dynamic system (2) have been defined as

$$\begin{aligned} \dot{x}(t) &= Ax(t) + Bu(t) \\ y(t) &= Cx(t) \end{aligned} \tag{3}$$

Considering (3) with single input and single output (SISO) and assuming D = 0, the open loop transfer function of the system can be obtained by

$$\begin{aligned} G(s) &= \frac{y(s)}{u(s)} \\ &= C(sI-A)^{-1}B \end{aligned} \tag{4}$$

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

$$\begin{aligned} G(s) &= \sum_{i=1}^{N} \frac{C\phi_i\psi_i B}{(s-\lambda_i)} \\ &= \sum_{i=1}^{N} \frac{R_{ijk}}{(s-\lambda_i)} \end{aligned} \tag{5}$$

Where R_{ijk} is the residue associated with ith mode, jth output and kth input? R_{ijk} Can be expressed as:

$$R_{ijk} = C_j v_i w_i B_k \tag{6}$$

Where VI**,** and w_i denote the right and left eigenvectors respectively associated with the ith eigenvalue.

This can be expressed in terms of mode controllability and observability. The controllability of mode i from the kth input is given by:

$$CI_{ik} = |w_i B_k| \tag{7}$$

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

$$Obsv_{ij} = |C_j v_i| \tag{8}$$

It is clear that

$$|R_{ijk}| = |C_j v_i w_i B_k| = obsv_{ij} * cont_{ik} \tag{9}$$

Each term in the denominator, R_{ijk}, of the summation is a scalar called residue. The residue R_{ijk} 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. It has been proven in (Cai 2004)that when the feedback control is applied, the shift of an eigenvalues can be calculated by

$$\Delta\lambda_i = \boldsymbol{R_i H(\lambda_i)} \tag{10}$$

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 (Sadikovi C 2006).

CALCULATION FOR MODEL RESIDUE

Dynamic model of the system

Each generator of the test systems is equipped with the AVR Type III which is the simplest AVR model that can be used for rough stability evaluations (Milano March 8, 2007)**.**The generator is described by six order non-linear mathematical model while exciter by third order**.**The sixth order model of generator is obtained assuming the presence of a field circuit and an additional circuit along the d-axis and two additional circuits along the q-axis. The generator state variables are $(\delta, \omega, e'_q, e'_d, e'_q\ and\ e''_d)$ while exciter has the following state variables (v_m, v_r, v_f) (Milano March 8, 2007).The state variables are also defined in (M.A. Pai *et al.*, 2004).

Model based on numerical linearization

In Power system analysis toolbox program, the test system linearization is done numerically as explained below.

$$\dot{x} = f(x,u) \tag{11}$$

$$0 = g(x,u) \tag{12}$$

$$y = h(x,u) \tag{13}$$

Linearizing equation (10) to (12) around the equilibrium point gives the following equations (13) to (15).

$$\Delta\dot{X} = A\Delta X + B\Delta U \tag{14}$$

$$0 = P\Delta X + Q\Delta U \tag{15}$$

$$\Delta\dot{Y} = C\Delta X + D\Delta U \tag{16}$$

Where A, B, P, Q, C, and D are the matrices of partial derivatives in (13) to (15) evaluated at equilibrium points. In (Milano March 8, 2007) those equilibrium points or initials conditions are obtained after power flow simulation of the test system.

Where

$$\Delta X = [\Delta\delta_i, \Delta\omega_i, \Delta e'_{di}, \Delta e'_{di}, \Delta e'_{qi}, \Delta e''_{qi}, \Delta v_{mi}, \Delta v_{ri}, \Delta v_{fi}] \tag{17}$$

$$\Delta U = [\Delta I_{di}, \Delta I_{qi}, \Delta I_{did}, \Delta\theta_i, \Delta V_i, \Delta\theta_k, \Delta V_k] \tag{18}$$

Iq and Id are the quadrature and direct axis components of the stator current, respectively, while $V\angle\theta$ is the complex bus voltage.

Residue factor for TCSC device

Consider a line l, having line reactance X_L, conneted between buses k and m. If the reactance of TCSC placed in the line l is Xc, the percentage of compensation of TCSC (kc) is given by

$$kc = \frac{X_C}{X_L} \tag{19}$$

The line power flows are functions of the degree of compensation of the TCSC. The real power (**P**$_{km}$) and reactive power (**Q**$_{km}$) in a line l (connected between buses k and m), with TCSC having degree of compensation Kc and neglecting the line resistance, can be written as (Bikash Pal and Chaudhuri 2005)

$$\boldsymbol{P_{km}} = \frac{\boldsymbol{K_c}}{\boldsymbol{K_c}-1}\boldsymbol{B_{km}V_kV_m\sin(\theta_k - \theta_m)} \tag{20}$$

$$\boldsymbol{Q_{km}} = \frac{\boldsymbol{K_c}}{\boldsymbol{K_c}-1}\boldsymbol{B_{km}}\left(\boldsymbol{V_k^2 - V_kV_m\cos(\theta_k - \theta_m)}\right) \tag{21}$$

Where B_{km} is the susceptance of the line l, $\boldsymbol{V_k}\ \angle\delta_k$ is the complex voltage at bus K. Considering the initial value of K_c to be zero, (20) and (21) can be Linearized, around Kc,

$$\Delta\boldsymbol{P_{km}} = \Delta K_c\boldsymbol{V_kV_mB_{km}\sin(\theta_k - \theta_m)} \tag{22}$$

$$\Delta\boldsymbol{Q_{km}} = \Delta K_c\boldsymbol{B_{km}}\left(\boldsymbol{V_k^2 - V_kV_m\cos(\theta_k - \theta_m)}\right) \tag{23}$$

Combining (22) and (23) with (15), yields

$$\boldsymbol{P}\Delta\boldsymbol{X} + \boldsymbol{Q}\Delta\boldsymbol{U} + \boldsymbol{F}\Delta\boldsymbol{K_c} = 0 \tag{24}$$

Where matrix F contains partial derivatives of power balance equation at all the buses with respect to degree of compensation, provided by TCSC, initially assumed to be placed in all the lines. The order of matrix F is (2m +2n) X nl, where nl is the number of lines
Solving (14), (15) and (24) provides

$$\Delta\boldsymbol{X}=\left(\boldsymbol{A}-\boldsymbol{BQ^{-1}P}\right)\Delta\boldsymbol{X}+(-\boldsymbol{BQ^{-1}F})\Delta\boldsymbol{K_c} \tag{25}$$

$$\Delta\boldsymbol{Y}=\left(\boldsymbol{E}-\boldsymbol{DQ^{-1}P}\right)\Delta\boldsymbol{X}+(-\boldsymbol{DQ^{-1}F})\Delta\boldsymbol{K_c} \tag{26}$$

Equations (25) and (26) can be rewritten as

$$\Delta\dot{\boldsymbol{X}}=\boldsymbol{A'}\Delta\boldsymbol{X}+\boldsymbol{F'}\Delta\boldsymbol{K_c} \tag{27}$$

$$\Delta\boldsymbol{Y}=\boldsymbol{C'}\Delta\boldsymbol{X}+\boldsymbol{D'}\Delta\boldsymbol{K_c} \tag{28}$$

The controllability index of the TCSC, placed in line *l*, to the kth mode is defined

$$\mathrm{CI}_i = w_k^T F_i' \tag{29}$$

While the observability index of the TCSC in line *l*, to the kth mode is defined

$$\mathrm{OI}_i = C_i' v_k \tag{30}$$

Where *w* and *v* are the left and right eigen vector of matrix A' corresponding to the kith mode respectively.
Therefore the product of equation (29) and (30) will give the Residue factor defined by equation (9)

SELECTION OF FEEDBACK SIGNALS FOR TCSC DEVICE

Right Hand Plane (RHP) Zeros Consider an open loop system with a transfer function from output y_i to input u_i as G(s).
Where

$$G(s)=\frac{b(s)}{a(s)} \tag{28}$$

There may be a finite values of s for which b(s) =0 and these are called the zeros of G(s), likewise the values of s that make a(s) =0 are called pole of G(s), let these zeros be donated as z_i and poles be p_i.
If the open loop system is applied, a constant controller Kp, the closed loop system with negative feedback can be express as

$$G_{closed}(s)=\frac{K_p b(s)}{a(s)+b(s)K_p} \tag{29}$$

From equation (29) the locations of zeros that is zi is maintained while poles location change from a(s) = 0 that is pi to [a(s) + b(s) Kp] = 0 by the feedback signal. From the same equation (29) we have the following observations:
If the feedback gain increases, the closed loop poles will moved from open loop poles to open loop zeros, this may lead to instability (Farsangi *et al.*, June 2005; Maciejowski 1989).

If the feedback gain decreases, the closed loop poles will move to open loop poles.

From observation number one, if the open loop zeros are in right half plane then the closed loop poles can change from stable pole to unstable and can lead to pole zero cancellation. Therefore, the selection of feedback signal should be made in such a way that the closed loop system has a minimum number of the RHP-zeros, which are required not to lie within the closed loop bandwidth (Farsangi *et al.*, 2004; Maciejowski 1989)

CRITERIA FOR OPTIMAL PLACEMENT OF TCSC DEVICE

Dynamic criterion based on residue

The TCSC controllers have been placed on the basis of the maximum value of the residue corresponding to the most critical mode. In this study, only inter-area modes of oscillations have been considered.TCSC has been placed at a line having maximum value of the residue.

For validating the placement of TCSC device for various operating conditions, few critical single-line (N-1) contingency cases were considered, and the residue factors were calculated for three critical contingency cases. The critical contingencies were selected on the basis of dynamic contingency selection base on damping factor (F. Albuyeh *et al*., 1982; Hsu November 1990).

The damping factor ς which is defined as the damping ratio of the critical inter- area rotor angle mode in the system under an operating condition is small-signal secure if $\varsigma \geq \varsigma_C$ where ς_C is the damping threshold (normally in the range of 3%–5%)(C. Y. Chung et al. 2004). But in this study ς_C is referred to a base case critical inter-area mode damping factor. If the damping factor of post contingency case is less than the base case damping factor or power flow diverges, then the case is selected as a severe case.

Procedure

Contingency assessment for small signal stability analysis involves the following steps:

(i) Perform free fault power flow and eigen value analysis;
(ii) Determine inter area mode from the eigen value of the system;
(iii) Performing damping analysis on the power flow condition base on inter area mode;
(iv) Select contingency base on overloaded lines; and
(v) Repeat step (1-3) for each contingency selected.

RESULTS AND DISCUSSIONS

The effectiveness of the proposed method was tested on TNB 25 bus system of south Malaysian network. The results for the system are presented as follows:

TNB 25 Bus Systems

The system consists of 12 generators, five consumers and 37 branches with generator 3 taken as reference generator. The equivalent power system of south Malaysian peninsular is depicted in Figure-1. Modal analysis shows that, in the base case, the critical mode that is an interarea mode has an eigen values of -0.11223±j6.2356 and damping ratio of 0.017995, which is relatively low.

The Residue Factors for weakly damped inter-area mode, computed for TCSC are given in Table-1. All the lines, excluding Transformer lines are considered. It is observed from Table-1 that line 8-13 has the maximum residue factor value for placement of TCSC device on base case but for validating the location critical contingency ranking as listed in Table-2 according eigen value concepts explained in previous section. The residue factors were computed for three different critical contingency cases only and are shown in Table-1. Also it can be seen that Line 8-13 has maximum residue factors for the outages of line 7-10 and 12-13, respectively. While for the outage of line 12-13 line 7-10 has the highest residue factor. After finding the average of the residue factor computed for all the cases, line 8-13 still found to be the most suitable location for the TCSC placement.

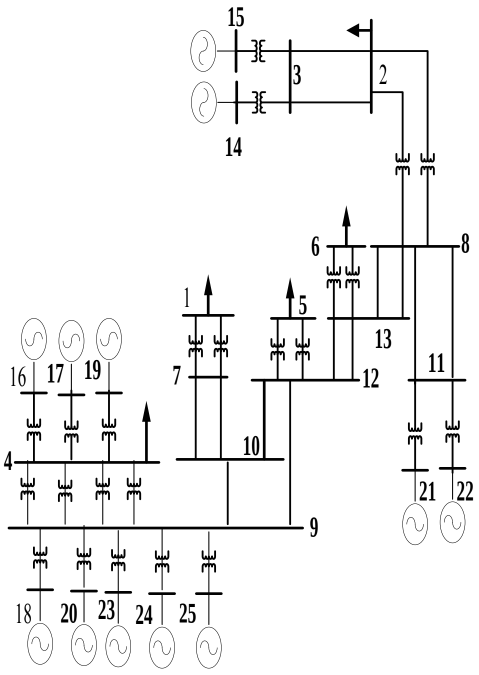

Figure 1. 25-Bus equivalent of south Malaysian power system

Table-1. Placement of TCSC using Residue Factor. Techniques with different operating conditions for TNB 25 Bus system.

Line	**Base Case**	**Line 7-10 outage**	**Line 8-13 outage**	**line 12-13 outage**	**Average**
7-10	0.001	0.0033	6.68E-11	0.019	0.0058
8 - 11	0.003	0.0029	0.1607	0.0031	0.0424
8-13	0.0895	0.102	0.6174	0.0065	0.2039
9-10	0.0087	0.011	0.026	0.0031	0.0122
9-12	0.0013	0.0021	0.2408	0.0247	0.0672
12-13	0.0179	0.0203	0.1137	0.0019	0.0385
2-3	0.014	0.001	4.32E-08	0.0046	0.0049

A Hankel singular value (HSV) and RHP zeros analysis explained in this paper were carried out to find the suitable feedback signals for the TCSC controller [25]. Line3-4 reactive power flow which is a local signal, has been obtained as the best feedback signal for the TCSC supplementary controller compared to others local and remote signals analyzed.

Table-2. (N-1) Dynamic critical contingency.

Line outage	Eigen values	Damping	Freq.	Ran-king
Base case	-1122±j6.2356	0.017995	0.99259	
8-13	-.11152±j6.244	0.017857	0.99396	1
12-13	-0.1117±j6.242	0.017891	0.99396	2
2-3	-.11187±j6.240	0.017925	0.99326	3
8-11	-11195±j6.239	0.017941	0.9931	4
7-10	-.11196±j6.239	0.017943	0.99308	5
9-10	- .1122±j6.236	0.017993	0.99262	6
10-12	- .11222±j6.236	0.017993	0.99262	7

Table-3. Damping for TNB 25 bus with TCSC and without.

	Real	Imag.	Damping
NO TCSC	-0.11223	6.2356	0.01799
TCSC	-0.2117	-6.243	0.03389

Performance evaluation of the system

To test the effective location, a supplementary controller is designed for TCSC using loop shaping techniques (Cai 2004). A three-phase fault was applied at bus 17 that was cleared 50 ms later, impacts on damping of the critical

Inter-area mode with and without TCSC controllers are given in Table-3. It can be seen that with the placement of TCSC controllers, the system damping improved significantly. The step input was applied to the exciter of generator G17 to observe the impact of TCSC controllers on the inter-area mode damping, generator G17 oscillates against G19, G23 and, G24. It is observed from Figure-2 that the speed deviation of generator G17 continues to oscillate without TCSC device. The speed deviation oscillations are damped out after the placement of TCSC device with the controller and settles down in about 7s. The remaining responses of the system are shown in Figures 3 and 4.

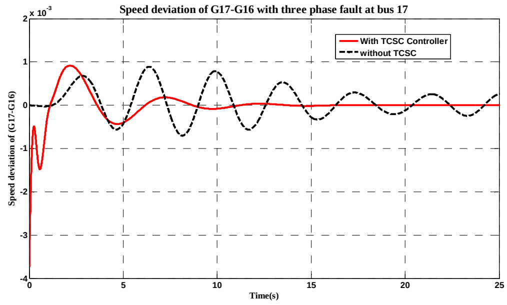

Figure-2. Speed deviation of (G17-16) response with three phase fault.

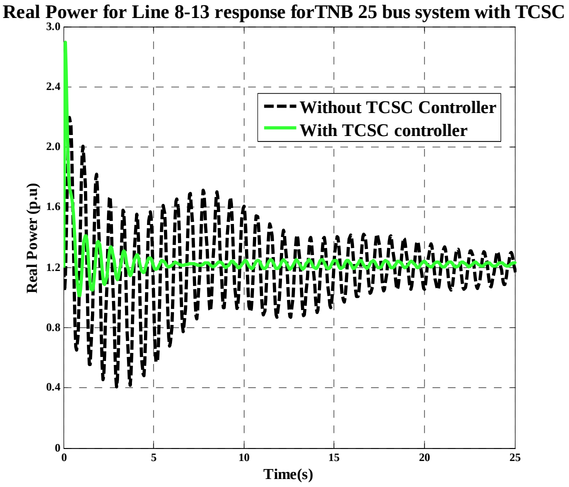

Figure-3. Line 8-13 real power responses with three phase fault.

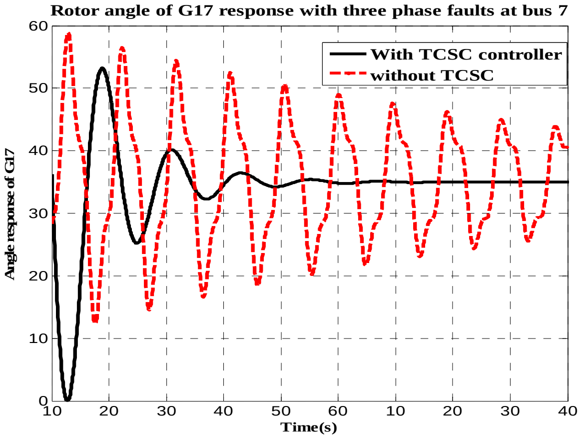

Figure-4. Rotor angle of G17 response with three phase fault.

CONCLUSIONS

Residue factor for the placement of TCSC device have been found corresponding to a critical inter-area mode for reduce model of 25 bus south Malaysian power system.

These factors have been computed for the base case and for dynamic critical contingencies and the TCSC device has been placed in a line having average value of the residue factor.

The time domain simulations have shown that the inter-area mode is significantly improved in the damping of oscillations with the TCSC device when placed at the best location using the proposed residue factor. All the simulations were done with PSAT toolbox in Matlab environment.

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