

Static and Dynamic Location of Variable Impedance Devices for Stability Studies

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ABSTRACT

This study used the concept of model controllability and observability in product form called residue factor to find the best location of Thyristor-Controlled based series and shunt devices called variable impedance devices. The success of this controller depends on its best possible location in busbar or line of power system network. The method is based on the relationship between the parameters of variable impedance devices to the vital modes. Linearization of non linear model of Power system and the thyristors based FACTS devices provide means of computing residue factor and singular value factor. The location of variable impedance or thyristors based controllers have been calculated for the base case only. The usefulness of these methods of placement considered 16 machines, 68 bus systems.

Keywords: Thyristor-Controlled Series Compensator (TCSC), Static Var Compensator (SVC), New England Test System (NETS), New York Power System (NYPS)

1. INTRODUCTION

FACTS devices based on Variable impedance devices or thyristors based controllers includes Static VAR Compensators (SVCs) and Thyristor-Controlled Series Capacitors (TCSC) can improve power control and system damping (Nazarpour *et al.*, 2006; Magaji and Mustafa, 2010). Positioning of these devices in large power system is very important in terms of controlling of system modes, therefore, there is need to consider several conditions in dealing with this difficulty. Among the factors to take into account are (Pal and Chaudhuri, 2005; Magaji and Mustafa, 2009a; 2009b; Larsen *et al.*, 1995; Hassan *et al.*, 2010):

- Identification of busbar for shunt FACTS devices
- Branches or lines for series FACTS devices
- Best stabilizing signals for supplementary controllers

Application of FACTS devices for evaluating system damping using various techniques are reported in

the literature (Pal and Chaudhuri, 2005; Magaji and Mustafa, 2009a; 2009b; Larsen *et al.*, 1995; Hassan *et al.*, 2010; Mustafa and Magaji, 2009; Sadikovic *et al.*, 2006; Milano, 2007) and the usefulness of damping the oscillations depends on the location of FACTS controllers.

Sadikovic *et al.* (2006) adopted the approach of location index for efficient damping, to find suitable location for damping inter-area mode of oscillations. The authors consider only one FACTS controller based on single operating condition.

The selection of best feedback signal to FACTS controllers and effective tuning for improving the damping controls is an important consideration. According to (Magaji *et al.*, 2010; Zhou, 1993) the best input signals for power oscillation controller are locally measured transmission line-current magnitude or locally measured active power. Lee and Liu (1994) and Zhou (1993) applied the remote signal that is generator angular speed as a auxiliary input signal. Controllability and observability measures is of

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particular interest when the issue of system damping is taken into account.

In this study, the approach adopted details the location of SVC and TCSC devices based on model residue factor and it has been compared with static approach based on Singular Value Decomposition (SVD) adopted from (Ekwue *et al.*, 1999). The proposed methods have been tested on a reduced order equivalent of the interconnected New England Test System and New York Power System. The effectiveness of the proposed method has been demonstrated through the time domain simulation in matlab software.

2. MATERIALS AND METHODS

2.1. Formulation of the State Equation

Multi-machine power system dynamic behavior in a small signals model is usually expressed as a set of non-linear Differential and Algebraic (DAE) equations. The high frequency network and stator transients are usually ignored when the analysis is focused on low frequency electromechanical oscillations. The initial algebraic variables such as bus voltages bus angles and some control variables are obtained through a standard power flow solution (Milano, 2007). The state model given by (Hassan *et al.*, 2010) is considered to represent system dynamic behaviour. In this model, the power system is seen as constituted of dynamic subsystems interacting through the transmission network. Two types of dynamic subsystems have so far been taken into account, that is to say synchronous machines and thyristor-controlled devices. The dynamic behaviour of system is expressed in (DAE) as shown in Equation 1-3 after it has been linearized around the equilibrium point:

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

$$0 = g(x, z, u) \tag{2}$$

$$y = h(x, z, u) \tag{3}$$

Linearizing (1) to (3) around the equilibrium point $\{x_0, z_0, u_0\}$ gives the following Equation 4-6:

$$\Delta \dot{x} = \frac{\partial f}{\partial x} \Delta x + \frac{\partial f}{\partial z} \Delta z + \frac{\partial f}{\partial u} \Delta u \tag{4}$$

$$0 = \frac{\partial g}{\partial x} \Delta x + \frac{\partial g}{\partial z} \Delta z + \frac{\partial g}{\partial u} \Delta u \tag{5}$$

$$y = \frac{\partial h}{\partial x} \Delta x + \frac{\partial h}{\partial z} \Delta z + \frac{\partial h}{\partial u} \Delta u \tag{6}$$

Elimination of algebraic variable vector Δz from Equation 4-6, gives Equation 7-13:

$$\begin{aligned} \Delta x &= A_1 \Delta x + B_1 \Delta u \\ \Delta y &= C_1 \Delta x + D_1 \Delta u \end{aligned} \tag{7}$$

where, A_1 is a system matrix, B_1 and C_1 are the input and output-vector matrices, respectively. Let $\lambda_i = \sigma_i + j\omega_i$ be the i -th eigenvalue of the state matrix A_1 . The real part of the eigenvalues gives the damping and the imaginary part gives the frequency of oscillation. The relative damping ratio is given by:

$$\zeta = \frac{-\sigma}{\sqrt{\sigma^2 + \omega^2}} \tag{8}$$

If the state space matrix A_1 has n distinct eigenvalues and Λ , Φ and Ψ below are the diagonal matrix of eigenvalues and matrices of right and left eigenvectors, respectively:

$$\begin{aligned} A_1 \Phi &= \Phi \Lambda \\ \Psi A_1 &= \Lambda \Psi \Rightarrow \Psi = \Phi^{-1} \end{aligned} \tag{9}$$

In order to modify a mode of oscillation by feedback, the chosen input must excite the mode and it must also be visible in the chosen output. The measures of those two properties are the controllability and observability, respectively. The modal controllability and modal observability matrices are defined as follows:

$$\begin{aligned} B_m &= \Phi^{-1} B_1 \\ C_m &= C_1 \Phi \end{aligned} \tag{10}$$

The mode is uncontrollable if the corresponding row of the matrix B_m is zero. The mode is unobservable if the corresponding column of the matrix C_m is zero. If a mode is either uncontrollable or unobservable, feedback between the output and the input will have no effect on the mode. The open loop transfer function of a SISO (single input single output) system is:

$$G(s) = \frac{\Delta y(s)}{\Delta u(s)} = C_1 (sI - A_1)^{-1} B_1 \tag{11}$$

$G(s)$ can be decomposed using partial fractions of the Laplace transform of y in terms of C_1 , B_1 , matrices and the right and left eigenvectors as:

$$G(s) = \sum_{i=1}^N \frac{C_i \phi_i \Psi_i B_i}{(s - \lambda_i)} \tag{12}$$

$$= \sum_{i=1}^N \frac{R_i}{(s - \lambda_i)}$$

Each term in the numerator, R_i , of the summation is a scalar called residue. The residue R_i of a specific mode i gives 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. When applying the feedback control, eigenvalues of the initial system $G(s)$ are changed. It can be proven, that when the feedback control is applied, the shift of an eigenvalues can be calculated by:

$$\Delta \lambda_i = R_i H(\lambda_i) \tag{13}$$

It can be observed from (19) that the shift of the eigenvalue caused by the controller is proportional to the magnitude of the corresponding residue.

2.2. Variable Impedance Models

2.2.1. TCSC Model

A thyristor Controlled Series Capacitor module consists of a fixed series Capacitor (FC) in shunt with a Thyristor Controlled Reactor (TCR) as shown in **Fig. 1**. The Thyristor Controlled Reactor is created by a reactor in series with a bi-directional thyristor valve that is fired with an angle ranging between ninety degree and one eighty degree with respect to the capacitor voltage (Magaji *et al.*, 2010).

2.3. Dynamic Model

The dynamic characteristics of the TCSC is assumed to be model by a first order time constant in place of the response time of the TCSC control circuit which is expressed a Equation 14:

$$\Delta k_c = \frac{1}{T_{tcsc}} (\Delta k_{ref} - \Delta k_c + \Delta k_{css}) \tag{14}$$

The low frequency dynamic model (Magaji and Mustafa, 2009a) of a thyristor controlled series capacitor is given in **Fig. 2**. The symbol Δk_c is the small change in value of k_c about the nominal value of 50% compensation. Δk_{ref} is the reference setting which is augmented by Δk_{css} within a limit of $\Delta k_{cmax} = 0.1$ and

$\Delta k_{min} = -0.1$ in the company of supplementary damping controller (Chaudhuri and Pal, 2004).

2.4. SVC Devices

The Static VAR Compensator (SVC) is a parallel device whose main work is to control the voltage at a chosen bus by appropriately regulating its equivalent reactance. A basic circuit consists of a cascade capacitor bank, C , in shunt with a thyristor-controlled reactor, L , as shown in **Fig. 3**. In practice the SVC can be seen as an regulating reactance (Nazarpour *et al.*, 2006) that can perform both inductive and capacitive compensation.

2.5. Dynamic Model

The low frequency dynamic model is shown in **Fig. 4**; the model that is used here assumes a time constant regulator. In this model, a total reactance b_{SVC} is assumed and the following differential equation holds (Milano, 2007; Magaji and Mustafa, 2008) Equation 15:

$$\dot{b}_{SVC} = (K_r (V_{ref} + v_{POD} - V) - b_{SVC}) / T_r \tag{15}$$

The regulator has an anti-windup limiter, thus the reactance b_{SVC} is locked if one of its limits is reached and the first derivative is set to zero (Milano, 2007; Magaji and Mustafa, 2008).

The auxiliary input Δv_{POD} is used to connect the POD controller for damping oscillations while V_{ref} to maintain acceptable voltage at the SVC bus. TCR of 150MVAR is normally connected in parallel with fixed capacitor of 200MVAR correspond to a limit of 2.0pu to -1.0 pu voltage (Milano, 2007).

2.6. Computational Procedure for Residue Factor

The allocation algorithm can be formulated as follows:

- Perform free fault power flow and eigenvalues analysis
- Identify inter area mode
- Model the FACTS device
- Place the TCSC in series and SVC in shunt in the model
- Perform power flow and obtain linear model of the system
- Calculate residue factor based on SVC/TCSC location under all operating conditions
- Repeat the procedure (i-vi) for all line and bus location to get the Highest value

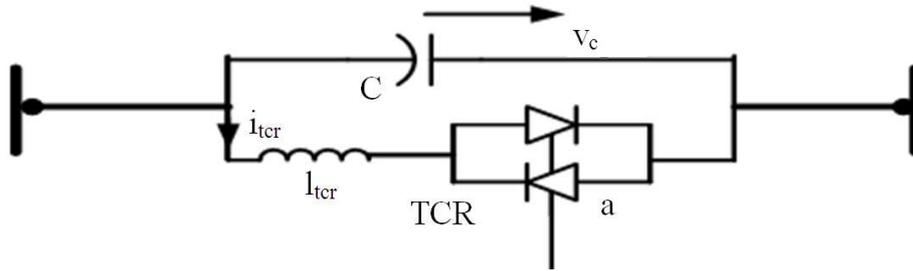


Fig. 1. TCSC model

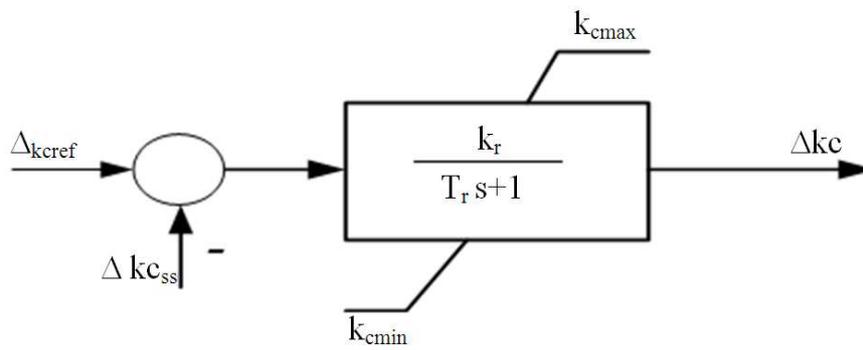


Fig. 2. TCSC regulator

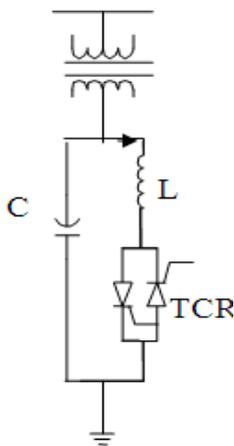


Fig. 3. SVC model

2.7. Singular Value Decomposition

SVD consists of finding the eigenvalues and eigenvectors of system either express in state space or transfer function of SISO $|G(s)|$ system which is more significant than eigenvalues techniques in terms of magnitude of According to (Ekwue *et al.*, 1998) the SVD theorem is stated as follows.

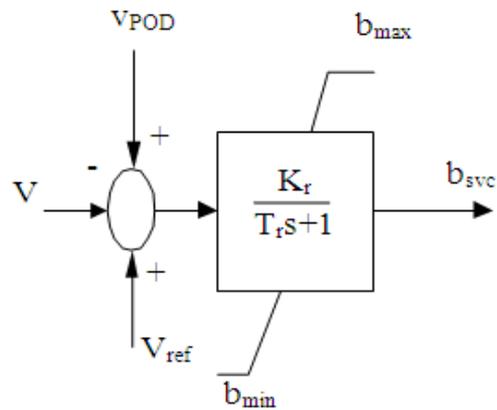


Fig. 4. SVC regulator

Let $G \in C_r^{m \times n}$ There exist unitary matrices $U_1 \in C^{m \times m}$ $V_1 \in C^{n \times n}$ such that $G = U_1 \Sigma V_1^H$.

Where:

$$\Sigma = \begin{bmatrix} s & 0 \\ 0 & 0 \end{bmatrix}$$

$s = \text{diag}(\sigma_1, \dots, \sigma_r)$ with $\sigma_1 \geq \sigma_2 \geq \dots \geq \sigma_r > 0$.

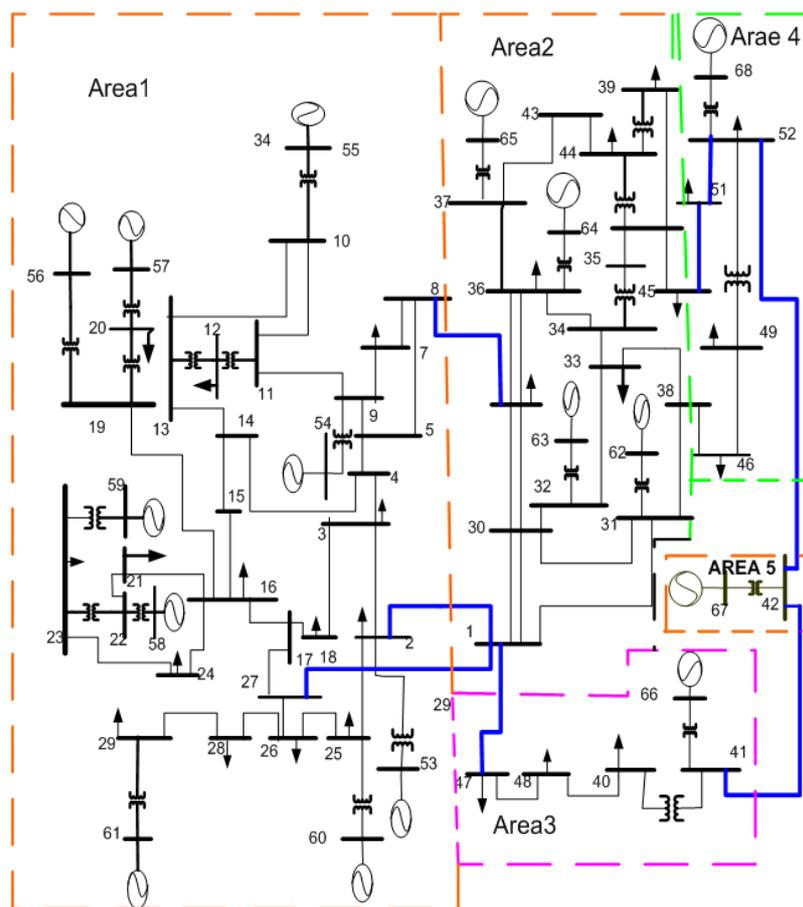


Fig. 5. One-line diagram for 16 machine 68-bus system

U_1 is a matrix of output singular vectors u_i and V_1 is a unitary matrix of input singular vectors v_i .

V_1^H is the complex conjugate transpose of V_1 . The singular values are positive square roots of the eigenvalues of $G^H G$ which are real because the matrix $G^H G$ is symmetric, or in other words Equation 16:

$$\sigma_i(G) = \sqrt{\lambda_i(G^H G)} \quad (16)$$

The input and output directions are connected through the singular value σ_i . σ_1 is the first singular value hence called maximum singular value, similarly σ_r is the minimum singular value.

2.8. Minimum Singular Value Decomposition

The minimum singular value, σ_{\min} could be used as an indicator of voltage stability. The closer to voltage instability the current operating condition is, the smaller

the singular value (Chaudhuri and Pal, 2004). Considering the power flow Equation 17:

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = J \begin{bmatrix} \Delta \theta \\ \Delta V \end{bmatrix} \quad (17)$$

Where:

P = Implies active power

Q = Implies reactive power

Θ = Node angles

V = Node voltage magnitudes and

J = Means the Jacobian matrix of power flow equations

According to the singular value decomposition theorem, the Jacobian matrix, J, is defined as Equation 19:

$$J = V \Lambda W^T = \sum_{i=1}^n V_i \Lambda_i W_i^T \quad (18)$$

where, Λ_i in Equation 18 are the singular values, V_i and W_i are the left and right singular vectors respectively of a power system model, while n is the number of system buses or lines.

As J is a non-singular matrix and V, W are unitary matrices, the effect of small changes in the active and reactive power injections on the bus voltage angles and magnitudes can be written as:

$$\begin{bmatrix} \Delta\theta \\ \Delta V \end{bmatrix} = J^{-1} \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \sum_{i=1}^n \sigma^{-1} W_i V_i^T \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} \quad (19)$$

When power system is close onto voltage collapse, the system characteristic is dominated by the minimum singular value σ_{\min} and its corresponding left and right singular vectors, that is described in Equation 20 and 21:

$$\begin{bmatrix} \Delta\theta \\ \Delta V \end{bmatrix} = \sigma_{\min}^{-1} W_{\min} V_{\min}^T \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} \quad (20)$$

Assuming:

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = V_{\min} \Rightarrow \begin{bmatrix} \Delta\theta \\ \Delta V \end{bmatrix} = \sigma_{\min}^{-1} W_{\min} \quad (21)$$

- From the power flow solution the smallest singular value will be a point to indicate a closeness to static stability limit
- The highest value in W_{\min} indicate the most responsive bus voltages and this indicate the weak buses
- The highest value in V_{\min}^T correspond to the most sensitive direction for changes of active and reactive power injections

2.9. Static Placement Based on Singular Value Decomposition

2.9.1. SVC Locations based on SVD

In this study, the principle used for finding best location of SVC controllers is based on ranking of voltage-weak buses. The value right singular vector with respect to the minimum singular value is considered as an indicator for ranking buses

The highest value in V_{\min} indicate the most responsive bus voltage (critical bus) hence, under any operating condition; those bus that is highest on the

ranked list is bus where SVC should be located for reactive power compensation to help voltage stability (Ekwue *et al.*, 1999).

2.10. TCSC Locations Based on SVD

The location of TCSC is based on reactive power losses of transmission line for voltage stability. The transmission line reactive power losses are the measurable information of transmission lines about voltage stability. The line with the highest change of reactive power loss is the most susceptible to voltage stability. From Equation 22, the incremental changes in reactive power loss for both the sending and receiving ends of transmission lines $\Delta Q_{\text{loss}}(i)$, can be calculated as defined in the study of Ekwue *et al.* (1999). The line is ranked based on participation factor for a transmission line which is defined as:

$$Lf_i = \frac{\Delta Q_{\text{loss}}(i)}{\sum_j \Delta Q_{\text{loss}}(j)} \quad j \in [\text{branches}] \quad (22)$$

3. RESULTS

Modal analysis shows that, in the base case, there is a critical interarea mode with low damping ratio of 0.028438, having eigenvalues $-0.15066 \pm j5.2957$. Analysis of phase angle of the right eigen vectors shows that in this inter-area mode, generator G15, which is in a neighborhood of NYPS, is oscillating against a cluster of generators G13 in NYPS, G9 and G6 in NETS. For this critical mode, the proposed residue, corresponding to the weakly damped inter-area mode, computed for SVC and TCSC are given in **Table 1**. These indices are expressed in the normalized form, only few buses/lines, having significant value of the residue of the two types of FACTS controllers for the base case were determined. **Table 1** shows that lines between buses 51-52 and bus 28 are the optimal locations for TCSC and SVC device respectively.

Hankel Singular Value (HSV) analysis was carried out to find the suitable feedback signals for the FACTS controllers (Magaji and Mustafa, 2009b). Line 51-50 real power flow which is a local signal has been taken as the feedback signal for the TCSC supplementary controller. Current magnitude of Line 27-28 from bus 27 is taken as the feedback signal for the SVC supplementary controller.

Optimal location of these FACTS controllers, based on static criterion was also found using SVD approach mention above and according to (Hassan *et al.*, 2010; Ekwue *et al.*, 1999). From **Table 2** and for two

different operating conditions, that is base case at 100% loading and contingency case at 120% loading the SVD method indicates that the load bus 44 is the Weakest bus hence best location of SVC device. Similarly optimal location of TCSC based on SVD by ranking of critical transmission lines in terms of voltage stability is found to be line between bus 25 and 26 as shown in **Table 3**.

3.1. Performance Evaluation

To test the effective location, a step input was applied to the exciter of generator G1 to observe the impact of FACTS controllers on the inter-area mode damping. It can be seen from **Fig. 6** the inter-area mode, with SVC device, has settled in 9-10 s. The damping is reduced to a minimum and settled in about 5s though with small oscillations after TCSC placed in line 51-52 compared to SVC placement.

Table 4 shows the eigen-value analysis of the system without any device, with TCSC and with SVC device. From this table the damping of different modes for both the variable impedance devices has been demonstrated.

For testing transient stability with variable impedance controllers placed in the system, a three-phase fault was applied at bus 27 for 120 ms, speed deviation and the rotor angle difference between generators G1 and G15, were plotted and are shown in **Fig. 6 and 7**.

Table 1. Residue factor of FACTS device for 68-bus test system

TCSC Placement		SVC Placement	
Line connection	N RF	Bus No.	N RF
2 3	0.17	4	0.089
2 25	0.27	5	0.090
10 11	0.10	6	0.089
10 13	0.12	8	0.096
16 19	0.21	11	0.082
21 22	0.23	14	0.084
23 59	0.47	16	0.078
9 36	0.25	18	0.083
36 37	0.63	28	1.000
34 36	0.75	39	0.178
44 45	0.11	40	0.398
45 50	0.45	43	0.158
51 52	1.00	45	0.290
50 51	0.19	49	0.244
41 40	0.15	51	0.131

Table 2. SVC Location based on Busbar ranking

100% loading Bus No.	MSV = 0.00051 Normalized V_{min}	120% loading Bus No.	MSV = 0.00051 Normalized V_{min}
44	1.0000	44	1.000
43	0.9531	43	0.872
37	0.0843	37	0.098
39	0.0437	39	0.078
45	0.0147	65	0.022
36	0.0091	36	0.022
51	0.0020	45	0.019
34	0.0015	51	0.003
35	0.0009	34	0.003
9	0.0007	35	0.002
30	0.0001	9	0.001
50	0.0001	64	0.001

Table 3. TCSC location based on transmission line rankings for the base case

Transmission line ranking	Bus No.	Bus No.	Normalized participating factor
1	25	26	1.00
2	14	15	0.86
3	41	40	0.63
4	17	27	0.52
5	50	51	0.49
6	21	22	0.45
7	30	32	0.43
8	42	41	0.41
9	3	18	0.39
10	19	20	0.38
11	48	40	0.36
12	1	47	0.35
13	3	4	0.31
14	26	28	0.28
15	45	51	0.27

Table 4. Damping ratio under different Conditions

Inter-area modes		Model1	Mode2	Mode3	Mode4
Without FACTS	Real	-0.43960	-0.24800	-0.31910	-0.21020
	Imag	4.56790	3.53920	2.99230	2.18010
	Freq.	0.73040	0.56470	0.47895	0.34858
	ζ	0.09580	0.06990	0.10605	0.09598
With TCSC	Real	-0.43970	-0.25970	-0.31810	-0.21130
	Imag	4.56790	3.49410	3.01100	2.18002
	Freq.	0.73040	0.55760	0.48188	0.35178
	ζ	0.09580	0.07410	0.10506	0.09648
With SVC	Real	-0.43960	-0.24970	-0.31880	-0.21030
	Imag	4.56720	3.53780	2.98860	2.17440
	Freq.	0.72690	0.56450	0.47834	0.34767
	ζ	0.09580	0.07041	0.10607	0.09624

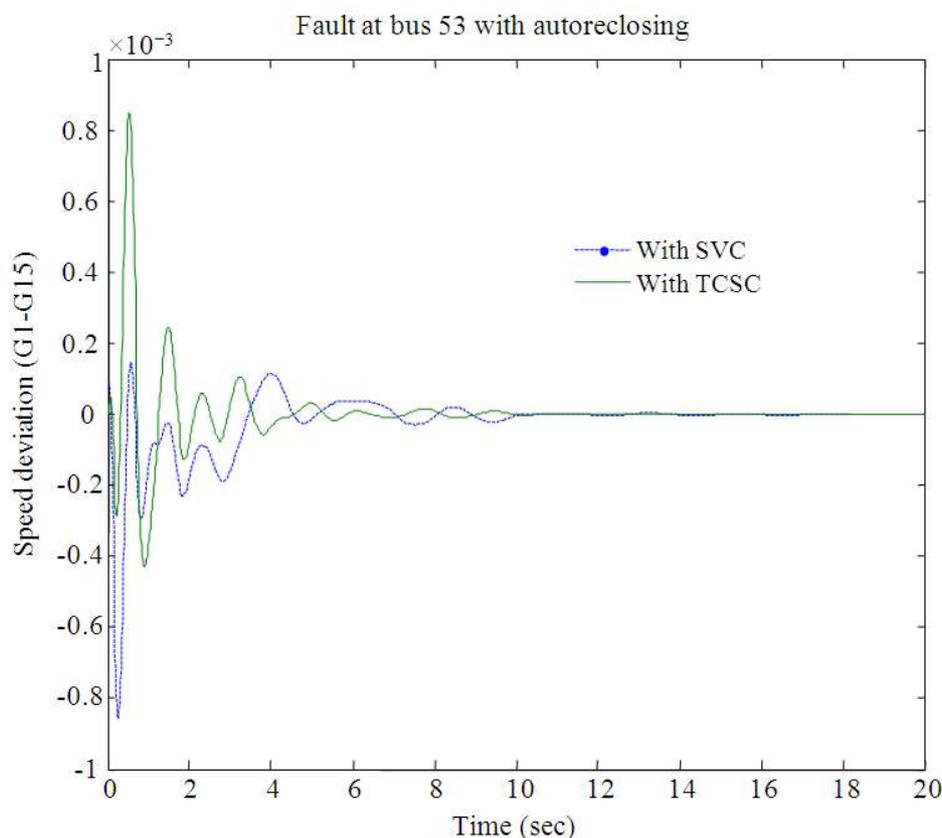


Fig. 6. Speed deviation of (G1-G15)

It can be observed from these figures that the response of the TCSC device with supplementary controller produce very low oscillation compared with TCSC and SVC device only. The response is poor for the

system with SVC device only. Therefore, the transient response improves and the oscillations of the relative angles between generators G1 and G15 decreases significantly with the two cases mentioned just now.

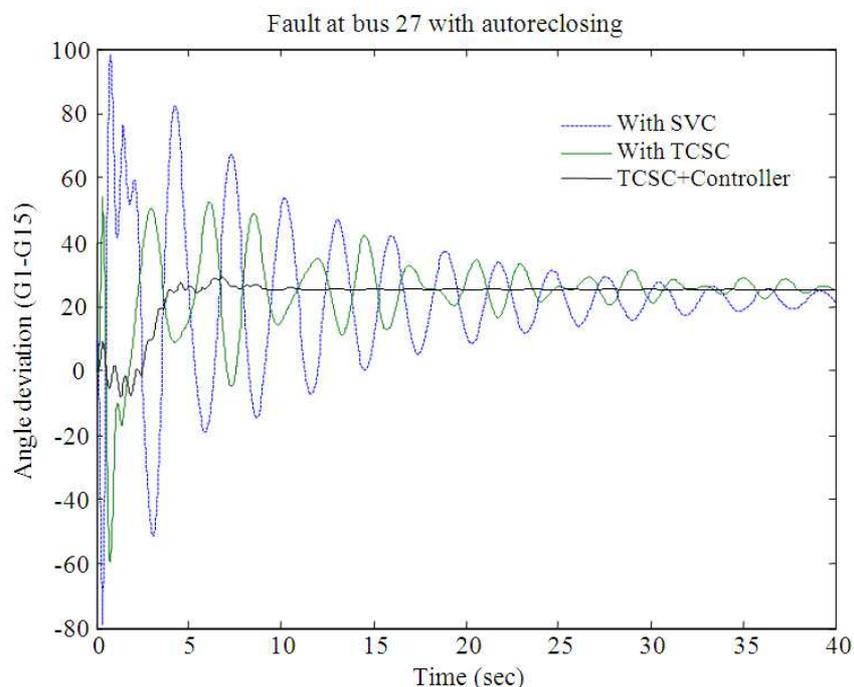


Fig. 7. Angle difference between generators G1 and G 15

4. DISCUSSION

The proposed methodologies are tested on a dynamic model of the reduced order equivalent of the interconnected New England Test System (NETS) and New York Power System (NYPS). The test system consists of 68 buses, 16 machines and five areas as shown in Fig. 5. The data are adopted from (Pal and Chaudhuri, 2005).

5. CONCLUSION

A set of Residue indices have been proposed in this study in order to find the optimal location of TCSC and SVC for enhancing damping of small signal oscillations and, thus, improving the system stability. Residue indices for the placement of FACTS controllers have been found corresponding to a critical inter-area mode in case of 68-bus systems. These indices have been computed for the base case only. Best location of FACTS was also found on the basis of static criteria utilizing singular Value decomposition for voltage stability. It was established that these two factors provide different optimal locations of the FACTS controllers.

TCSC controller in the study is found to be more effective in improving the transient performance compared with the SVC device.

Application studies on a complex power system have shown that SVC and TCSC have the potential to substantially increase system damping. All the simulations were done with PSAT, PST or MatNet Eig toolbox in MATLAB.

6. ACKNOWLEDGEMENT

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