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Application of SVC Device for Damping Oscillations Based On Eigenvalue Techniques

IJPEAI
International Journal of Power, Energy and Artificial Intelligence

Abstract—SVC devices are used to improve voltage and reactive power conditions in ac systems. An additional task of SVC is to increase transmission capacity as result of power oscillation damping. Eigenvalue-based methods for analysis and control of power system oscillations using SVC have been developed. The characterization of power system oscillations using the eigenvalues and eigenvectors of the state matrix is detailed. Design of power system damping controllers using residue method is addressed.

Keywords – **SVC, Power system oscillations, linear models, eigenvalues, eigenvectors, participation factors, residues.**

I. INTRODUCTION

The concept of flexible ac transmission systems (FACTS) is made possible by the application of high power electronic devices for power flow and voltage control [l]. In addition a number of FACTS devices have already been installed to aid power system dynamics which help to mitigation a low frequency oscillations often arise between areas in a large interconnected power network [2].

Eigenvalue sensitivities are one important outcome of the modal analysis and control of oscillatory behavior and dynamic stability in power systems. The pioneering work [3] considers the local oscillation of a single machine by means of a transfer function model. The usually complex pattern of oscillations in a large power system can be studied through linear, time invariant, state-space models based on the perturbations of the system state variables from their nominal values at a specific operating point

Power system oscillations occur due to the lack of damping torque at the generators rotors. The oscillation of the generators rotors cause the oscillation of other power system variables (bus voltage, bus frequency, transmission lines active and reactive powers, etc.). Power system oscillations are usually in the range between 0.1 and 2 *Hz* depending on the number of generators involved in [4]. Local oscillations lie in the upper part of that range and consist of the oscillation of a single generator or a group of generators against the rest of the system. In contrast, inter-area oscillations are in the lower part of the frequency range and comprise the oscillations among groups of generators. In addition, power system oscillations exhibit low damping compared to oscillations found in other dynamic systems: an oscillation of 10% damping is commonly accepted as well damped. To improve the damping of oscillations in power systems, supplementary control laws can be applied to existing devices. These supplementary actions are referred to as power oscillation damping (POD) control

This paper reviews the basic concepts of eigenvalue analysis of linear systems. The physical meaning of eigenvalues, eigenvectors, participation factors, residues and controllability and observability indices will be introduced and illustrated in small scale power systems. This technique has been successfully used in location and tuning of power system stabilizers [5]

The application of sensitivity measures to the design of power system damping (POD) controllers has been applied to SVC. The design method utilizes the residue approach; this presented approach solves the optimal sitting of the SVC device, selection of the proper feedback signals and the controller design problem

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II. BASIC CONCEPTS OF LINEAR SYSTEMS ANALYSIS

Low frequency electromechanical oscillations range from less than 1 Hz to 3 Hz other than those with sub-synchronous resonance (SSR) [6]. Multi-machine power system dynamic behavior in this frequency range is usually expressed as a set of non-linear differential and algebraic (DAE) equations. The algebraic equations result from the network power balance and generator stator current equations. The initial operating state of the algebraic variables such as bus voltages and angles are obtained through a standard power flow solution. The initial values of the dynamic variables are obtained by solving the differential equations

A. Eigenvalues, Eigenvectors and Modes

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

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

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

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

A meaningful solution method of (2) is based on the eigenvalues and eigenvectors of the state matrix A. An eigenvalue λ_i of the state matrix A and the associated right v_i and left w_i eigenvectors are defined according to: $Av_i = \lambda_i v_i$.In a matrix with all distinct eigenvalues (not a necessity but it is easier to understand when it is so), all the right eigenvectors and eigenvalues can be expressed as a compact matrix expression

$$AV = VA \quad (3)$$

where,

$$V = (v_1, v_2 \ldots\ldots v_{n-1}\ v_n,) \qquad \Lambda = diag\,(\lambda_1\ \lambda_2 \ldots\lambda_{n-1}, \lambda_n) \quad (4)$$

Pre-multiplying both sides of *(3)* by V^{-1} gives

$$V^{-1}AV = \Lambda \quad (5)$$

A similar expression holds for the left eigenvectors W such that

$$WA = \Lambda W \quad (6)$$

Where

$$W = [\,\omega_1^t, \omega_2^t \ldots\ldots \omega_{n-1}^t\ \omega_n^t\,]^t \quad (7)$$

Post-multiplying both sides of *(6)* by W^{-l}, gives

$$WAW^{-1} = \Lambda \quad (8)$$

The transformed physical state variables *(x)* can be put into modal variables *(2)* with the help of eigenvector matrices V and W

$$x = Vz \qquad z = Wx \quad (9)$$

In power system literature, the right eigenvector matrix **v** is known as the mode shape matrix, that is, eigenvector v_i is known as the ***i^th^*** mode shape, corresponding to eigenvalue $\boldsymbol{\lambda_i}$. The mode shape provides important information on the participation of an individual machine or a group of machines in one particular mode.

solution of (2) can be expressed in terms of the eigenvalues and eigenvectors of the state matrix as:

$$\Delta x(t) = Ve^{\Lambda t}W\Delta x(\mathbf{0}) = \sum_{i=\mathbf{1}}^{N} v_i e^{\lambda_i t}[w_i^T \Delta x(\mathbf{0})] \quad (10)$$

The analysis of equation **(10)** allows to draw the following conclusions:

The system response is the combination **of** the system response to each of the N modes.

The eigenvalues determine the system stability. **A** real positive (negative) eigenvalue determines exponentially increasing (decreasing) behavior. **A** complex eigenvalue of positive (negative) real part results in a increasing (decreasing) oscillatory behavior.

The components of the right eigenvector $\mathbf{v_i}$ measure the relative activity of each variable in the ith mode.

The components of the left eigenvector $\boldsymbol{w_i}$ weight the initial conditions in the i-th mode

Participation factors

It is natural to suggest that the significant state variables influencing a particular mode are those having large entries corresponding to the right eigenvector of λ_i. The participation factor of the j-th variable in the k-th mode is defined as the product of the j-th's components of the right v_{jk} and left w_{ki} eigenvectors corresponding to the k-th mode [7]

$$P_{jk} = W_{jk}V_{kj} \quad (11)$$

The product $\boldsymbol{W_{jk}V_{kj}}$ is a dimensionless measure which is called participation factor. In other words, they are independent on the units of the state variables. In addition, both the sum of the participation factors of all variables in a mode and the sum of the participation of all modes in a variable are equal to one. Other interesting measure is the subsystem participation. The subsystem participation is the magnitude of the sum of the participation factors of the variables that describe a subsystem in a mode.

B Modal controllability and observability factors

The effectiveness of control in power system can be indicated through controllability and observability indices. This is important as control cost is influenced to a great deal by the controllability and observability of the plant. These issues are addressed through modal controllability and observability

C Controllability index

Assume that an input Δu(t) and an output Δy(t) of the linear dynamic system (2) have defined

$$\Delta\dot{x}(t) = A\Delta x(t) + B\Delta u(t) \qquad \Delta y(t) = C\Delta x(t) \quad (12)$$

The application of a linear transformation defined by the eigenvectors of the state matrix to the system as described by (12) results in: equation (13):

Let v and w be the right and left eigen vector matrices of A, respectively. If eigenvalues of A are distinct, then $w^T v = I$, where w^T is conjugate transpose of w and I is the identity matrix. Substituting Δx =wΔz in (12), we obtain

$$\Delta\dot{z}(t) = w^T Aw\Delta z(t) + w^T B\Delta u(t) \qquad \Delta y(t) = cw\Delta z(t) \quad (13)$$

Equation (13) can be written for kth eigen mode as

$$\Delta\dot{z}(t) = \lambda_k \Delta z_k(t) + \sum_{i=\mathbf{1}}^{m} w_k^T B_i \Delta v_i(t) \quad (14)$$

Where w_k is the left eigenvector corresponding to kth mode and B_i is the ith column vector of matrix B. From (14), one can find the controllability of kth eigen mode with respect to the ith input. The controllability index (CI) of an ith input to the kth mode [8, 14] is defined as

$$CI_i = w_k^T B_i \qquad (15)$$

The input i, for which the value of $w_k^T B_i$ is maximum, is considered the suitable parameter to be controlled for affecting the kth eigen mode to maximum extent.

D Observability index

The observability index (cvi) of an ith input to the kth mode is defined as

$$OI_i = C_i w_k \qquad (16)$$

The study of equations (15) and (16) leads to the following conclusions:

CI_i Measures the controllability of the mode associated to the variable $x_i(t)$ from the input $\Delta u(t)$.In other words, if the mode λ_i can be controlled from the input $\Delta u(t)$

OI_i Measures the observability of the mode associated to the variable $x_i(t)$ form the output $\Delta y(t)$. In other words, if the mode λ_i can be observed from the variable $\Delta y(t)$

Therefore, a mode can be controlled if only if it is controllable from the input $\Delta u(t)$ and observable from the output $\Delta y(t)$

Therefore, a mode can be controlled if only if it is controllable from the input $\Delta u(t)$ and observable from the output $\Delta y(t)$

E Residue

Considering (12) with single input and single output (SISO) and assuming D = 0, the open loop transfer function of the system can be obtained by

$$\begin{aligned} G(s) &= \frac{\Delta y(s)}{\Delta u(s)} \\ &= C(sI - A)^{-1} B \end{aligned} \qquad (17)$$

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

$$\begin{aligned} G(s) &= \sum_{i=1}^{N} \frac{C\phi_i \psi_i B}{(s - \lambda_i)} \\ &= \sum_{i=1}^{N} \frac{R_i}{(s - \lambda_i)} \end{aligned} \qquad (18)$$

Each term in the denominator, R_i, of the summation is a scalar called residue. The residue Ri of a particular 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. Fig. 1 shows a system G(s) equipped with a feedback control H(s). 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

$$\Delta\lambda_i = \boldsymbol{R_i H(\lambda_i)} \qquad (19)$$

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. For a certain mode, the same type of feedback controls H(s), regardless of its structure and parameters can be tested at different locations. For the mode of the interest, residues at all locations have to be calculated.

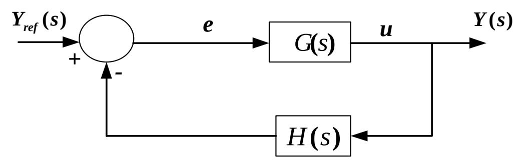

Fig. 1 Closed loop system with POD controller

The largest residue then indicates the most effective location to apply the feedback control.

F Power Oscillation Damper Controller Design

Supplementary control action applied to FACTS devices to increase the system damping is called Power Oscillation Damping (POD). Since FACTS controllers are located in transmission systems, local input signals are always preferred, usually the active or reactive power flow through FACTS device or FACTS terminal voltages. Fig. 1 shows the considered closed-loop system where G(s) represents the power system including FACTS devices and H(s) FACTS POD controller. In order to shift the real component of λ_i to the left, FACTS POD controller is employed. That movement can be achieved with a transfer function consisting of an amplification block, a wash-out block and *m*c stages of lead-lag blocks. We adapt the structure of POD controller given in [8, 12], i.e. the transfer function of the FACTS POD controller is:

$$\begin{aligned} \boldsymbol{H(s)} &= \boldsymbol{K} * \frac{1}{1 + s\boldsymbol{T_m}} * \frac{s\boldsymbol{T_w}}{1 + s\boldsymbol{T_w}} \left(\frac{1 + s\boldsymbol{T_{lead}}}{1 + s\boldsymbol{T_{lag}}} \right)^{m_c} \\ &= \boldsymbol{KH_1(s)} \end{aligned} \qquad (20)$$

Where K is a positive constant gain, and $H_1(s)$ is the transfer function of the wash-out and lead-lag blocks. The washout time constant, Tw, is usually equal to 5-10 s. The lead –lag parameters can be determined using the following equations:

$$\varphi_{comp} = 180^0 - arg(R_i) \qquad (21)$$

$$\alpha c = \frac{T_{lead}}{T_{lag}} = \frac{1 - sin\left(\varphi_{comp} / m_c \right)}{1 + sin\left(\varphi_{comp} / m_c \right)} \qquad (22)$$

$$T_{lag} = \frac{1}{\omega_i\sqrt{\alpha c}}, \quad T_{lead} = \alpha_c T_{lag} \qquad (23)$$

Where arg(Ri) denotes phase angle of the residue R_i, ω_i is the frequency of the mode of oscillation in rad/=sec, $\mathbf{m_C}$ is the number of compensation stages (usually m_C = 2),the angle compensated by each block should be 30º-50º. The controller gain K is computed as a function of the desired eigenvalue location λ_{ides} according to equation 24:

$$\boldsymbol{K} = \left|\frac{\lambda_i - \lambda_d}{\boldsymbol{R}_i \boldsymbol{H}_1(\lambda_i)}\right|. \qquad (24)$$

III. DYNAMIC MODEL OF THE TEST SYSTEMS

A. Generator model

Each generator of the test systems is described by six order non-linear mathematical model **[13]:** The sixth order model 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 system has six state variables $(\delta, \omega, e'_q, e'_d, e'_q \text{ and } e''_d)$ and the following equations:

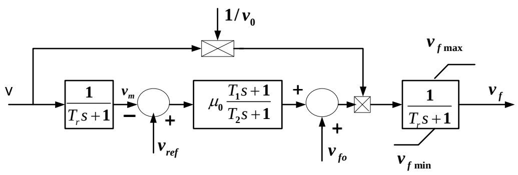

Fig. 2 Exciter system

$$\dot\delta = \Omega_b(\omega - 1) \qquad (25)$$

$$\dot\omega = (P_m - P_e - D(\omega - 1))/M \qquad (26)$$

$$\dot e'_q = (-fs(e'_q) - (x_d - x'_d - \frac{T''_{d0}}{T'_{d0}}\frac{x''_d}{x'_d}(x_d - x'_d)i_d + (1 - \frac{T_{AA}}{T'_{d0}})v_f)/T'_{d0} \qquad (27)$$

$$\dot e'_d = (-e'_d + (x_q - x'_q - \frac{T''_{q0}}{T'_{q0}}\frac{x''_q}{x'_q}(x_q - x'_q)i_q)/T''_{q0} \qquad (28)$$

$$\dot e''_q = (-e''_q + e'_q - (x'_d - x''_d + \frac{T''_{d0}}{T'_{d0}}\frac{x''_d}{x'_d}(x_d - x'_d)i_d + \frac{T_{AA}}{T'_{d0}}v_f)/T''_{d0} \qquad (29)$$

$$\dot e''_d = (-e''_d + e'_d + (x'_q - x''_q - \frac{T''_{q0}}{T'_{q0}}\frac{x''_q}{x'_q}(x_q - x'_q)i_q)/T''_{q0} \qquad (30)$$

Stator algebraic equation are given by

$$v_q + r_a I_q - e''_q + I_d\left(x''_d - x_l\right) = 0 \qquad (31)$$

$$v_d + r_a I_d - e''_d - I_q\left(x''_q - x_l\right) = 0 \qquad (32)$$

B. Exciter

The AVR model depicted in Fig.2 is considered in this work [13] and described by the following equations:

$$\dot v_m = (V - v_m)/T_r \qquad (33)$$

$$\dot v_r = (\mu_0(1 - \frac{T_1}{T_2})(v_{ref} - v_m) - v_r)/T_2 \qquad (34)$$

$$\dot v_f = ((v_r - \mu_0\frac{T_1}{T_2})(v_{ref} + v_{f0})\frac{V}{V_0} - v_f)/T_e \qquad (35)$$

C. SVC Device

The Static VAr Compensator (SVC) is a shunt connected device whose main functionality is to regulate the voltage at a chosen bus by suitable control of its equivalent reactance. The model that is used here assumes a time constant regulator, as depicted in Fig. .4.

In this model, a total reactance b_{SVC} is assumed and the following differential equation holds [13].

$$\dot b_{SVC} = (K_r(V_{ref} + v_{POD} - V) - b_{SVC})/T_r \qquad (36)$$

The model is completed by the algebraic equation expressing the reactive power injected at the SVC node:

$$Q = -b_{SVC}V^2 \qquad (37)$$

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 [8].

The supplementary input Δ_{POD} is used to connect the POD controller for damping oscillation while Vref to maintain acceptable voltage at the SVC bus.TCR of 150MVAr is connected in parallel with fixed capacitor of 200MVAr correspond to a limit of 2.0pu to -1.5 pu at 1.0 pu voltage [9].

D. Model based on numerical linearization

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

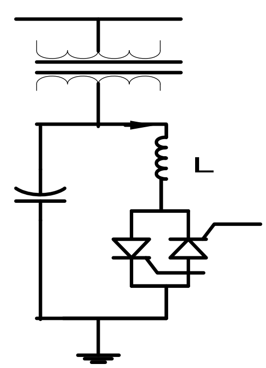

Fig 3 SVC Topology

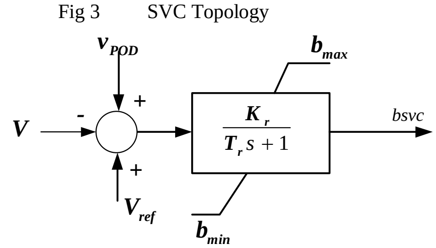

Fig. 4 SVC Regulator

$$\dot{x} = f(x,z,u) \quad (36)$$
$$0 = g(x,z,u) \quad (37)$$
$$y = h(x,z,u) \quad (38)$$

The order of x is k=9*m*+*n* where m is number of generators and n is the order of the FACTS (SVC) device with the six order machine and three order exciter dynamic components.

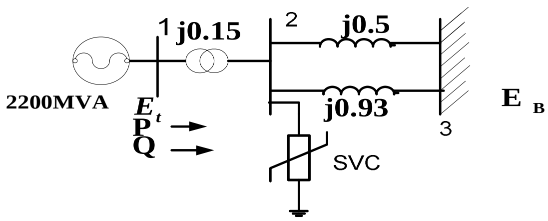

Fig..5 SMIB with SVC device

m=1 and 4 in test system1 and system 2 respectively while *n* =1 in both cases.

Linearizing equation (36) to (38) around the equilibrium point gives the following equations (39) to (41).

$$\Delta\dot{x} = \frac{\partial f}{\partial x}\Delta x + \frac{\partial f}{\partial z}\Delta z + \frac{\partial f}{\partial u}\Delta u \quad (39)$$
$$0 = \frac{\partial g}{\partial x}\Delta x + \frac{\partial g}{\partial z}\Delta z + \frac{\partial g}{\partial u}\Delta u \quad (40)$$
$$\Delta\dot{x} = \frac{\partial h}{\partial x}\Delta x + \frac{\partial h}{\partial z}\Delta z + \frac{\partial h}{\partial u}\Delta u \quad (41)$$

Elimination of the vector algebraic variable Δz from equation (39) and (40), gives

$$\Delta\dot{x} = A\Delta x + B\Delta u$$
$$\Delta y = C\Delta x + D\Delta u \quad (42)$$

TABLE I
COMPLEX EIGENVALUES OF SMIB WITH SVC

No.	Eigenvalue	Frequency (Hz)	Damping %
1,2	0.29835±7.8548	1.2501	3.80
3,4	0.04718±0.20797	0.0331	22.12
5,6	1.4854 ±14.1564	2.2531	10.44
Complex eigenvalues of SMIB without SVC			
1,2	0.29835±j7.8548	1.222	2.57

Where *A*, *B*, *C*, *D* are the matrix of partial derivatives in (39) to (41) evaluated at equilibrium points. In PSAT those equilibrium points or initials conditions are obtained after power flow simulation of the test system.

IV. RESULTS AND DISCUSSION

A. Single machine connected to an infinite bus with SVC

The case of a single generator connected to an infinite bus is considered first with and without SVC. The generator model contains accurate representations of the synchronous machine and the excitation systems. The generator is equipped with an excitation system shown in Fig. 2 [11]. A static var compensator is connected at bus 2. The linear model of this system is described by 10 state variables. The synchronous machine, the exciter and the SVC are described respectively by 6, 3 and 1 state variables. The eigenstructure of the state matrix contains 3 pairs of complex eigenvalues and 4 real eigenvalues the critical mode has a damping ratio less than 5% which is shown in tables I.

Eigenvalues accurately determine linear systems stability: this system is close to instability due to the presence of a poorly damped oscillatory mode. However, if the connections between eigenvalues and state variables are sought, participation factors have to be used. Table II details the participation of the generator subsystems: rotor dynamics, synchronous machine, exciter, and SVC in all modes. Table II clearly indicates that the poorly damped oscillatory mode (eigenvalues 1 and 2) is associated to the rotor dynamics and that the other oscillatory mode (eigenvalues 3 and 4) describes the interaction between the synchronous machine and the exciter. The mode associated to the rotor dynamics is also known as electromechanical mode. This mode with SVC has higher damping ratio compared without SVC but still below the minimum of 10%.

B. Two areas four machine with SVC

In this study, a two area interconnected four machine power system shown in Fig. 6 is considered. The system consists of four machines arranged in two areas inter-connected by a weak tie line [11].

The location of SVC is indicated in the diagram. The system is operating with area 1 exporting 400 MW to area 2. The equivalent circuit of the system is shown in Fig. 6

Network and generator data can be found in [11]. We have

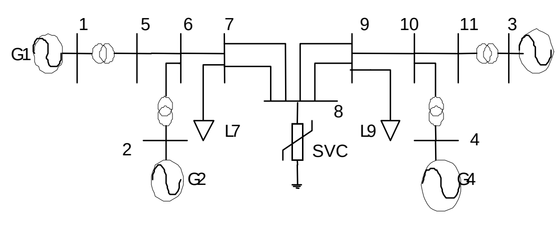

Fig. 6 Two Area four Machine model

assumed that the generators are equipped with exciter model in Fig. 2 systems and steam turbines. In this study, the SVC is treated as a variable capacitance.

From table III three pairs of poorly damped eigenvalues are found. They result to be associated to the rotor dynamics. The slowest eigenvalues are associated to the speed-governing systems whereas the fastest are associated to the excitationTable IV detail the participation of the generators in each mode. The fastest mode is associated with local modes: mode -0.7647 ±j7.5680 is dominated by generator

G3 and G4 and mode -0.7514 ± 7.3036i is dominated by generators G1 and G2. While mode -0.1211 ± 3.7559i is an inter-area mode since the participation is distributed among all generators.

C. Design of SVC POD controller using residue method

1) Four machines two area test system

The uncontrolled system, Fig.6, has one inter-area oscillatory mode characterized by λ = -0.1211 ± j3.7559 with damping ratio ζ= 3.22%. According to Table V, the bus 8 has the largest residue and therefore the most effective location of the SVC and to apply the feedback control. Using the method presented above, POD controller parameters are calculated in order to shift the real part of the oscillatory mode, to the left half complex plane. The obtained transfer function for the SVC POD controller

$$H(s) = K * \frac{1}{1+0.1s} * \frac{10s}{1+10s} \frac{1+0.0674s}{1+1.044s} * \frac{1+0.0674s}{1+1.044s}$$

Eigenvalue of our interest moves form the original location λ = -0.1211 ± j3.76 *to* the desired location λ_d= -0.7675 ± j3.76 to give about 20% damping as:

$$K = \left| \frac{\lambda_i - \lambda_d}{R_i H_1(\lambda_i)} \right| = 102.3$$

TABLE II
EIGENVECTOR AND NORMALIZED PARTICIPATION FACTOR CORRESPONDING POOR MODE -0.29835+J7.8548

S/N	Right eigenvector	Left eigenvector	***Participation factor***	***Participation state***
1	0.7492	-3.4830 + j0.0000	0.48018	Machine angle δ_1
2	-0.0006 + j0.0178	-0.0065 - j0.0000	0.48018	Machine speed ω_1
3	-0.0020 + 0.0264	7.5335 + j0.0000	0.02047	**q-axis damper e'_q**
4	0.0033 - j0.0071	-2.0275 + j1.8330	0.00072	**d-axis damper e'_d**
5	-0.0753 + j0.0385	-2.0275 - j1.8330	0.01593	**q-axis damper e''_q**
6	0.0205 - j0.0103	-0.0060 - j0.0126	0.00119	**d-axis damper e''_d**
7	-0.0613 + j0.0161i	-0.0060 + j0.0126	0.0001	***Exiter*** v_m
8	0.3732 + j0.5283	-0.1162 - j0.0000	0.00037	***Exiter*** v_{r1}
9	0.0046 + j0.0105	0.0130 + j0.0014	0.00015	***Exiter*** v_{r2}
10	-0.0750 - j0.0425	0.0130 - j0.0014	0.00037	***Exiter*** v_f
11	0	0	0.00037	SVC

TABLE III
COMPLEX EIGENVALUE OF TWO AREA FOUR MACHINE TEST

Mode No.	Complex Eigenvalue	Frequency (Hz)	Damping ratio %	Dominant state
1,2	-38.9130 j0.5195	0.08	99.99	**$\Delta e''_d$ and $\Delta e''_q$ of G2,G4**
3,4	- 38.6438± j0.5235	0.08	99.99	**$\Delta e''_d$ of G2 and $\Delta e''_q$ of ,G1**
5,6	-16.2015 ± j3.3165	0.53	97.97	**ΔV_{r1} of Exc.3 and $\Delta V_{r1}$of Exc.4**
7,8	- 16.1676 ±j2.7048	0.43	- 98.63	**ΔV_{r1} of Exc.2 and $\Delta V_{r1}$of Exc.1**
9,10	-0.7647 ±j7.5680	1.20	10.05	**$\Delta\delta,\Delta\omega$ of G2 ,G3 and G4**
11,12	-0.7514 ± j7.3036	1.16	10.23	**$\Delta\delta,\Delta\omega$ of G1 ,G3 and G2**
13,14	-0.1211 ± j3.7559	0.60	3.22	**$\Delta\delta,\Delta\omega$ of G3 ,G1 G4 and G2**
15,16	-8.3489 ± j0.6210	0.10	99.72	**ΔV_f of Exc.3 and $\Delta V_f$of Exc.4**
17,18	-8.3031 ± j0.5799	0.09	99.76	**ΔV_f of Exc.1 and $\Delta V_f$of Exc.2**
19,20	-0.8417 ± j0.4294	0.07	89.08	**$\Delta e'_q$ of G2 and G1**
21,22	-0.5219 ± j0.4762	0.08	73.87	**$\Delta e'_q$ of G3 and ΔV_{r2} of Exc.4**
23,24	-0.3704 ± j0.3102	0.05	76.67	**$\Delta e'_q$ of G2 and G1**
25,26	-0.3577 ± j0.3073	0.05	75.85	**$\Delta e'_q$ of G4 and ΔV_{r2} of Exc.3**

D. Short circuit test

A three phase fault is applied for second test model at the

TABLE IV
PARTICIPATION OF THE GENERATORS IN THE ELECTROMECHNICAL MODES OF THE TWO AREA TEST SYSTEM

Mode No.	Eigen value	G1	G2	G3	G4
9,10	-0.7647 ±7.5680i	0.0115	0.0429	0.4101	0.5522
11,12	-0.7514 ± 7.3036i	0.4110	0.5364	0.0277	0.0123
13,14	-0.1211 ± 3.7559i	0.2461	0.1420	0.3459	0.2434

TABLE V
SITING INDICES OF SVC FOR TWO AREA FOUR MACHINE TEST

SVC Bus location	Complex Residue	$\lvert R_i \rvert$
5	0.00023-0.00015	0.00028
6	1.6×10^{-6} $-6.6i\times10^{-7}$	1.73×10^{-6}
7	$(-8.2+2.53i)\times10^{-7}$	8.58×10^{-7}
8	-0.0028 - 0.0043i	0.0052
9	$(3.84-7.3i)\times10^{-8}$	8.23111×10^{-8}
10	0.0031-0.0029i	0.0042
11	-0.00042 - 0.00063i	0.00075

TABLE VI
INTER AREA MODE COMPARISON FOR TEST SYSTEM 2

Mode No.	**Operating Condition**	**Frequency (Hz)**	**Damping ratio %**
13,14	Without SVC	**0.49**	**2.98**
13,14	**With SVC**	**0.6**	**3.22**
13,14	**SVC with POD**	**0.5913**	**20%**

bus 9 and cleared after 74ms. The original system is restored upon the fault clearance. The transient stability performances of the system with no SVC, SVC without POD and SVC with POD controller are shown in Figs. 7-11. The SVC with voltage controller stabilizes Fig. 7 to Fig. 9, though the damping is poor but fail to stabilize Fig 10-11 .The oscillations of the system from Fig. 7 to Fig. 11 are well damped with POD controller

V. CONCLUSION

This paper has reviewed methods for analysis and control of power system oscillations with SVC device based on the eigenstructure of the state matrix of the linear model of the power system. Residue-based methods also provide valuable information on how to design power system damping controllers. Although eigenvalue based methods are very powerful, the complexity of the power system stability problem requires the complementary use of other methods such as non-linear time domain simulation. All the simulations were done with PSAT toolbox in Matlab environment.

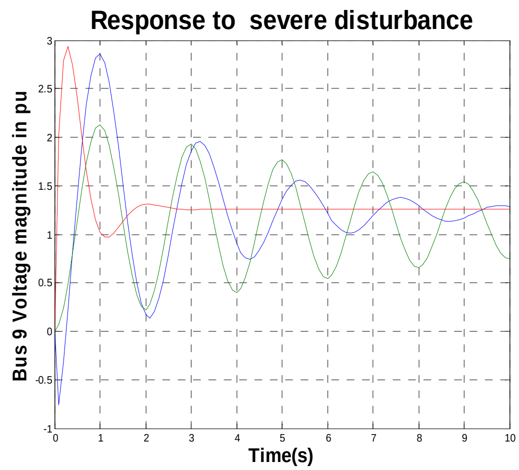

Fig. 7 Voltage Response

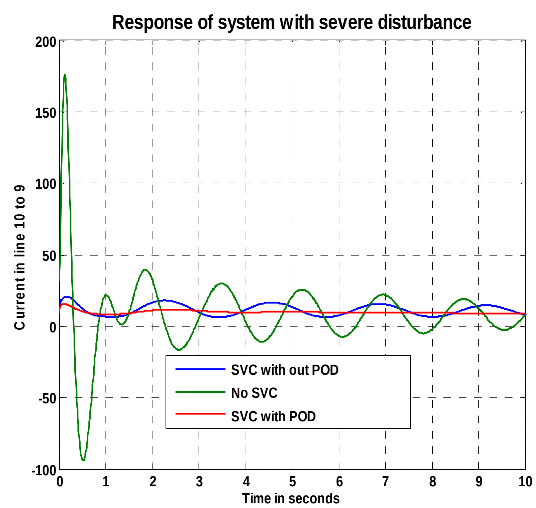

Fig.8. Current response between buses 9 to bus10

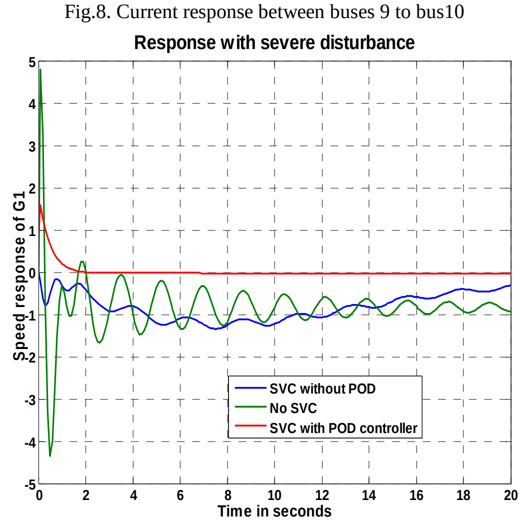

Fig. 9 Speed response of G1

VI. ACKNOWLEDGEMENTS

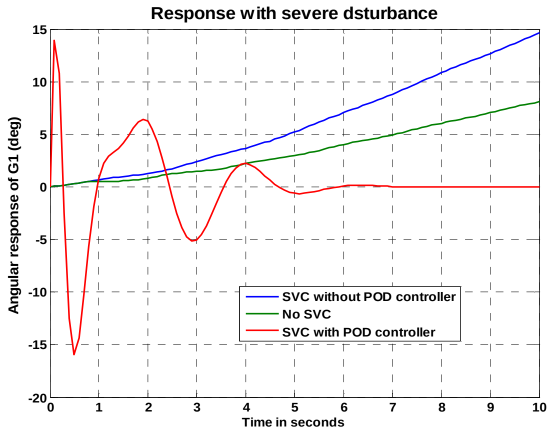

Figure.10 Angular response of G1

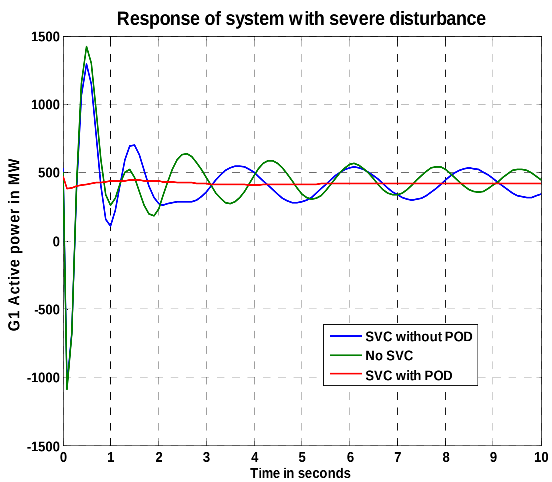

Figure.11 Active power response of G1

The authors would like to express their appreciation to the University Teknologi Malaysia (UTM) and Ministry of Science Technology and Innovation (MOIST) for funding this research.

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