

Dynamic Stability Enhancement in a Multimachine Power System using SVC along with a Controller

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Abstract

This paper presents a mathematical analysis namely linearization technique for small signal stability enhancement in multi machine power system using a FACTS device SVC. Using eigen values and participation matrix the small signal dynamic behavior of the multimachine power system is investigated. Secondly with a FACTS device SVC the same system enhanced dynamic behavior using eigen values and participation matrix is also studied. Finally, with SVC along with a controller the same system effective dynamic stability using linearization technique is seen. Local stabilizing signals such as bus voltage deviations and bus angle perturbations are used as control inputs for the damping controller in FACTS device. Proposed technique is implemented on the standard WSCC 3 Machine 9 Bus system. The system is simulated in PSAT software and the computations are carried out using MATLAB.

Keywords- FACTS, SVC, linearization technique

Introduction

Considering today's scenario, power demand is increasing and necessary too. Stability is an important factor in the area of power system, power system oscillates accordingly electromechanical oscillations. Because of these there will be more oscillations towards the generating units as well as transmission unit too, which ultimately makes the entire system inadequate and weak as the load increased. To a single generator or a generator plant these oscillations may be local (local oscillations, 0.8 – 2 Hz), or widely separated geographically different groups of generators these are interarea (interarea oscillations, 0.2 – 0.8 Hz). These electromechanical oscillations lead to power interruption [1].

The approach to solve the problem, FACTS is introduced [2]. The main objectives of FACTS, to increase transmission capacity and control of power flow. Although PSS'S provide supplementary feedback stabilizing signals, but still variations in voltage profile and they may result in leading power factor operation under severe disturbances.

Because of above factor, power system must be retuned accordingly with operating state. Since power system is highly non-linear, the controllers and converters operating condition cannot cope with changes in operating conditions for security loads, power flow control and voltage control in transmission system [3]. Now controllers provided

with stabilizing loops are found to be effective for damping out power system oscillations.

Static Var Compensator (SVC) control strategies for enhancing the dynamic and transient stabilities in a simple two machine system was discussed in[4]. The modeling and interfacing techniques of SVC and TCSC for a long term dynamic simulation in[5]. Optimal tuning of FACTS based stabilizers for

Dynamic Stability enhancement in Multimachine power systems was analyzed in [6]. From the above review of references, the present paper using a mathematical analysis namely linearization technique. Linearizing the system performance equations and using them in standard form of state space model, the small signal dynamic behavior enhancement of a multi machine power system with FACTS device SVC simulations along with computations is further discussed.

SVC

A. CIRCUIT ARRANGEMENT AND PRINCIPLE OF OPERATION

The schematic diagram of a FC-TCR type SVC is shown in Fig.1. This shows that the TCR and FC are connected on the secondary side of a step-down transformer. The voltage signal is taken from the high voltage SVC bus using a potential transformer.

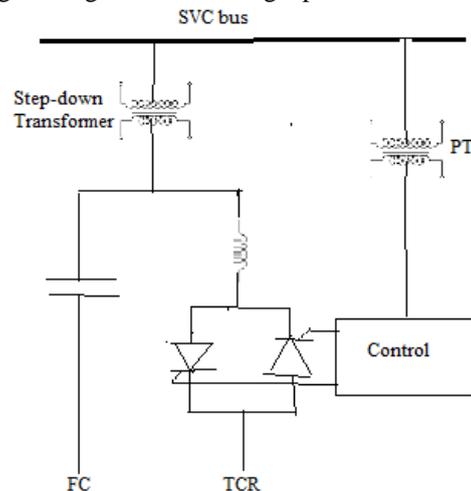


Figure 1: SVC (FC-TCR) configuration

The reactive current 'I' drawn by the SVC is determined by the SVC bus voltage and the total susceptance of the SVC 'B' (i.e. $B = B_C - B_L(\alpha)$).

$$I = (B_C - B_L(\alpha)).V$$

The corresponding reactive power 'Q' exchanged can be expressed as follows:

$$Q = (B_C - B_L(\alpha)).V^2$$

By controlling thyristor controlled reactor (TCR), and hence the amplitude of 'V' of SVC internally generated voltage, the reactive power flow can be controlled. To generate the reactive power, the SVC current is negative with SVC susceptance is capacitive. To absorb the reactive power, the SVC current is positive with SVC susceptance is inductive.

The controllability is provided by varying the 'α' (phase control) of the TCR branch. The current in a TCR can be continuously varied from zero (corresponding to zero conduction angle) to maximum (corresponding to zero conduction angle of 180°) by phase control in which the firing angle 'α' (with respect to the zero crossing of the voltage) is varied from 180° to 90°.

The fixed capacitor designed as a filter to reduce the generated higher harmonic currents in the FC-TCR type SVC.

A. Characteristics of SVC

The steady state control characteristic of SVC is shown in Fig. 2. where ADB is the control range. OA represents the characteristic where the SVC hits the capacitor limit, BC represents the SVC at its inductor limit. Note that SVC current is considered positive when SVC susceptance is inductive. Thus

$$I_{SVC} = -B_{SVC}V_{SVC}$$

The slope of OA is B_C (susceptance of the capacitor) and the slope of OBC is B_L (susceptance of the reactor). A positive slope (in the range of 1-5%) is given in the control range to

- (a) enable parallel operation of more than one SVC connected at the same (or) neighboring buses and
- (b) prevent SVC hitting the limits frequently.

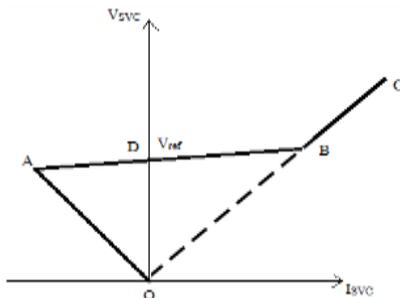


Figure 2 : Control Characteristic of SVC

LINEARIZATION TECHNIQUE

SMIB

To explain the linearization technique consider a single machine connected to an infinite bus with

machine transient voltage E¹, infinite bus voltage E_s, total reactance X. The system is shown in Fig.4 below

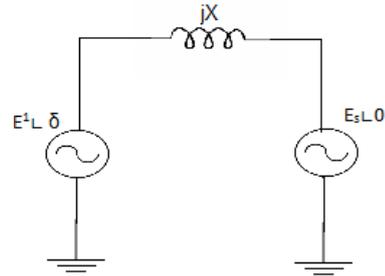


Figure 3: Single Machine Infinite Bus system[1] The motion equations of the machine are,

$$\dot{w} = \frac{T_m - T_e - K_D(w - 1)}{2H} \text{ pu, } t \text{ in sec}$$

$$\dot{\delta} = w_0(w - 1) \text{ rad, } t \text{ in sec}$$

'K_D' is the damping constant

Here electrical torque (T) = electrical power (P) (since w≈1). substituting this in above equations

$$\dot{w} = \frac{P_m - P_e(\delta) - K_D(w - 1)}{2H}$$

$$= \frac{P_m - \left(\frac{E^1 E_s}{X} \sin \delta\right) - K_D(w - 1)}{2H}$$

$$\dot{\delta} = w_0(w - 1)$$

These are non-linear equations. So linearizing them is as follows:

Considering small perturbations, $w = w_0 + \Delta w = 1 + \Delta w$ (i.e. at steady-state $w = w_0 = 1$)

$$\delta = \delta_0 + \Delta \delta$$

Therefore the above equations become by linearization,

$$\Delta \dot{w} = \frac{1}{2H} \left[\Delta P_m - \frac{E^1 E_s}{X} \cos \delta_0 \cdot \Delta \delta - K_D \cdot \Delta w \right]$$

$$\Delta \dot{\delta} = w_0 \cdot \Delta w$$

Here, Synchronizing coefficient

$$K_s = \frac{E^1 E_s}{X} \cos \delta_0$$

Therefore,

$$\Delta \dot{w} = \frac{1}{2H} [\Delta P_m - K_s \cdot \Delta \delta - K_D \cdot \Delta w]$$

$$\Delta \dot{\delta} = w_0 \cdot \Delta w$$

Therefore the standard form of equations in state-space model is,

$$\begin{bmatrix} \Delta \dot{w} \\ \Delta \dot{\delta} \end{bmatrix} = \begin{bmatrix} \frac{-K_D}{2H} & \frac{-K_s}{2H} \\ w_0 & 0 \end{bmatrix} \begin{bmatrix} \Delta w \\ \Delta \delta \end{bmatrix} + \begin{bmatrix} 1 \\ 0 \end{bmatrix} \frac{\Delta P_m}{2H}$$

So the system state matrix 'A' is obtained. Now by writing the characteristic equation and solving it gives the eigen values and eigen vectors of the system.

A. Modal Analysis

The modal analysis is explained as follows [1],

Given system, with $X(0) = X_0$ and $u=0$

$$\dot{X} = AX$$

Let define a modal vector 'Z',

$X = \Phi Z$ (' Φ ' is a eigen vector matrix)
 $Z = \Phi^{-1}X = \Psi X$
 Now,

$$\dot{X} = A\Phi Z$$

$$\Phi \dot{X} = \Phi A\Phi Z$$

$$\dot{Z} = \Delta Z \quad [\Delta = \text{diag}(\lambda_1, \lambda_2, \dots), \lambda_1, \lambda_2, \dots \text{ are eigen vectors}]$$

Therefore, Modal analysis;

$$\dot{Z} = \Delta Z$$

$Z_0 = \Psi X_0$, it is called 'mode excitation' (i.e. depending on state given we have mode)

Its solution is,

$$Z_1 = Z_{10} e^{\lambda_1 t} \text{ and}$$

$$Z_2 = Z_{20} e^{\lambda_2 t}$$

Participation factor,

$$P_{ki} = \Phi_{ki} \Psi_{ik}$$

'k' represents the state

'i' represents the mode

So here it gives the participation of kth state into ith mode.

$$\Phi \dot{X} = \Phi A\Phi Z$$

II. SMALL SIGNAL STABILITY ENHANCEMENT WITH SVC CONTROLLER

A SVC along with a controller is used to enhance the dynamic behavior of a 3 Machine 9 bus system [7]. The 3 Machine 9 bus system, consisting of three generators with automatic regulators connected at each generator buses 1,2 and 3 and the remaining buses with loads are connected through transmission lines as shown in Fig.

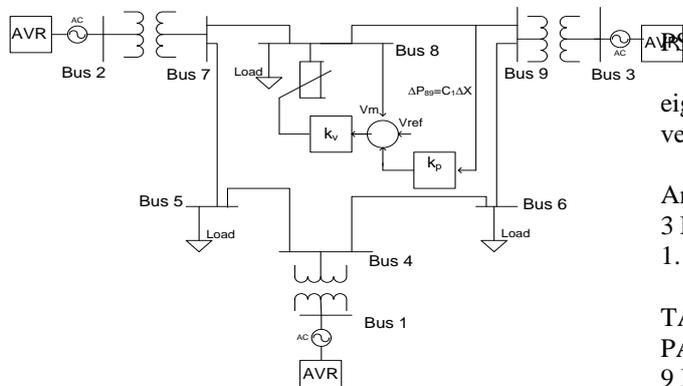


Figure 4: Closed-loop system with controller of FACTS

Under normal operation, from the participation matrix which is obtained from eigen vector matrix it gives the result that the system state oscillatory frequencies are high. So to enhance the dynamic behavior, the system is connected with SVC at bus-8. With SVC, the system oscillating frequencies are reduced very small. So the system dynamic behavior doesn't affect much with SVC. Therefore to enhance the dynamic stability, the power flow at bus-9 corresponding to disturbances is measured (using linearization technique) and given to SVC along with a controller whose gain is 'k'. And by increasing gain

value 'k' starting from '0' it was shown how modes especially mechanical modes are moved from right side of the s-plane to left side.

Results and Discussion

A. System states condition without SVC & with SVC

The state matrix 'A' of the 3 Machine 9 Bus system around the operating state is obtained after running the PSAT mfile using the MATLAB.

The eigen values obtained from the state matrix 'A' using MATLAB.

This gives eigen vector matrix and along with eigen value matrix. The system 24 eigen values are given below:

$$\lambda_1 = -1000$$

$$\lambda_2 = -1000$$

$$\lambda_3 = -1000$$

$$\lambda_4, \lambda_5 = -0.72 \pm 12.74i$$

$$\lambda_6, \lambda_7 = -0.19 \pm 8.37i$$

$$\lambda_8, \lambda_9 = -5.49 \pm 7.95i$$

$$\lambda_{10}, \lambda_{11} = -5.22 \pm 7.81i$$

$$\lambda_{12}, \lambda_{13} = -5.32 \pm 7.92i$$

$$\lambda_{14} = -5.178$$

$$\lambda_{15} = -3.3996$$

$$\lambda_{16}, \lambda_{17} = -0.44 \pm 1.21i$$

$$\lambda_{18}, \lambda_{19} = -0.44 \pm 0.74i$$

$$\lambda_{20}, \lambda_{21} = -0.43 \pm 0.5i$$

$$\lambda_{22} = 0$$

$$\lambda_{23} = 0$$

$$\lambda_{24} = -3.23$$

The eigen value calculations matched with the PSAT eigen value report.

Participation Matrix 'P' is obtained from eigen vector matrix 'v' say ' Φ ' and inverse of eigen vector matrix ' Ψ ' i.e.

$$P = \Phi \cdot \Psi^T$$

Analyzed results from the participation matrix of the 3 Machine 9 Bus system above is displayed in Table 1.

TABLE 1 ANALYZES RESULTS FROM THE PARTICIPANTION MATRIX FOR 3 MACHINE 9 BUS SYSTEM

Mode with Eigen values	Oscillating frequency (Hz)	Associated states
$Z_{14} \& Z_{15} = 0$	-	δ_1, ω_1
$Z_1 = -1000$	-	$V_{m_Exc_1}$
$Z_2 = -1000$	-	$V_{m_Exc_1}$
$Z_3 = -1000$	-	$V_{m_Exc_3}$
$Z_9 = -5.178$	-	E_{2d}, E_{3d}
$Z_{10} = -3.3996$	-	E_{2d}, E_{3d}
$Z_{16} = -3.23$	-	E_{1d}
$Z_4 = -0.72 \pm 12.74i$	2.03	δ_3, ω_3
$Z_5 = -0.19 \pm 8.37i$	1.33	δ_2, ω_2

$Z_6 = -5.49 \pm 7.95i$	1.265	$V_{f2}, V_{r_Exc_2}$
$Z_7 = -5.22 \pm 7.81i$	1.244	$V_{f1}, V_{r_Exc_1}$
$Z_8 = -5.32 \pm 7.92i$	1.261	$V_{r_Exc_3}, V_{f3}$
$Z_{11} = -0.44 \pm 1.21i$	0.193	E_{1q}
$Z_{12} = -0.44 \pm 0.74i$	0.118	E_{1q}
$Z_{13} = -0.43 \pm 0.5i$	0.079	E_{3q}

It can be observed that the system is stable with two modes eigen values zeros and the non-oscillatory modes whose eigen values consists only real values and the oscillatory modes whose eigen values consists both real and imaginary values. The oscillatory modes oscillating frequencies are high values.

Table II displays the effect of FACTS device 3 Machine 9 Bus system. The shunt connected SVC device is located at bus-8 to enhance dynamic stability of the system. The SVC is initialized with the desired voltage at bus-8 (obtained from power flow solution) using a PV generator with zero active power. The data for the SVC is listed in the appendix.

The state matrix ‘A’ of the system now also obtained after running the PSAT mfile like above.

The eigen values obtained from the state matrix ‘A’. The system 25 eigen values are shown below:

- $\lambda_1 = -1000$
- $\lambda_2 = -1000$
- $\lambda_3 = -1000$
- $\lambda_4, \lambda_5 = -0.68 \pm 12.78i$
- $\lambda_6, \lambda_7 = -0.17 \pm 8.38i$
- $\lambda_8, \lambda_9 = -5.46 \pm 7.95i$
- $\lambda_{10}, \lambda_{11} = -5.21 \pm 7.81i$
- $\lambda_{12}, \lambda_{13} = -5.31 \pm 7.92i$
- $\lambda_{14} = -5.25$
- $\lambda_{15}, \lambda_{16} = -2.29 \pm 1.56i$
- $\lambda_{17}, \lambda_{18} = -0.51 \pm 0.85i$
- $\lambda_{19}, \lambda_{20} = -0.43 \pm 0.48i$
- $\lambda_{21}, \lambda_{22} = -0.60 \pm 0.42i$
- $\lambda_{23} = 0$
- $\lambda_{24} = 0$
- $\lambda_{25} = -3.226$

The eigen value calculations matched with the PSAT eigen value report.

Participation Matrix ‘P’ is obtained from eigen vector matrix ‘Φ’ and inverse of eigen vector matrix ‘Ψ’ i.e.

$$P = \Phi \cdot \Psi^T$$

Analyzed results from the participation matrix of the 3 Machine 9 Bus system with SVC above is displayed in Table II.

TABLE II ANALYZED RESULTS FROM THE PARTICIPATION MATRIX FOR 3 MACHINE 9 BUS SYSTEM WITH SVC

Mode with Eigen values	Oscillating frequency (Hz)	Associated states
$Z_{14} \& Z_{15} = 0$	-	δ_1, ω_1
$Z_1 = -1000$	-	$V_{m_Exc_3}$
$Z_2 = -1000$	-	$V_{m_Exc_3}$
$Z_3 = -1000$	-	$V_{m_Exc_1}$
$Z_9 = -5.25$	-	E_{1d}, E_{2d}
$Z_{16} = -3.226$	-	E_{3d}
$Z_4 = -0.68 \pm 12.78i$	2.03	δ_3, ω_3
$Z_5 = -0.17 \pm 8.38i$	1.335	δ_2, ω_2
$Z_6 = -5.46 \pm 7.95i$	1.265	$V_{f2}, V_{r_Exc_2}$
$Z_7 = -5.21 \pm 7.81i$	1.242	$V_{f1}, V_{r_Exc_1}$
$Z_8 = -5.31 \pm 7.92i$	1.261	$V_{r_Exc_3}, V_{f3}$
$Z_{10} = -2.29 \pm 1.56i$	0.248	B_{SVC}
$Z_{11} = -0.51 \pm 0.85i$	0.136	E_{3q}
$Z_{12} = -0.43 \pm 0.48i$	0.076	E_{2q}
$Z_{13} = -0.60 \pm 0.42i$	0.067	B_{SVC}

It can be observed from the results that, with the addition of the SVC the system state oscillating frequencies reduced very small. And the system is stable with two modes eigen values zeros and the non-oscillatory modes whose eigen values consists only real values and the oscillatory modes whose eigen values consists both real and imaginary values.

B. System states condition with SVC along with a Controller

The system connected with SVC doesn’t affect dynamic stability much. So to enhance dynamic stability of the system the active power flow output (i.e. at bus-9) is measured corresponding to disturbances is measured and given to SVC along with a gain ‘k’.

The active power flow at bus-9 w.r.t. bus-8,

$$P_{89} = \frac{V_8 V_9}{X_{89}} \sin(\theta_8 - \theta_9)$$

By linearizing,

$$\Delta P_{89} = \left[\frac{V_9}{X_{89}} \sin(\theta_8 - \theta_9) \right] \Delta V_8 + \left[\frac{V_8}{X_{89}} \sin(\theta_8 - \theta_9) \right] \Delta V_9 + \left[\frac{V_8 V_9}{X_{89}} \cos(\theta_8 - \theta_9) \right] \Delta \theta_8 - \left[\frac{V_8 V_9}{X_{89}} \cos(\theta_8 - \theta_9) \right] \Delta \theta_9$$

From the the system state variable matrix ‘y’ which is obtained from PSAT m file, bus voltage magnitudes and bus voltage angles of bus-8 and 9 are noted and calculated ΔP_{89} shown below.

$$= \left[\frac{1.0355}{0.1008} \sin(0.67 - 1.93) \right] \Delta V_8 + \left[\frac{1.025}{0.1008} \sin(0.67 - 1.93) \right] \Delta V_9 + \left[\frac{1.025 \times 1.0355}{0.1008} \cos(0.67 - 1.93) \right] \Delta \theta_8 - \left[\frac{1.025 \times 1.0355}{0.1008} \cos(0.67 - 1.93) \right] \Delta \theta_9$$

= -0.226 ΔV_8 -0.2237 ΔV_9 + 10.53 $\Delta \theta_8$ -10.53 $\Delta \theta_9$
 From the PSAT output matrix ‘C’, rows corresponding to $\Delta V_8, \Delta V_9, \Delta \theta_8, \Delta \theta_9$ are found.

Therefore,

$$\Delta P_{89} = C_1 \Delta X$$

Using feedback, u= -ky

where u = control input

k (k_p) = constant gain value changing from ‘0’ to high value

y = measured power corresponding to disturbances

The system new ‘A’ matrix becomes:

$$A_{cl} = A - B \times k \times C1$$

The eigen value presentation with the new state matrix ‘A’ of the system in s-plane using the MATLAB is shown below:

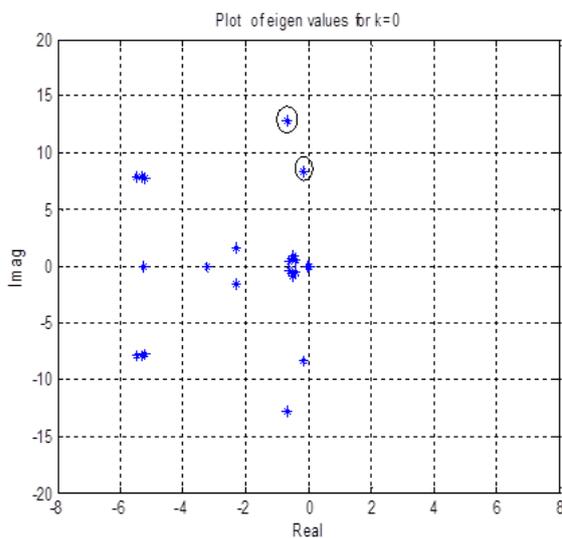


Figure 5: Plot of eigen values for k=0

TABLE III EIGENVALUE ANALYSIS – EFFECT OF SVC CONTROLLER FOR K = 0

Eigen Values
-1000.00
-1000.00
-1000.00
-0.68±12.78i
-0.17±8.38i
-5.46±7.95i
-5.21±7.80i
-5.31±7.92i
-5.25
-2.30±1.56i
-0.51±0.85i
-0.43±0.48i
-0.60±0.42i
-0.00
0.00
-3.23

The Figure above presents the eigen values of the system is s-plane for gain value k=0. The positions of the dynamic modes (i.e. modes 4 & 5) are circled to see how their positions are moved to left side of the s-plane when gain value ‘k’ is increased from 1 to 10 to see improvement in dynamic behavior of the system.

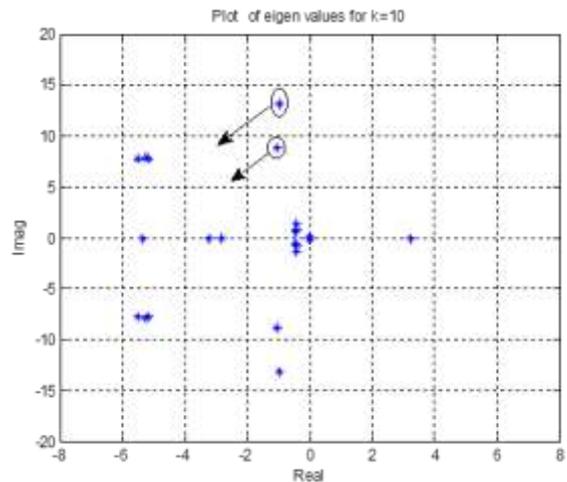


Figure 6: Plot of eigen values for k=10

TABLE IV EIGENVALUE ANALYSIS – EFFECT OF SVC CONTROLLER FOR K = 10

Eigen Values
-1000.00
-1000.00
-1000.00
-1000.00
-0.99±13.18i
-1.06±8.80i
-5.51±7.83i
-5.19±7.81i
-5.24±7.93i
-5.35
3.23
-2.82
-0.43±1.35i
-0.42±0.72i
-0.45±0.56i
0.00
-0.00
-3.23

The Figure presents eigen values of the system for gain k=10. The dynamic modes movement to left side of the s-plane is more by increasing gain value 'k' to 10. This can also be observed by looking at eigen values where the dynamic modes negative real values are increased. Therefore dynamic stability of the system is increased. Here by increasing gain value the controller action becomes fast and it introduces positive damping into the system therefore dynamic stability is improved.

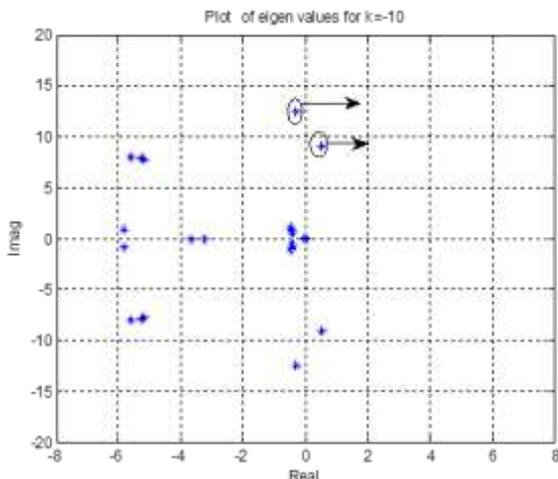


Fig.7: Plot of eigen values for k= -10

TABLE V EIGENVALUE ANALYSIS – EFFECT OF SVC CONTROLLER FOR K = -10

Eigen Values
-1000.00
-1000.00
-1000.00
-1000.00
-0.29±12.51i
-0.53±9.01i
-5.61±8.03i
-5.21±7.79i
-5.28±7.88i
-5.82±0.92i
-3.67
-0.47±1.06i
-0.40±0.62i
-0.46±0.59i
-0.00±0.00i
-3.23

The Figure above presents eigen values of the system for gain 'k' = -10. The dynamic stability of the system is deteriorated for a negative gain value 'k'= -10 because the the eigen values are moved to right side of the s-plane. This can also be observed by looking at eigen values for the modes 4 & 5. That means controller action is slow and it introduces negative damping into the system, therefore dynamic stability become worsen.

Conclusion

This paper has presented using linearization technique the small signal dynamic behavior enhancement of a multi machine power system with FACTS device SVC controller. The improved dynamic stability using FACTS device controller when compared to without controller have proved. The proposed mathematical technique can used directly for small signal stability investigations which would make programming task simpler. It should be noted that this paper makes use of local feedbacks as stabilizing signals for the FACTS based damping controller SVC. The results are shown both with simulation and computation. This work can be implemented or can be further implemented with different other techniques which resolve issues more prominently by avoiding complicity by avoiding programming task.

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