Coordinated control of multi-FACTS to enhance the small disturbance stability of the power system

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***Abstract*--The widespread application of FACTS will be an obvious tendency with the development of power system, as FACTS have the ability to optimize power flow, reduce the network loss, increase power system damping, improve voltage stability and so on. Therefore , there is particular urgent needs to study the coordinated control of the multiple FACTS in the system. This article uses the robust control method to control the TCSC and SVC in a system, the power system is equivalent to a two-machine system, all-state equations of the system can be written according to the generator equations and flow equations, from which we can solve the robust problem and get the control law of FACTS. The robust control strategy of FACTS is simulated by the software of PSASP on a power system of 4 generators, and the results show that the Robust control strategy can improve the small signal stability of the system.**

***Index Terms*--Linear robust control, small signal stability, TCSC, SVC**

I. INTRODUCTION

The power grid of China has entered the era of developing ultra-high voltage (UHV) and large interconnected power system. The interconnection of national grid has greatly increased the complexity of the grid structure and the difficulty in operation. In addition, the development of smart grid brings operators more challenges to run the grid. The future smart grid needs more flexible and reliable control methods to improve the flow distribution, reduce network losses, raise the level of system damping and improve the system voltage stability and so on.

Individual FACTS device is fast and reliable in improving the operation state of the local power grid, and using the coordinated control of multiple FACTS devices can provide an optimization control of the entire grid or parts of the grid. With the extensive application of FACTS devices, the problem of interaction and coordination control of FACTS devices is acquiring an increasingly important position[1].

There are two ways in studying multi-FACTS coordination and optimal control. One way is based on the interaction effect of multiple FACTS devices. The modal analysis method[2], the relative gain matrix analysis method[3], singular value decomposition method and Gramm determinant-based analysis method[4] can be used to quantify the extent of interaction of FACTS devices. And researchers then plan the installation location or optimize the control parameters of FACTS devices using the variable-based multivariable PI controller parameters tuning method[5], the batch method[6] , the multi-objective hybrid evolutionary algorithm[7] and so on. The second way completely abandons the conventional control strategies of FACTS and reformulate new control strategies according to the target, the target can be set as improving system transient stability or small signal stability. Methods of energy function [8], adaptive fuzzy damping control[9] and robust nonlinear control[10] are used to achieve the target.

Robust control theory based on all-state equations of the system achieves the optimization goal of the whole system. In published reports, robust control was used to achieve coordination control mostly on the single machine infinite bus system[11] or to study coordinated control of FACTS and the generator excitation. In this paper, robust control theory is used to control a TCSC and a SVC, large grid is equivalent to a two-machine system, one TCSC is serried between the two-machine system, in which the SVC is paralleled. All-state equations of the system can be written according to the generator equations and flow equations , from which we can solve the robust problem and get the control law of TCSC , the SVC is control by voltage of the bus as usual ,but the control strategy of TCSC involves the influence of SVC. The new control strategy is verified by PSASP.

II. INTRODUCTION OF LINEAR ROBUST CONTROL

Linear robust control is all named linear H_∞ control. H_∞ norm is an energy gain index from the interference signal to the evaluation signal. H_∞ control is a method to makes the H_∞ norm of interference signal to the evaluation signal minimum and reduce the effect of interference and increase the system robust stability.

A. Standards problem of linear robust control

Figure 1 shows the system, u is the output of the controller, y is the input of the controller , w is the interference signal (or auxiliary signal). z is the control object (or evaluation signal). The transfer function matrix from the input signal u, w to the output signal z, y is called the augmented controlled object. *K(s)* is the controller.

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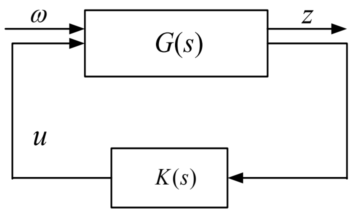

Figure 1 H_∞ standard design problem system diagram

System model is:

$$\begin{aligned} \dot{x} &= \boldsymbol{A}x + \boldsymbol{B_1}w + \boldsymbol{B_2}u \\ z &= \boldsymbol{C_1}x + \boldsymbol{D_{11}}w + \boldsymbol{D_{12}}u \\ y &= \boldsymbol{C_2}x + \boldsymbol{D_{21}}w + \boldsymbol{D_{22}}u \end{aligned} \tag{1}$$

Where x is a n-dimensional state variable, w is r -dimensional vector, u is p -dimension, z is m -dimension, y is the q -dimensional signal vector.

Transfer function matrix G (s) is :

$$\begin{aligned} \boldsymbol{G}(s) &= \begin{bmatrix} \boldsymbol{G}_{11}(s) & \boldsymbol{G}_{12}(s) \\ \boldsymbol{G}_{21}(s) & \boldsymbol{G}_{22}(s) \end{bmatrix} \\ &= \left[\begin{array}{c:cc} \boldsymbol{A} & \boldsymbol{B_1} & \boldsymbol{B_2} \\ \hdashline \boldsymbol{C_1} & \boldsymbol{D_{11}} & \boldsymbol{D_{12}} \\ \boldsymbol{C_2} & \boldsymbol{D_{21}} & \boldsymbol{D_{22}} \end{array}\right] \end{aligned} \tag{2}$$

The closed-loop transfer function from w to z is

$$\begin{aligned} \boldsymbol{T}_{zw}(s) &= LFT(\boldsymbol{G}(s), \boldsymbol{K}(s)) \\ &= \boldsymbol{G}_{11} + \boldsymbol{G}_{12}\boldsymbol{K}(\boldsymbol{I} - \boldsymbol{G}_{22}\boldsymbol{K})^{-1}\boldsymbol{G}_{21} \end{aligned} \tag{3}$$

The H_∞ optimal design problem can be stated as follows: For a given augmented controlled object $\boldsymbol{G}(s)$, seeking feedback controller $\boldsymbol{K}(s)$ makes the closed-loop system stable and $\|\boldsymbol{T}_{zw}(s)\|_\infty$ is minimum, that is

$$\min_K \|\boldsymbol{T}_{zw}(s)\|_\infty = \gamma_0 \tag{4}$$

And the H_∞ sub-optimal design problem can be described as: For a given augmented controlled object $\boldsymbol{G}(s)$ and $\gamma(\geq \gamma_0)$, Seeking feedback controller $\boldsymbol{K}(s)$ makes the closed-loop system internally stable and $\boldsymbol{T}_{zw}(s)$ satisfies:

$$\|\boldsymbol{T}_{zw}(s)\|_\infty < \gamma \tag{5}$$

B. The solution of linear robust control

Combined with the practical problems discussed in this article, here are just a special case when $\boldsymbol{D}_{11} = \boldsymbol{0}$, $\boldsymbol{C}_2 = \boldsymbol{I}$, $\boldsymbol{D}_{21} = \boldsymbol{0}$, $\boldsymbol{D}_{22} = \boldsymbol{0}$.

Inspect system consisting of the following state space equation and output equation

$$\begin{cases} \dot{\boldsymbol{x}}(t) = \boldsymbol{A}\boldsymbol{x}(t) + \boldsymbol{B}_1\boldsymbol{w}(t) + \boldsymbol{B}_2\boldsymbol{u}(t) \\ \boldsymbol{z}(t) = \boldsymbol{C}\boldsymbol{x}(t) \end{cases} \tag{6}$$

Where $\boldsymbol{x}(t)$ is n -dimensional state vector, $\boldsymbol{u}(t)$ is the r -dimensional control vector, $\boldsymbol{w}(t)$ is the p dimension disturbance variable, $\boldsymbol{A,B,C}$ is the corresponding dimension matrix.

Linear H_∞ control problem of system (6) is: given $\gamma > 0$, design a state feedback controller $\boldsymbol{U} = -\boldsymbol{KX}$, makes the corresponding closed-loop system internally stable, and $\forall w(\cdot) \in L_2[0,\infty)$, if the initial of system is $\boldsymbol{X}(0) = \boldsymbol{0}$, the response $\boldsymbol{z}(t)$ of the system (6) satisfy the following inequality

$$\int_0^\infty \|\boldsymbol{z}(t)\|^2 dt \leq \gamma \int_0^\infty \|\boldsymbol{w}(t)\|^2 dt \tag{7}$$

Where γ reflects the level of interference suppression of the closed-loop system.

Linear H_∞ control problem has the following solving steps:

The first step: solve the feedback matrix;

solve the equation

$$\boldsymbol{A}^T\boldsymbol{P} + \boldsymbol{P}\boldsymbol{A} + \frac{1}{\gamma^2}\boldsymbol{P}\boldsymbol{B}_1\boldsymbol{B}_1^T\boldsymbol{P} - \boldsymbol{P}\boldsymbol{B}_2\boldsymbol{B}_2^T\boldsymbol{P} + \boldsymbol{C}^T\boldsymbol{C} < 0 \tag{8}$$

to get a semi-positive definite solution $\boldsymbol{P} \geq \boldsymbol{0}$

The second step: construct H_∞ control law.

If the equation has semi-positive definite solution, we name it $\hat{\boldsymbol{P}}$, the H_∞ control law is

$$\boldsymbol{u} = -\boldsymbol{B}_2^T\hat{\boldsymbol{P}} \cdot \boldsymbol{x}(t) \tag{9}$$

III. ROBUST CONTROL OF THE POWER SYSTEM

A. Power system model

Consider the two regional power system (Complex systems can be simplified to two-machine system through the network equivalence and generator equivalence.), TCSC and SVC is installed on the contact line. Equivalent circuit diagram is shown in Fig.2 :

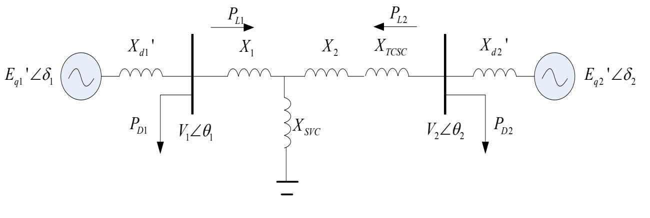

Figure 2 The equivalent two-machine system schematic

Use the generator second-order model, that is, voltage behind the transient impedance of the generator E_q' and the mechanical power P_m are constant. Ignore the damping of the generator, the system robust model can be written as:

$$\begin{cases} \dot{\iota} \qquad -1) \\ \dot{\iota} \qquad \frac{}{T_{J1}} \; {}_{m1} - P_{e1}) \\ \dot{\iota} \qquad -1) \\ \dot{\iota} \qquad \frac{}{T_{J2}} \; {}_{m2} - P_{e2}) \end{cases} \tag{10}$$

$\delta_1, \delta_2, \omega_1, \omega_2, P_{m1}, P_{m2}, P_{e1}, P_{e2}$ are generator rotor angle, rotational speed, mechanical power and electric power of the two generators. The control models of the TCSC and SVC are show as below:

$$\Delta\dot{} \qquad \frac{}{T_X} \qquad -\Delta X] \tag{11}$$

$$\Delta\dot{} \qquad \frac{}{T_B} \qquad -K_A\Delta V - \Delta B] \tag{12}$$

The power of the tieline is

$$P_{L1} = \frac{V_1V_2\sin(\theta_1 - \theta_2)}{X_1 + X_2 + X_{TCSC} - B[X_1(X_2 + X_{TCSC})]} \tag{13}$$

The voltage of the bus which the SVC is tied on is

$$V = \frac{\sqrt{(X_\Sigma V_1)^2 + (X_1V_2)^2 + 2V_1V_2\cos\theta_{12}X_1X_\Sigma}}{X_1 + X_\Sigma - BX_1X_\Sigma} \tag{14}$$

P_{D1},P_{D2} are loads in the two areas.

$$\begin{aligned} P_{e1} &= P_{D1} + P_{L1} \\ P_{e2} &= P_{D2} + P_{L2} \end{aligned} \tag{15}$$

B. Linearization of system model

$$\begin{cases} \Delta\dot{\iota} \qquad \dot{} \\ \Delta\dot{\iota} \qquad \frac{}{T_{J1}} P_{e1} - \frac{1}{T_{J2}}P_{e2}) + (\frac{1}{T_{J1}}P_{m1} - \frac{1}{T_{J2}}P_{m2}) \end{cases} \tag{16}$$

In which:

$$\begin{aligned} \Delta\delta_{12} &= \delta_1 - \delta_2 - (\delta_{10} - \delta_{20}) \\ \Delta\omega_{12} &= \omega_1 - \omega_2 - (\omega_{10} - \omega_{20}) \end{aligned} \tag{17}$$

Assume both sides of the generators are coherent, so

$$\begin{aligned} \Delta\theta_{12} &= m_1\Delta\delta_{12} \\ \Delta f_{12} &= m_2\Delta\omega_{12} \\ m_1 &\approx m_2 \end{aligned} \tag{18}$$

θ_1, θ_2 is the phase angle of generator voltage, m_1 and m_2 are unknow, then (16) becomes

$$\begin{cases} \Delta\dot{\iota} \qquad m_2 \quad {}_0\dot{\Delta} \qquad \dot{} \\ \frac{1}{m_2}\dot{\Delta} \qquad \frac{}{T_{J1}} P_{e1} - \frac{1}{T_{J2}}P_{e2}) + (\frac{1}{T_{J1}}P_{m1} - \frac{1}{T_{J2}}P_{m2}) \end{cases} \tag{19}$$

Ignore the influence from governors in both areas, then $P_{m1} = P_{e10}, P_{m2} = P_{e20}$,and $P_{L1} = -P_{L2}$,if we ignore the change of loads, (19) becomes

$$\begin{cases} \Delta\dot{\iota} \\ \dot{\Delta} \qquad \frac{1}{T_{J1}} + \frac{1}{T_{J2}})\Delta P_{L1} \end{cases} \tag{20}$$

To design the control strategy of TCSC, If (13) is linearized near the operation point, then (20) becomes

$$\begin{cases} \dot{} \qquad t) + \boldsymbol{B_1}\boldsymbol{w}(t) + \boldsymbol{B}_2u_1(t) \\ z(t) = \boldsymbol{Cx}(t) \end{cases} \tag{21}$$

In (21), state variables are $\boldsymbol{x}(t) = [\Delta\theta_{12}, \Delta f_{12}, \Delta X]$, the interference set are $\boldsymbol{w}(t) = [\Delta B, \Delta V_1, \Delta V_2]$ (which means set the change of SVC as interference to TCSC), the matrixes are

$$\boldsymbol{A} = \begin{bmatrix} 0 & \omega_0 & 0 \\ -m_2(\frac{1}{T_{J1}} + \frac{1}{T_{J2}})P_{L10} \cdot \cot\theta_{120} & 0 & m_2(\frac{1}{T_{J1}} + \frac{1}{T_{J2}})\frac{1 - B \cdot X_1}{X_1 + X_\Sigma - B \cdot X_1 \cdot X_\Sigma}P_{L10} \\ 0 & 0 & -\frac{1}{T_X} \end{bmatrix}$$

$$\boldsymbol{B_1} = \begin{bmatrix} 0 & 0 & 0 \\ -m_2(\frac{1}{T_{J1}} + \frac{1}{T_{J2}})\frac{X_1 \cdot X_\Sigma}{X_1 + X_\Sigma - B \cdot X_1 \cdot X_\Sigma}P_{L10} & -m_2(\frac{1}{T_{J1}} + \frac{1}{T_{J2}})\frac{P_{L10}}{V_1} & -m_2(\frac{1}{T_{J1}} + \frac{1}{T_{J2}})\frac{P_{L10}}{V_2} \\ 0 & 0 & 0 \end{bmatrix}$$

$$\boldsymbol{B}_2 = \begin{bmatrix} 0 \\ 0 \\ \frac{1}{T_X} \end{bmatrix}$$

From (21), we can get the linear model of the system to design the strategy of the TCSC, we can use the same method to design the control strategy of the SVC, the difference are $\boldsymbol{x}(t) = [\Delta\theta_{12}, \Delta f_{12}, \Delta B]$, $\boldsymbol{w}(t) = [\Delta X, \Delta V_1, \Delta V_2]$ and the change of loads shouldn't be ignored but calculated in the matrixes of A and B_1.

C. solving the control problem

After setting $\boldsymbol{C}$ and m_2, we can use the method of part II to solve the linear robust problem for system (21) to get the feedback:

$$u_1 = k_1\Delta\theta_{12} + k_2\Delta f_{12} + k_3\Delta X \tag{22}$$

The control block for TCSC is shown in figure 3.

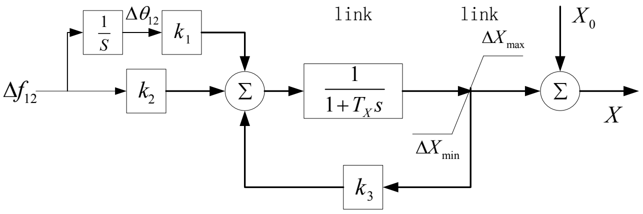

Figure 3 Control block for TCSC

Use the same method to get the control strategy of SVC,

$$u_2 = k_1\Delta\theta_{12} + k_2\Delta f_{12} + k_3\Delta B \tag{23}$$

The control block for SVC is shown in figure 4.

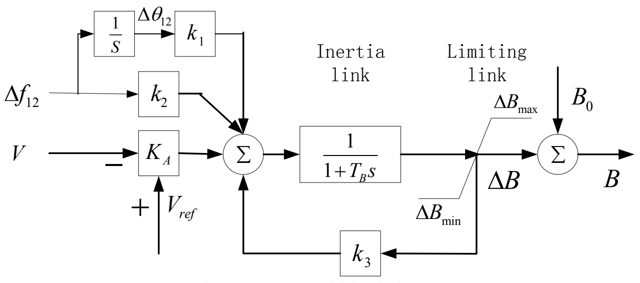

Figure 4 Control block for SVC

IV. SIMULATION EXAMPLE

A. Introduction of the system

This article uses the software of PSASP (Power System Analysis Software Package) to simulate the four-generator system, the original parameters of the four-machine system specific can be seen in [12]. In this article, the two AC lines between bus 7 and bus 8, are combined into one line, and so are the two lines between bus 8 and bus 9. Single line figure of the system is shown in Fig.3:

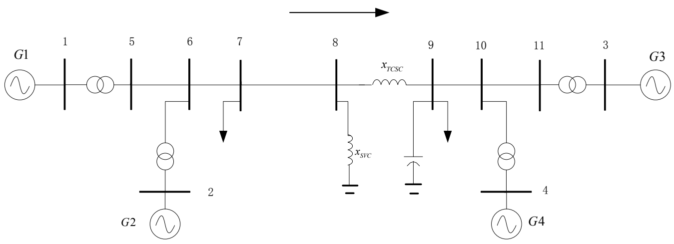

Figure 4 the single line figure of four-machine two-region systems

SVC is paralleled on bus 8, TCSC is serried on the line between bus 8 and bus 9. In the process of simplifying ,components between bus 7 and bus 9 are kept unchanged, other parts are equivalent to two machines. The two generators are connected to the bus 7 and bus 9, and T_J of the two generators are the sum of original generator 1, 2 and the sum of original generator 3, 4 separately.

B. The simulation results

Small disturbance of the system is set as: there is a three-phase short circuit occurred between bus 5 and bus 6, which is near to bus 5. The fault occurred at 1s, and stops at 1.05s.

The coefficients of robust control of TCSC (22) or SVC(23), k_1,k_2,k_3 change very little when m_2 changes from 0.5 to 1, so we assure m_2 to be 1 when we solve the robust problem for system (21).

Figure 5 shows the comparision of robust control TCSC and conventional control TCSC when the SVC is under conventional control.

The conventional control of SVC is

$$\Delta B = \frac{K_A}{1+T_A s}\Delta U \tag{24}$$

The conventional control of TCSC is

$$\Delta X = (K_P + \frac{K_I}{s})\Delta P \tag{25}$$

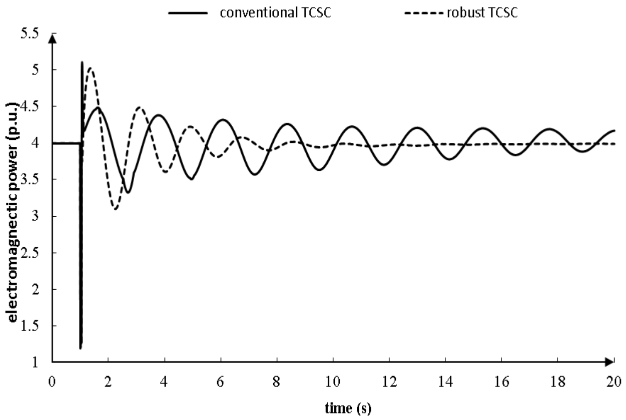

Figure 5 Electric power of the line between bus 8 and bus 9

Figure 6 shows the comparision of robust control SVC and conventional control SVC when the TCSC is under conventional control.

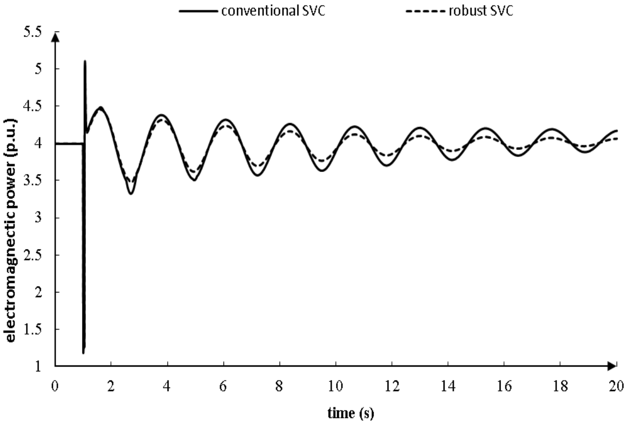

Figure 6 Electric power of the line between bus 8 and bus 9

The following three conditions are compared in the simulation:

Situation 1 : The TCSC under conventional control and SVC under robust control.

Situation 2: The TCSC under robust control and SVC under conventional control.

Situation 3: The TCSC under robust control and SVC under robust control..

The electric power of the line between bus 8 and bus 9 , and the voltage of bus 8 of the 3 situations are as Fig.7 and Fig .8:

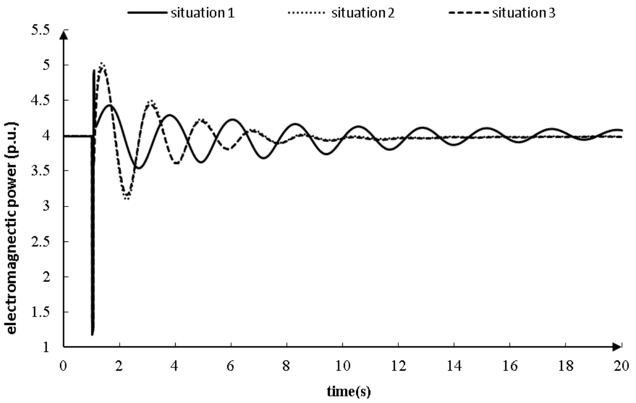

Figure 7 Electric power of the line between bus 8 and bus 9

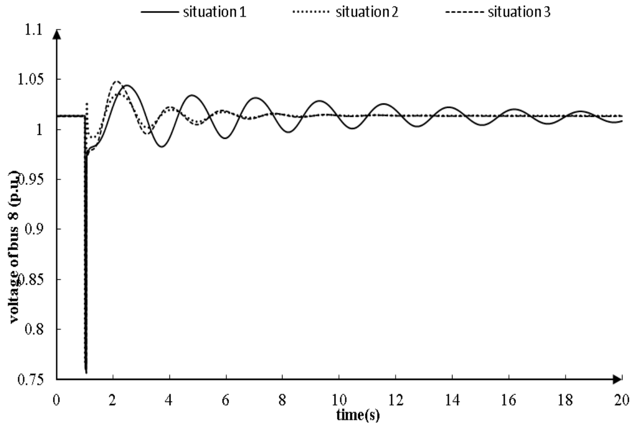

Figure 8 Voltage of bus 8

Then we compared the change of SVC's equivalent admittance and TCSC's equivalent impedance in the situation three situation, results are shown in Fig.9 and Fig.10 :

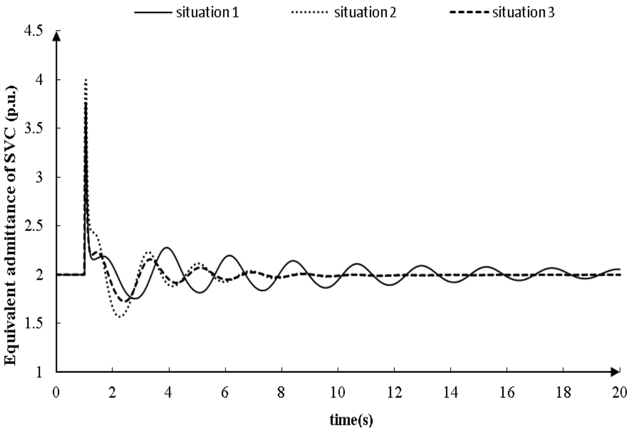

Figure 9 Equivalent admittance of SVC

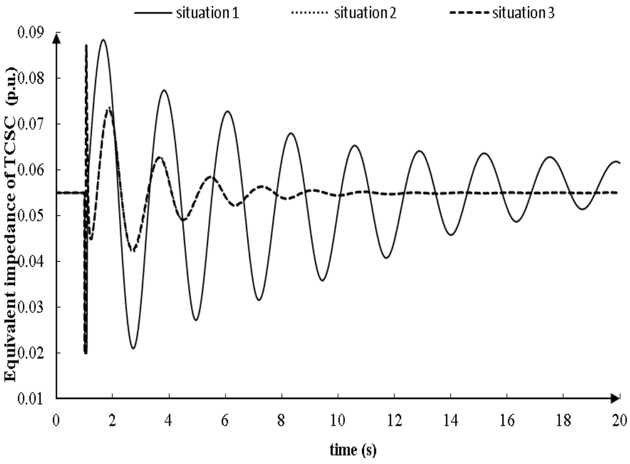

Figure 10 Equivalent impedance of TCSC

It can be seen that in the situation three, the oscillation of the electric power of the AC line damps the fastest, and the voltage stability of bus 8 is also the best. The adjustment of TCSC and SVC quickly quell in situation three. The simulation curves show that the coordinated control of FACTS----robust control used in this article is more effective to improve small signal stability of the system compared to conventional control.

V. SUMMARY

Coordination control of FACTS has become a hot topic. Robust control is widely used as a global control method. In this paper, robust control is used to get coordination control of TCSC and SVC , in the process, the power system is equivalent to two-generator system which includs one TCSC and one SVC. We deduce the state equations of the two-generator system from the generator equations and flow equations, and then use the feedback liberalized robust control method to design the FACTS control law of the system.

This article simulate the robust control law in the four-generator system by PSASP. Simulation results show that the robust control of FACTS can improve the small signal stability of the system more compared to conventional control.

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VII. BIOGRAPHIES

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