Paper

EVALUATION STUDY ON ASVC AND SVC FOR POWER SYSTEM OSCILLATION DAMPING

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This paper proposes a design method of damping controllers of two facts devices, namely Synchronous Voltage Source when it is used only for reactive shunt compensation, i.e. 'Advanced Static Var Compensator' (ASVC) and Static Var compensator (SVC). The applications of ASVC and SVC for damping control are demonstrated and the comparison is made about the damping control capabilities paying attention to the difference in the design philosophy and detailed dynamic performances. An important issue in designing this kind of controllers is to suppress overvoltage that appears under large disturbance. This overvoltage problem sometimes appears in the existing SVC system. To cope with this overvoltage problem, it is proposed to use the control sensitivity function to regulate indirectly the controller output so that the overvoltage problem is treated in the design step. Another important issue is that we point out the zero problem tends to appear inherent in a typical ASVC system making the controller design difficult. To design robust controllers under this condition, we suggest to use the bilinear transform to design a robust H_∞-optimal controller. It is shown that the proposed controller provides more robust stability and better performance for additional damping for power system oscillations while suppressing overvoltages. Performance comparison is also made between ASVC and SVC cases.

Key words: low-frequency oscillations, H_∞-optimal control, ASVC, SVC, performance, robustness

1. Introduction

The idea behind the concept of FACTS (Flexible AC Transmission Systems) is to control the active and reactive power in AC transmission systems as desired and to utilize the existing transmission facilities to their thermal limits by improving the transient stability. A family of FACTS devices has been developed. Basically, The FACTS devices are oriented to controlling the three basic electric parameters of transmissions (impedance, phase-shift angle and voltage).

In planning and operating today's power system, the ability to maintain power oscillation damping has become a growing concern. Among the family of FACTS devices, the Synchronous Voltage Source (SVS) has the unique capability of controlling the transferred active and the reactive power [2]. If the energy storage is of suitable rating, the SVS can exchange both reactive and real power with the ac system. The reactive and real power, generated or absorbed by the SVS, can be controlled independently, and any combination of real power generation/absorption with var generation/absorption is possible. The SVS, which is operated only for reactive shunt compensation is called as advanced static var compensator (ASVC).

As already demonstrated in a number of applications, static var compensator (SVC) can also provide good damping for power system oscillations [4,5], although this kind of FACTS device can only control the transferred reactive power. This makes it interesting to make a comparison between the ASVC and SVC regarding the performances. An important issue in designing this kind of controllers is to take account of an overvoltage problem that appears under severe disturbance [6], where unacceptable overvoltage may damage power system equipments, which make them costly in the long run.

In the previous paper [1-5] linear control technique has been used for designing the ASVC and SVC controller, however, it has lack of robustness. They can not guarantee the stability and the performance of the system under a wide range of operating conditions due to uncertainties in the system models. H_∞- optimal control theory is a useful countermeasure for this problem [7,8]. Up to now, there have been no application to ASVC design and also there is no comparison evaluation yet about robust controller design of ASVC and SVC for damping control.

Another important issue is about zeros problem (zeros in the right half plane) inherent in a typical ASVC system. The systems with such zeros are called as Non minimum phase system. This problem can cause difficulty in controller design and also reduce performance and robustness of a controller.

The objective of this paper is to present a design method of damping controllers for ASVC and SVC using the H_∞-optimal control theory. It is shown that, concerning overvoltage problem in case of SVC supplementary damping controller design, the use of the control sensitivity function is effective in the design step to regulate indirectly the controller output. And to design robust controllers under zeros problem inherent in the ASVC system, the use of bilinear transform is suggested. It is demonstrated through numerical simulations that the effectiveness of the proposed design method. Furthermore, the comparison is made about the damping control capabilities under the assumption that the ASVC and the SVC of the same ratings are installed in the same transmission line. It is shown that ASVC controller provides more robust stability and better performance for additional damping during power system oscillations.

2. SVC

A Static Var Compensator (SVC), or Fixed Capacitor – Thyristor Controlled Reactor (FC-TCR) type Static Var System (SVS), composed of a shunt capacitor and a controllable shunt reactor is widely used to provide voltage support at midpoint of long transmission lines. The high-speed response feature of SVC can provide also many opportunities for enhancing the performance of power systems.

It is found that a bus voltage controlled SVC does not contribute significantly to system damping [4]. A significant contribution to system damping can be achieved when an SVC is controlled by some auxiliary signals superimposed over its voltage control loop.

Modeling of SVC

The case study is a synchronous generator to an infinite bus over a long distance transmission line, which is compensated at its midpoint by an SVC. A PI (Proportional-Integral) controller is used for the voltage regulation at the SVC bus. The illustrative block diagram of the system is given in figure 1(a) and 1(b). Where B_c is TCR susceptance corresponds to the thyristor firing angle α_0, ΔB is the variation in TCR susceptance, K_r and T_r are SVC main controller parameter, ΔV_F represents the incremental auxiliary signal, ΔV_{busSVC} is the terminal voltage perturbation.

Since the objective of the supplementary controller is to provide additional damping of power system oscillations in a particular frequency band, the design emphasis is different from that of tracking a reference input signal, i.e. for controlling the bus voltage at a desired level. The block diagram representation of such a control system is shown in figure 2. The "plant" *G(s)* represents the block diagram of the entire transfer function shown in Fig. 1a. The output *y(s)* is the feedback signal of the supplementary controller. In this paper, *y(s)* is chosen to be magnitude of the line current, I_m. This selection of feedback signal is quite typical for SVC supplementary controller to effectively increase the system damping [9,11]. *K(s)* represents the damping controller to be designed. Signal *d(s)* is disturbance acting on the system output *y(s)*. *u* and u_1 are the plant input and output, respectively.

3. ASVC

In this paper, we consider the Synchronous Voltage Source (SVS) is used only for reactive shunt compensation (called as ASVC), then the dc energy storage device can be replaced by a relatively small dc capacitor, as shown in figure 3. In this case, the steady-state power exchange between the SVS and the ac system can only be reactive.

When the SVS is used for reactive power generation, the inverter itself can keep the capacitor charged to the required voltage level. This is accomplished by making the output voltages of the inverter lead the system voltages by a small angle. In this way the inverter absorbs a small amount of real power from the ac system to replenish its internal losses and keep the capacitor voltage at the desired level. The same control mechanism can be used to increase or decrease the capacitor voltage for the purpose of controlling the var generation or absorption [2].

The V-I characteristic of an ASVC is shown in Fig. 4a. As can be seen, the ASVC can provide both capacitive and inductive compensation. It is able to control the maximum controllable current independent of the ac system voltage. This is in contrast to the SVC, which the maximum controllable current is strictly determined by the magnitude of the system voltage and the size of the capacitor. The ASVC is, therefore, superior to the SVC in providing voltage support and can further enhance its dynamic performance.

Modeling of ASVC

An advanced static var compensator (ASVC) is installed in the same transmission line as SVC case study. The ASVC is modeled in this paper based on a simplified representation of figure 3, including a dc-side capacitor, *C*, an inverter, and series inductances, *L*, in the three lines connecting to the transmission line [3]. This inductance accounts for the leakage of the actual power transformers. The circuit also includes resistance in shunt, R_p, with the inverter, and resistance in series, Rs, with ac-lines to represent the inverter and transformer conduction losses. The state vector corresponding to the ASVC is $x_c^T = [\,\Delta i_d,\ \Delta i_q,\ \Delta v_{dc}\,]^T$, where Δi_d and Δi_q are respectively the d-axis and q-axis current components, Δv_{dc} is the dc voltage. A detailed explanation about the modeling is given in appendix.

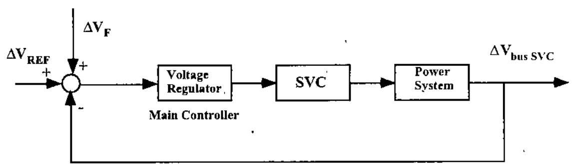

Fig. 1a Block Diagram of The Entire System

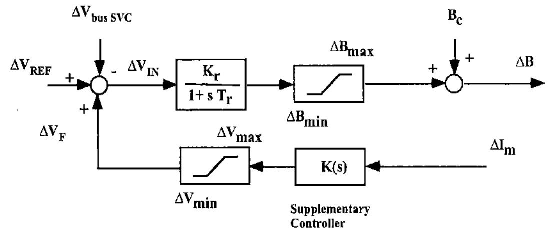

Fig. 1b Block Diagram of the SVC Controller

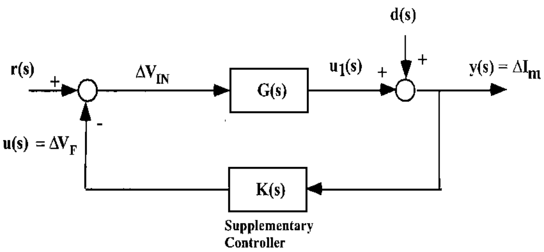

Fig. 2 The plant and the supplementary controller.

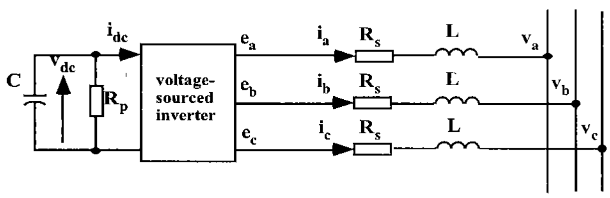

Fig. 3 Equivalent Circuit Diagram of the Inverter Connected to the System

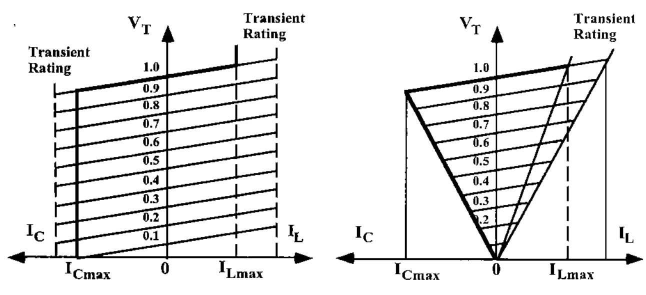

Fig. 4 V-I characteristic of the ASVC (a) and of SVC (b)

Same as in SVC case, a PI (Proportional-Integral) controller shown in figure 5(a) is usually used as a voltage regulator in real system, where the supplementary signal, ΔV_F, is not used. In this paper, using this configuration of voltage regulator, we will design a supplementary controller K(s) in figure 5(b) to damp power system oscillation. This configuration of control system is also quite typical as discussed in [3,11,15]. In this figure, the voltage regulator in figure 5(a) is described more precisely, where $\Delta\theta$ is the phase angle of the system voltage V_T ($\Delta\theta = \tan^{-1}(V_{Tq} / V_{Td})$);

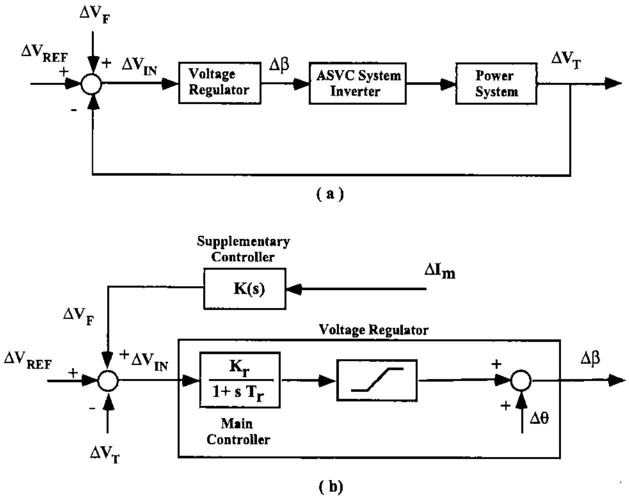

Fig. 5 (a) Block diagram of the entire ASVC system
(b) The ASVC controller

$\Delta\beta$ is the input to ASVC inverter; ΔV_F represents the incremental auxiliary signal from the supplementary controller.

Remarks

To know more about the system behavior, a standard frequency domain analysis can be done by using the transfer function of the ASVC model for small perturbations. With neglecting the system power losses (i.e. $R_s=0$, $R_p=\infty$), the corresponding transfer function relating to q-axis current inverter, Δi_q and the input to ASVC inverter, $\Delta\beta$ is as follows [3]:

$$\frac{\Delta i_q(s)}{\Delta\beta(s)} = \frac{L''[s^2 + L''C'']v_{dco} + [L''C''\omega_b]i_{qo}}{s[s^2 + \omega_b{}^2 + L''C'']} \qquad (1)$$

where $L'' = \dfrac{k\omega_b}{L}$; $C'' = \dfrac{3k\omega_b C}{2}$;

k is a factor for the inverter which relates the dc-side voltage to the amplitude of the voltage at the inverter ac-side terminal, and ω_b is rotor-speed base [3]. The undamped poles of the system are thus at

$$s = 0 \text{ and } s = \pm j\omega_b\sqrt{\left(1 + \frac{3k^2C}{2L}\right)} \qquad (2)$$

The transfer function, eqn. (2), also has a pair of complex zeroes on the imaginary axis. These move along the imaginary axis as a function of i_{qo}. The existence of these zeros results in the unstable zeros of the open loop system G(s), which will cause difficulties in designing the controller.

4. Comparison Between ASVC and SVC for Damping Capability.

A comparison study has been made between ASVC and SVC with equal rating condition. To compare the performance of the closed-loop system with the designed damping controller between ASVC and SVC, an improved robust H_∞-optimal control technique is used in this study. In this improved method, the standard H_∞-optimal control technique is combined with bilinear transform to treat the zeros problem and enhance the power swings damping.

4.1 Damping Control based on H_∞-optimization theory

The H_∞- optimization technique have been successfully applied to ASVC and SVC. However, there is much difference in the design philosophy between designing ASVC and SVC controller. The basic principle difference in the design philosophy between ASVC and SVC controller is shown in Table 1.

4.1.1. SVC Supplementary Controller Design

Previously, for solving the tracking/command following problem and/or disturbance rejection problem, the plant was assumed to be known exactly. This is rarely the case due to unmodelled dynamics, parameter variations, etc. When the controller designed for a nominal plant model is implemented on the real system, there are no guarantees on the resulting performance of the system. The deviation from the expected behavior of the system clearly depends on the accuracy of the model. Since modeling uncertainty is inevitable, it is imperative to include stability and performances robustness to model uncertainty as a design objective. Instead of considering a single nominal time-invariant plant, G_o, we shall instead consider a collection of plants. For multiplicative uncertainty representation, the set of perturbed plants G(s) may be defined as:

$$G(s) := [I + \Delta_M(s)W_3(s)]G_o(s) \qquad (3)$$

where $\Delta_M(s)$ denote multiplicative uncertainty, and satisfy :

$$\|\Delta_M(s)\|_\infty \le 1,$$

Table 1. The Basic Principle Difference For Damping Control Design

	SVC	ASVC
Static Characteristic	The maximum controllable current is strictly restricted by the magnitude of the system voltage and the size of the capacitor.	The maximum controllable current is independent of the ac system voltage. (A larger transient rating)
Damping Controller Restriction	The supplementary controller must be designed not to disturb the main controller.	Not Special.
Zeros problem	No zeros usually exist in the right half plain.	The system has zeros in the imaginary axis and usually has zeros in the right half plain (non minimum phase system).This condition could influence the controller performance.

where $\| . \|_\infty$ denotes the maximum magnitude of the vector over all ω. W_3 is fixed weighting function containing all the information available about the frequency distribution of the uncertainty. W_3 is chosen such that $\|\Delta_M(s)\|_\infty \le 1$, which implies that Bode plots of W_3 cover the Bode plots of all possible plants.

Some common issues in the standard H_∞-approach is concerned with the following issues:

(i) Disturbance attenuation characteristic is given by

$$y=S(s).d \quad (4)$$

where $S(s)$ is sensitivity function defined by

$$S(s)=(I + K(s)G_0(s))^{-1}$$

(ii) For any perturbation of $\Delta(s)$, $\| \Delta(s) \|_\infty \leqq 1$, stability is guaranteed if

$$\|W_3(s)T(s)\|_\infty \le 1 \quad (5)$$

$T(s)$ is complementary sensitivity function defined by $T(s)=(I + K(s)G_0(s))^{-1}K(s)G_0(s)$ or $T(S)=1-S(s)$.

In H_∞ -approach, the robust stability goal is met the minimizing for instance the complementary sensitivity function $T(s)$ for the multiplicative uncertainty representation. On the other hand, the nominal performance design goal such as disturbance rejection is achieved by minimizing the H_∞-norm of the sensitivity function $S(s)$. Such conditions can be satisfied by appropriate choice of W_1. W_1 is a high gain, low pass weighting function representing the desired disturbance attenuation.

Furthermore, the SVC supplementary controller must be designed that the control output between desired limits. However, the control limits are not proper uncertainties. In order to satisfy this condition, the control limits are modeled as a performance weighting function. Such conditions can be satisfied by appropriate choice of weighting function W_2 in(6). In other words, setting $R(s)$, which is the transfer function from disturbance to controller output, is used to regulate the controller output for SVC. The weight on the control output W_2 should be chosen close to a differentiator to penalize fast changes and large overshoot in the control output.

$$\|W_2(s)R(s)\|_\infty \le 1 \quad (6)$$

where $R(s)$ is control sensitivity function defined by $R(s)=(I + C(s)G_0(s))^{-1}C(s)$.

W_2 is fixed weighting function containing all the information available about the control limit.

The controller is found by using frequency dependent weighting function W_1, W_2 and W_3 to guide the design so that a trade-of between performance and stability robustness can be obtained, see eqn. (7), and the feedback loop will take the form as shown in figure 6. .

$$\min_{K(s)} \left\| \begin{matrix} W_1(s)S(s) \\ W_2(s)R(s) \\ W_3(s)T(s) \end{matrix} \right\|_\infty \quad (7)$$

Bilinear Transform

The existing H_∞-approach has limitation in designing controller for system with zeros on the boundary of the stability domain. Another limitation is for the cancellation of the plant's poorly damped poles by the controller's zeros. In this case, a controller designed with the standard H_∞ -approach is unable to

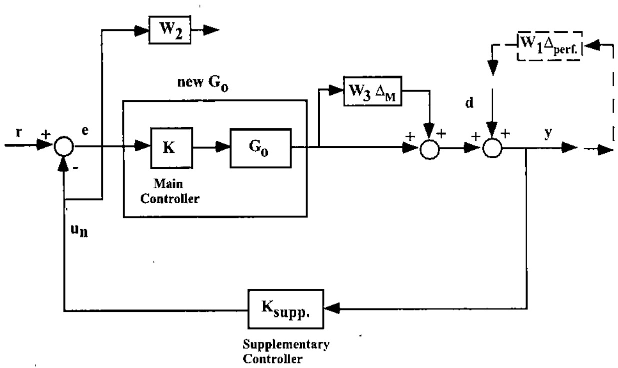

Fig. 6 Configuration for the damping control problem

increase the damping. From the viewpoint of H_∞-optimal control theory, this leads to singularities in the equations, which determine the state-space realization of the H_∞-control law. In this case the standard Riccati based H_∞-synthesis algorithms are not directly applicable.

To cope with this, bilinear transformation method has been applied to the plant in our design. Therefore, we transformed the original s-plane into a new complex plane be $\tilde{s}$-plane.
Letting the new complex plane be $\tilde{s}$-plane, the transformation is written as follows [7,10]:

$$s = \frac{(\tilde{s} + p_1)}{(1+\tilde{s}/p_2)} \quad (8)$$

By setting the parameters of the bilinear transform appropriately, the critical zeros and poles are moved away from the j ω-axis and places in right-half plane. After the controller is computed, the inverse bilinear transform is used to map the controller back to the original s-plane.

4.1.2. ASVC Controller Design

For designing the ASVC- controller, we can do almost same procedure as SVC case. However we must take account about the following point.

The controller design should be taken account with the zeros problem inherent in the transfer function of the ASVC system of figure 5, which is a typical configuration for damping controller [3,11,15]. The plant system has zeros in the imaginary axis and usually has zeros in the right-half plane (non minimum phase system). For the plant which have zeros in the right half plane (non-minimum phase plant, NMP), it is only possible to find a stable controller if the open loop plant is strongly stabilizable (SS). The plant is strongly stabilizable if and only if all (unstable) poles occur in the right side of all NMP zeros in either odd or even numbers [12.13]. The existence of zero does not always imply the degradation of performance if the controller is carefully designed. However, it is a fact that the zero make the design of the controller quite difficult. To cope with this problem, it is necessary to combine the standard H_∞-approach with special technique, such as bilinear transformation method. So that, the critical zeros problem can be treated and the designed controller can reassign the closed-loop poles of the system to more stable location in the left half s-plane.

These zeros could be also represented as multiplicative dynamic uncertainty, like another uncertainties in the parameter of the poles and gain. For using the multiplicative uncertainty to describe uncertainty in zeros of the transfer function, it is necessary to use a special technique, such as by choosing minimum phase part

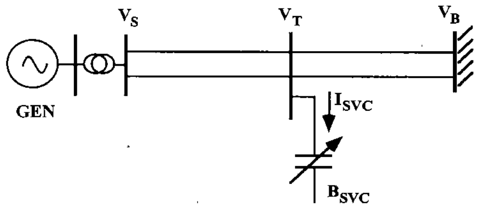

Fig. 7 Single Machine infinite Bus, which is compensated at its midpoint by an SVC

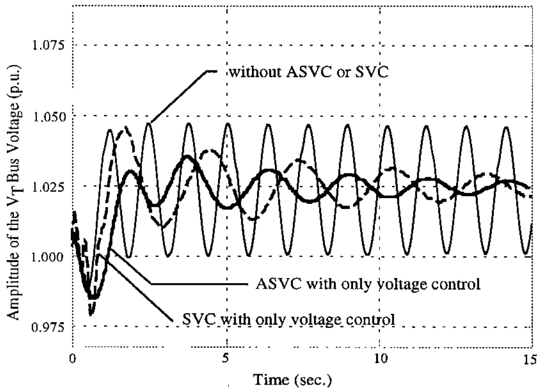

Fig. 8 V_T bus voltage responses, which ASVC or SVC with only voltage control.

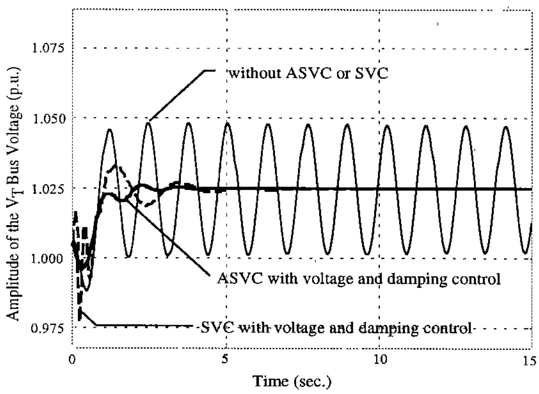

Fig. 9 V_T bus voltage responses, which ASVC or SVC with voltage and damping control.

of plant (without zeros in the right-half plane) will be chosen as nominal model, G_o.

The controller is found by solving the following mixed sensitivity formulation, eqn. (9), and the feedback loop will take the form as shown in figure 6 without taking account control sensitivity function, ***R(s)***.

$$\min_{K(s)} \left\| \begin{matrix} W_1(s)S(s) \\ W_3(s)T(s) \end{matrix} \right\|_\infty \qquad (9)$$

4.2. Performance and Robustness

In this section, the dynamic performance and robustness of single machine to infinite bus system shown in figure 7, which is compensated at its midpoint (V_T bus voltage) by SVC or ASVC are evaluated. Concerning the generating unit, the 7^{th} order model of the synchronous machine is used to represent the dynamics of the generator with AVR [14], and the supplementary controller output limiter is also taken into account in the design stage as well as in numerical simulations. These data are given in the appendix B.

Although the main purpose of this paper is the power system

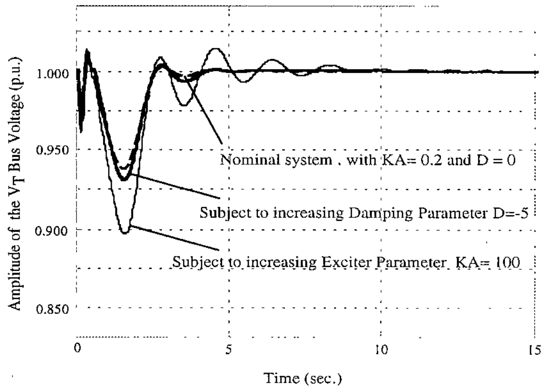

Fig. 10 V_T bus voltage responses with ASVC controller for nominal system and other pre-specified set of system conditions.

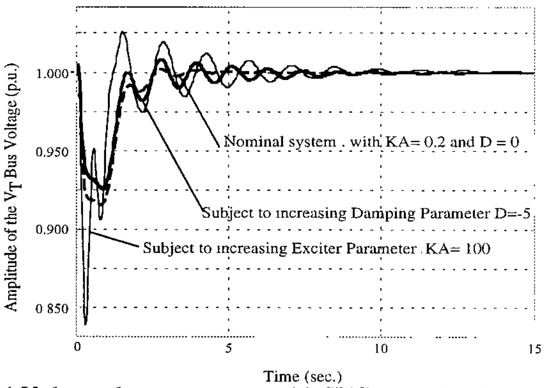

Fig. 11 V_T bus voltage responses with SVC controller for nominal system and other pre-specified set of system conditions.

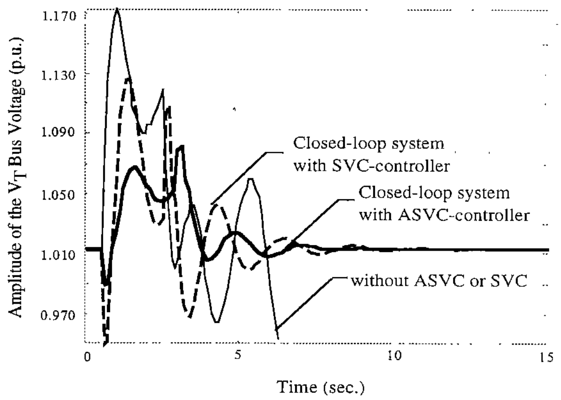

Fig. 12 V_T bus voltage responses with ASVC or SVC controller subject to line outage.

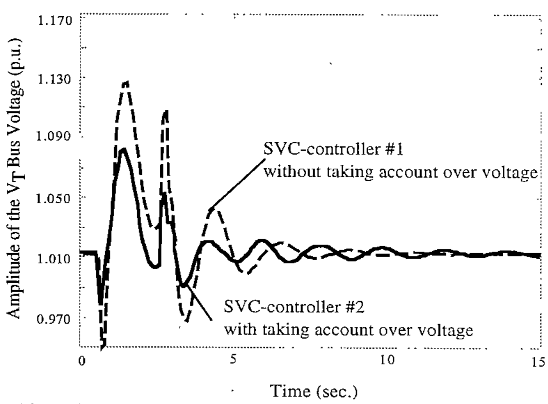

Fig. 13 V_T bus voltage responses with SVC controller subject to over voltage.

Table 2 Damping ratio of Open-loop and Closed-loop System

System Configuration	Local Model Damping Ratio			
	Open-loop	Closed-loop with SVC (#1)	Closed-loop with SVC (#2)	Closed-loop with ASVC
Nominal System, with Parameter KA= 0.2 ; D = 0	0.0009	0.238	0.127	0.300
Subject to Increasing Exciter Parameter KA=100	0.0004	0.054	0.023	0.070
Subject to Decreasing Damping Parameter D = -5	- 0.0977	0.065	0.036	0.105

* #1 : without taking account over voltage problem
#2 : with taking account over voltage problem

Table 3. Stability Margin

	Stability Margin, μ
Closed-loop system with SVC Controller # 1	1.013
Closed-loop system with SVC Controller # 2	0.927
Closed-loop system with ASVC	1.025

oscillation damping, we will examine the voltage waveforms and the overvoltage problem at the midpoint bus only to save the space since the shape of power swing is quite similar to that of voltage oscillation.

Figure 8 and 9 show time responses for the V_T bus voltage with ASVC or SVC -controller after a small disturbance is applied by a step variation to V_{ref}. In this case the system without ASVC or SVC is a poorly damped poles plant (as shown in Table 2 for nominal system, damping ratio is 0.0009). First, figure 8 shows that the ASVC and SVC with only voltage control improves the transient stability of the power system to some extent, however, it does little to help the system oscillation stability (damping ratio is 0.0085 in case of ASVC and 0.0062 in case of SVC). In this case, even if we adjust the gain of the controller, it is impossible to increase the damping any more. Secondly, the ASVC and SVC where the damping control is added are shown in figure 9, where we can see that they are effective in adding damping of power system oscillations (damping ratio is 0.3 in case of ASVC and 0.238 in case of SVC). In the first several swings, the closed-loop system with SVC is more pronounced than ASVC case. This may come from the ASVC's superior capability in providing controllable current. However, both controllers give almost same damping. In the ASVC case, the response signal of the ASVC case is quit different than SVC case. This kind of ASVC response signal ('back swing'), is one of the characteristic of non minimum phase system, which is known to be difficult to avoid.

Figure 10 and 11 shows time responses for the V_T bus voltage with ASVC or SVC -controller, respectively, under the nominal operating condition and other two different pre-specified sets of system conditions, i.e Gain exciter, KA, Machine damping parameter, D. A small disturbance is introduced by a suddeìLvariation in the voltage setpoint of terminal generator. From these figures, it can be observed that both the improved H_∞ - ASVC and SVC controller can still maintain stability of the system, which implies the robustness of both the controllers. As shown also in Table 2, when the damping parameter, D decreases to -5, the system becomes unstable (damping ratio is -0.0977), while with ASVC or SVC the system is still stable (damping ratio is 0.105 in case of ASVC and 0.065 in case of SVC). Same response characteristics are observed in these figures as discussed before.

In figure 12, the following disturbance is considered: a 3L-OC is assumed near the sending end at one of the double transmission line for 2 second. The line was opened at 0.5 second and closed at t=2.5 second. Again similar response characteristics are observed as already discussed before. In this situation both the controllers introduces enough damping to maintain stability. Although the system without ASVC or SVC become unstable. However under such severe disturbance, in case of SVC higher transient voltage appears at V_T bus voltage, which may lead to overvoltage problem. On the other hand, in case of ASVC enough voltage depressions are seen at the V_T bus voltage, due to a larger transient rating.

In order to avoid the overvoltage problem of SVC controller (controller #1), further design modification is needed. Therefore, we have designed an SVC controller (controller #2) to achieve the same voltage suppression capability as the ASVC controller. From figure 13, it can be observed, without taking account the over - voltage problem, the desired damping of dominant oscillation mode is achieved (as shown in Table 2, damping ratio is 0.238). However, by taking account the overvoltage problem, the damping ratio become smaller (damping ratio is 0.127), i.e. it takes more time to achieve steady state condition. This means also that the robustness will be influence.

Eigenvalue analysis

The robustness and performance of the controllers are compared through eigen value analysis. The damping ratios of the open and closed-loop system are listed in Table 2. From this table, it is clear that the desired damping of the dominant oscillation mode is achieved for nominal system case. However, it is seen that the damping capability is restricted by the voltage suppression capability from the comparison between SVC controllers #1 and #2. It can be observed that closed-loop system with ASVC has better damping, i.e. the closed loop poles have been placed to more stable locations. Thus, more robust stability has been realized in ASVC controller and almost satisfactory response is achieved, in spite of the critical zeros problem.

The margin stability

Robustness of the controllers are evaluated also in terms of the inverse of the H_∞ -norm of the complementary sensitivity matrix T(s) , μ , as list in Table 3. Let μ be defined as follows :

$$\mu = \|T(j\omega)\|_\infty^{-1} \tag{10}$$

The larger μ, the larger is the stability margin in the presence of a multiplicative uncertainty. This table has shown that the same tendency is obtained as discussed through eigen valueanalysis.

6. Conclusion

In this paper, a comparison study has been made between ASVC and SVC with equal rating condition. To achieve the full utilization of the ASVC and SVC for damping power system oscillations an improved H_∞-optimization technique is applied. From these studies, we can conclude the followings:

(1) Both FACTS device can perform almost same damping power swings in nominal system condition for small disturbances. As disturbance become large, an ASVC controller can be more effective in suppressing power swings because of a larger transient rating.

(2) Design of ASVC controller design is more difficult than SVC case, due to zeros problem ('back swing'). However when suitably designed, satisfactory robust stability and robust performance can be realized.

(3) Due to a trade of between performance and prevention of overvoltage problem in designing SVC controller, the damping capability of the SVC controller tends to be decreased.

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Appendix

A. System's data

Generator data (MVA base: 900)

xd=1.8 xq=1.7 xd'=0.3 xq'=0.55 xd''=0.25 xl=0.2 ra=0.0025

Tdo'=8 tdo''=0.03 tqo''=0.05 H=6.5 D=0.025

Excitation Data : Ka=0.003 Ta=0.05 Kf=0.02 Tf=0.8

Network Data (MVA base: 100) :

r=0.0001 pu/km x=0.001 pu/km b2=0.00175 pu/km

Transformer Data (MVA base : 900) : re=0 xe=0.15 pu

SVC Data: Kr=25 Tr= 1 Bc= 0.013 ΔB_{min} = -0.1 ΔB_{max} = 0.075

Supplementary controller output limitter: ΔV_{min} = -0.1 ΔV_{max} = 0.2

ASVC Data: R_s: 0.01 R_p:128 C: 0.013 L: 0.15

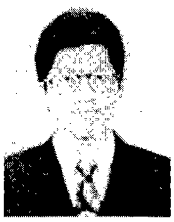
B. ASVC Model (Based on reference [3])

The state space model of the inverter connected to the system is obtained based on figure 3. It is to be noted that the per unit system is adopted for modeling the ASVC circuit is the same as for the rest of the system.

$$p\begin{bmatrix}\Delta i_d\\ \Delta i_q\\ \Delta v_{dc}\end{bmatrix}=[A_\Delta]\begin{bmatrix}\Delta i_d\\ \Delta i_q\\ \Delta v_{dc}\end{bmatrix}+[B_\Delta]\begin{bmatrix}\Delta v\\ \Delta\beta\end{bmatrix}$$

$$[A_\Delta]=\begin{bmatrix}\dfrac{-R_s\omega_b}{L} & \omega_b & \dfrac{k\omega_b}{L}\cos(\beta_o)\\ -\omega_b & \dfrac{-R_s\omega_b}{L} & \dfrac{k\omega_b}{L}\sin(\beta_o)\\ -\dfrac{3}{2}kC\cos(\beta_o) & -\dfrac{3}{2}kC\sin(\beta_o) & \dfrac{-\omega_b C}{R_p}\end{bmatrix}$$

$$[B_\Delta]=\begin{bmatrix}\dfrac{-\omega_b}{L} & \dfrac{k\omega_b v_{dco}}{L}\sin(\beta_o)\\ 0 & \dfrac{k\omega_b v_{dco}}{L}\cos(\beta_o)\\ 0 & \dfrac{3}{2}kC\omega_b(i_{do}\sin(\beta_o)-i_{qo}\cos(\beta_o))\end{bmatrix}$$



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