Application of Static Var Compensators to Increase Power System Damping

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Abstract: A theory to analyze power system damping enhancement by application of static var compensators (SVC) has been developed based on the well-known equal area criterion. Some fundamental issues as the SVC effect on a power system, how to control an SVC to improve system damping, the differences between continuous and discontinuous control of SVC reactive power output and the best SVC location in a power system to achieve the maximum damping improvement are discussed. Based on these discussions a discontinuous SVC control approach is proposed, in which the change of SVC reactive power output at discrete points is determined by the power deviation on a transmission line. The time-domain simulations of the proposed control approach in a one-machine system to increase swing oscillation damping and in a 4-machine system to increase the damping of an interarea oscillation mode demonstrate that the developed analysis theory and the proposed SVC control approach may be applied to solve practical power system damping problems.

Keywords: Static var compensators (SVC), power system damping, swing oscillations, power system stability

1. Introduction

Dynamic voltage support and reactive power compensation have been long recognized as a very significant measure to improve the performance of electric power systems. The rapid advances in power electronics area have made it both practical and economic to design powerful thyristor controlled reactive power compensation devices, Static Var Compensators (SVC) [1]. Both theoretical analysis and field tests have proved the excellent SVC performances.

The primary purpose of SVC applications is to maintain bus voltage at or near a constant level. In addition SVC may improve transient stability by dynamically supporting the voltage at key points and steady state stability by helping to increase swing oscillation damping. The theory of transient stability improvement by SVC is now well understood in light of the equal area criterion[1]. As for the damping improvement, although computer simulations and field test results have shown the improvement [2,3,4], the author feels that some fundamental issues still need to be discussed in order to explain why power system damping can be improved by SVC applications and how. This paper attempts to address these issues by using the well-known equal area criterion.

It is found that a bus voltage controlled SVC does not contribute significantly to system damping[2,6,7]. A significant contribution to system damping can be achieved when an SVC is controlled by some auxiliary signals superimposed over its voltage control loop[2,3]. Usually SVC control systems are designed to have a voltage control loop with continuous auxiliary damping control signal superimposed. It was found in [2] that while the voltage regulation with continuous damping control signal design has good performances when system oscillations are small in magnitude, it fails in providing damping in some critical large oscillation cases. It has been suggested that discontinuous "bang-bang" type of controls should be used for damping large oscillations[2,4,7]. In the application of SVC to a power system its contribution to system damping depends on SVC location in the system. In [8,9] the best SVC location to achieve the maximum damping improvement in a two-area power system was studied by numerical methods. It is found that the mid-point of the transmission circuit is the best SVC location[9].

This paper begins with an investigation of the SVC effect on a simple one-machine power system. It is found that an SVC can dynamically alter the system transfer characteristics by changing its reactive output. Then some basic control actions, to change machine mechanical power and/or to alter the transfer characteristics of a power system, to increase power system damping are discussed based on the equal area criterion. It is explained why a bus voltage controlled SVC does not contribute significantly to system damping and that an SVC should be controlled by a signal or signals in phase with (maybe after phase compensation) machine speed deviation to increase system damping. The differences between continuous control and discontinuous "bang-bang" type of control of SVC reactive power output are discussed, and why the discontinuous control is more effective than the continuous control is explained, which was found in [2] by numerical simulations of a power system. Also the best SVC location in a power system to achieve the maximum damping improvement is investigated by some theoretical analysis of the problem.

Based on the discussions of such fundamental issues concerning SVC applications to increase power system damping, as the SVC effect on a power system, how to control an SVC to increase system damping and the differences between continuous and discontinuous control of SVC reactive power output, a discontinuous SVC control approach is proposed in the paper. The change of SVC reactive power output in the approach at discrete points is determined by the power deviation on a transmission line. With the help of time-domain simula-

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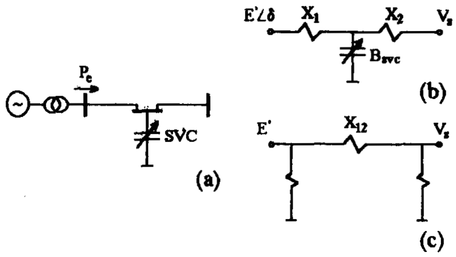

Fig.1 A one-machine system with an SVC

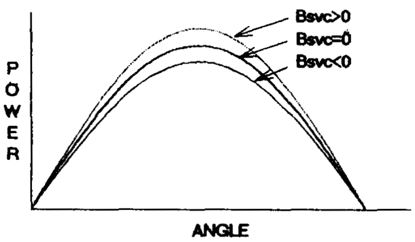

Fig.2 SVC effects on system P-δ curve

tions the proposed approach is evaluated in a one-machine power system to increase swing oscillation damping and in a 4-machine power system to increase the damping of a low frequency interarea oscillation mode. Some preliminary results of this study have been reported in [10,11].

2. SVC Effect on a Power System

To understand the SVC effect on the dynamic behaviour of a power system, let us investigate a simple one-machine system with an SVC as shown in Fig.1(a). The equivalent circuit for the investigation is shown in Fig.1(b), where the generator is represented by a transient e.m.f. E' behind a reactance X' which has been included into the reactance X_1. The SVC is represented as a variable susceptance B_{svc}. When the SVC provides reactive power to the system, B_{svc} is capacitive and $B_{svc}>0$; when the SVC is inductive, absorbing reactive power from the system, $B_{svc}<0$.

To probe the problem further, the equivalent circuit in Fig.1(b) is transferred to a Δ-connection circuit by the Y-Δ circuit transformation rule[5] as shown in Fig.1(c), where the transfer reactance X_{12} is as follows :

$$X_{12} = X_1 + X_2 - B_{svc} X_1 X_2 \tag{1}$$

From the above equation, when the SVC is capacitive, $B_{svc}>0$, $X_{12}<X_1+X_2$, and when the SVC is inductive, $B_{svc}<0$, $X_{12}>X_1+X_2$.

It is well known that the power-angle (P-δ) curve of a power system plays a decisive role in determining system dynamic behaviour. For the system with an SVC the P-δ relationship is as follows :

$$P_e = \frac{E' V_s}{X_{12}} \sin\delta \tag{2}$$

where the symbols are defined in Fig.1. When SVC is capacitive, $B_{svc}>0$, system P-δ curve is "raised" by the SVC, delivering reactive power to the system, as shown in Fig.2; When SVC is inductive, $B_{svc}<0$, system P-δ curve is "lowered" by the SVC, absorbing reactive power from the system.

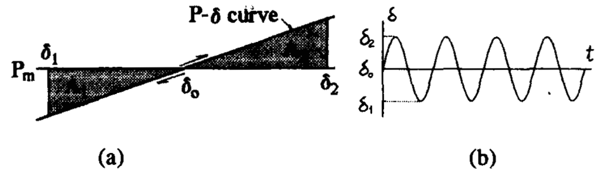

Fig.3 Swing oscillations without damping

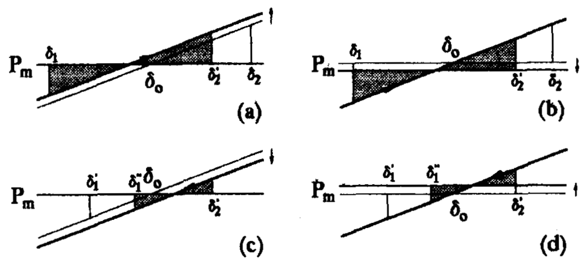

Fig.4 Basic control actions to increase damping
(a) δ increasing, $\Delta\omega>0$, P-δ curve "raised"
(b) δ increasing, $\Delta\omega>0$, P_m reduced
(c) δ decreasing, $\Delta\omega<0$, P-δ curve "lowered"
(d) δ decreasing, $\Delta\omega<0$, P_m increased

It is clear now that the change of SVC output B_{svc} will alter ("raise" or "lower") the transfer characteristics or P-δ curve of a power system. Therefore SVC effect on the dynamics of a power system may be investigated in light of the dynamic alteration of the P-δ curve. It was found in [9] that SVC become more effective in damping the swing oscillations in a two-area power system for high power transfer levels. This is because that the magnitude of the alternation of the P-δ curve by the SVC become larger, and therefore the SVC more effective, with the increase of the power transfer level, as shown in Fig.2. Also SVC effect on a power system depends on SVC rating and the location where an SVC is placed. The best SVC location problem will be discussed in Sec.5.

3. SVC Control Strategy Study

When the system shown in Fig.1 is without SVC and is subjected to a small-disturbance, the machine angle will oscillate with a constant amplitude as shown in Fig.3(b), because no damping is assumed. Based on the equal area criterion the system oscillates in such a way that $A_1=A_2$ in Fig.3(a), where P_m is machine mechanical power. A_1 is the acceleration area when δ is increasing, $\Delta\omega>0$; A_2 is the acceleration area when δ is decreasing, $\Delta\omega<0$.

The acceleration area or the transient energy must be reduced in the oscillation process by certain control means in order to bring the disturbed system back to its equilibrium condition, δ_0 in Fig.3(a). When δ is increasing ($\Delta\omega>0$) the P-δ curve should be "raised", as shown in Fig.4(a) and/or the mechanical power P_m reduced, as shown in Fig.4(b) in order to bring the system closer to the equilibrium point δ_0. When δ is decreasing ($\Delta\omega<0$) the P-δ curve should be "lowered" and/or the mechanical power P_m increased to increase system damping as shown in Figs.4(c),(d). As can be seen in the figures,

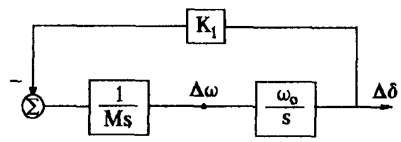

Fig.5 A block diagram for swing oscillation analysis

with the alterations of the P-δ curve or the mechanical power P_m the angle movement is δ_1->δ_2'->δ_1'', bringing the disturbed system closer to δ_o, instead of δ_1<->δ_2 constant amplitude oscillations without the alterations.

Speed governors control machine mechanical power. Due to the very slow responses of governors, their effects on system damping usually are very small. The P-δ curve of a power is determined by eqn(2). Power system stabilizers (PSS) can increase system damping by altering E' dynamically according to machine speed deviation $\Delta\omega$. As discussed in Sec.2 an SVC can alter the P-δ curve by changing its output B_{svc}. A major advantage of SVC over other kinds of reactive compensation equipments is that it can change its reactive power output in a vary fast speed. Therefore if an SVC is controlled properly, it could alter ("raise" or "lower") system transfer characteristics (P-δ curve) in such a way that it may provide significant damping to the system.

The Phillips-Heffron model is usually used to study power system damping[12]. For the system shown in Fig.1 the block diagram of the model for swing oscillation analysis is shown in Fig.5, where K_1 is the synchronous torque coefficient, M machine inertia constant, ω_o=2πx60, and s Laplace operator. There are two state variables in the model, machine speed deviation $\Delta\omega$ and machine angle deviation $\Delta\delta$. Basically SVC output B_{svc} can be controlled according to $\Delta\omega$ or $\Delta\delta$.

Δδ-Control

In the $\Delta\delta$-Control SVC output B_{svc} is controlled according to machine angle deviation $\Delta\delta$ as follows :

$$B_{svc} = K_{\Delta\delta}\,\Delta\delta \qquad (3)$$

where $K_{\Delta\delta}$ is the control gain and $\Delta\delta=\delta-\delta_o$. SVC control loop is very fast as compared to system swing oscillations. Therefore the delay of SVC control loop is neglected for the purpose of this analysis.

Suppose that the system with an SVC is subjected to the same small disturbance as in the case in Fig.3. When $\Delta\delta$>0, B_{svc} is positive according to eqn.(3). Therefore the $\Delta\delta$-controlled SVC "raises" the P-δ curve when $\Delta\delta$>0, as shown in Fig.6. When $\Delta\delta$<0, the SVC "lowers" the P-δ curve. As the result, the $\Delta\delta$-controlled SVC reduces the oscillation amplitude (δ_1'<->δ_2' instead of δ_1<->δ_2 in Fig.6) and increases system synchronous torque coefficient as indicated by the increase of the P-δ curve slope. Obviously, the $\Delta\delta$-controlled SVC does not have any effect on system damping. The system oscillation is still with a constant amplitude.

It is found that a bus voltage controlled SVC does not contribute significantly to system damping[2,7]. For the one-machine system in Fig.1 the voltage deviation at the SVC bus is almost in phase with $\Delta\delta$ in swing oscillations. Therefore a voltage controlled SVC basically is a kind of $\Delta\delta$–controlled

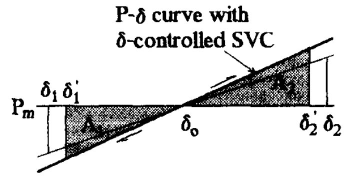

Fig.6 Swing oscillations with the $\Delta\delta$-controlled SVC

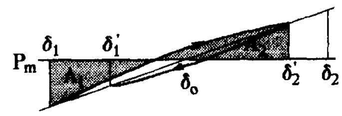

Fig.7 Swing oscillations with the $\Delta\omega$-controlled SVC

SVC. This explains why a voltage controlled SVC has no or vary small damping effect on power systems.

Δω-Control

In the $\Delta\omega$-control SVC output B_{svc} is controlled according to machine speed deviation $\Delta\omega$ as follows :

$$B_{svc} = K_{\Delta\omega}\,\Delta\omega \qquad (4)$$

where, $K_{\Delta\omega}$ is the control gain. The control effect on the P-δ curve is shown in Fig.7. When the machine angle δ is increasing, $\Delta\omega$>0, the $\Delta\omega$-controlled SVC outputs positive B_{svc} according to eqn.(4) and "raises" the P-δ curve. Inherently the system is without damping, the equal area criterion may still apply (A_1=A_2). When δ is decreasing, $\Delta\omega$<0, the SVC "lowers" the P-δ curve. Through these dynamic alterations of the P-δ curve by changing B_{svc} according to $\Delta\omega$ (eqn(4)), it is quite clear from the figure that the $\Delta\omega$-controlled SVC can improve system damping. The angle movement is δ_1->δ_2'->δ_1' in Fig.7, bringing the disturbed system closer to the equilibrium point δ_o, instead of δ_1<->δ_2 in the case without SVC.

A significant contribution to system damping can be achieved when an SVC is controlled by some auxiliary signals superimposed over its voltage control loop[2,3]. The auxiliary signals should be in phase with (maybe after phase compensation) $\Delta\omega$ according to the above analysis. Practically $\Delta\omega$ could not be used as an SVC control signal, because usually $\Delta\omega$ is not available on the site where an SVC is placed. The various local signals reported in literature for improving system damping include deviation in bus frequency, tie-line power and current, etc[6].

4. Continuous Control or Discontinuous Control

Usually to improve power system damping SVC control systems are designed to have a voltage control loop with continuous auxiliary damping control signals superimposed. While the continuous voltage regulation with damping control signal design has good performances when system oscillations are small, it was found in [2] that it fails in providing damping in some critical large oscillation cases. It has been suggested that discontinuous "bang-bang" type of controls should be used for damping large oscillations. The "bang-bang" control is usually a microprocessor based control system[7].

To understand the difference between the continuous control and the discontinuous control let us consider the one-

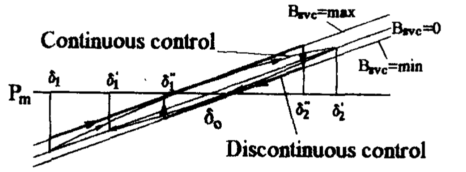

Fig.8 Continuous and discontinuous controls

machine system shown in Fig.1 again. One important thing to remember is that the output of an SVC is physically limited by its rating as follows :

$$B_{min} < B_{svc} < B_{max} \tag{5}$$

where, B_{min}, B_{max}, are minimum and maximum values of B_{svc} respectively. As shown in Fig.8 the system can be only "dynamically operated" in the area between B_{max} and B_{min} lines. The angle movement when the SVC is continuously $\Delta\omega$-controlled is shown in Fig.8 (δ_1->δ_2'->δ_1'). For the discontinuous $\Delta\omega$-control the SVC is controlled in such a way that when the machine angle is increasing ($\Delta\omega$>0) the SVC puts all its capacitive sources into the system, B_{svc}=B_{max} to "raise" the P-δ curve; when the machine angle is decreasing ($\Delta\omega$<0) the SVC puts all its inductive sources into the system, B_{svc}=B_{min}, the angle movement is δ_1->δ_2''->δ_1'' as shown in the figure. It is quite clear from the figure that the system with the discontinuously $\Delta\omega$-controlled SVC has better damping because it makes more full use of the available B_{svc} to reduce the acceleration area.

For the discontinuous control SVC output B_{svc} only changes at discrete points when $\Delta\omega$=0, when $\Delta\delta$ reaches its maximum or minimum value. In the one-machine system the line power deviation ΔP_e is proportional to (or in phase with) $\Delta\delta$. It can be easily measured at the site where the SVC is placed. The point when $\Delta\omega$=0 can be determined by that ΔP_e reaches its maximum value ΔP_{max} or minimum value ΔP_{min}. Therefore the SVC can be controlled in such a way that its output B_{svc} changes discretely at the points when ΔP_e reaches ΔP_{max} or ΔP_{min} according to :

$$B_{svc} = \begin{cases} -K_{svc}\,\Delta P_{max} & (\Delta P_e=\Delta P_{max}) \\ -K_{svc}\,\Delta P_{min} & (\Delta P_e=\Delta P_{min}) \end{cases} \tag{6}$$

where, K_{svc} is the control gain. The minus signs in the above equation are due to the fact that when the line power reaches its maximum value ΔP_{max}, the machine angle δ will be decreasing afterwards. SVC should put inductive reactive power (negative B_{svc}) into the system to "lower" system P-δ curve to reduce the acceleration area, as shown in Fig4.(c).

In eqn(6) there is a remaining unanswered question, that is how to choose the gain K_{svc}. In an oscillation process, at δ=δ_1 in Fig.9, suppose $\Delta\omega$=0 and ΔP_e reaches its minimum value ΔP_{min}. If the SVC can change its output B_{svc} at this point such that the P-δ curve can be "raised" by $\frac{1}{2}\Delta P_{min}$, the system will be in the equilibrium position δ_o just in "one-step" as shown in Fig.9, according to the equal area criterion. Therefore, from eqn(2) we have :

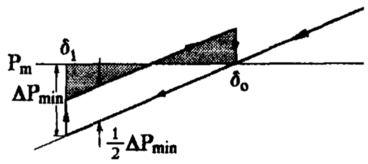

Fig.9 "Raise" P-δ curve by $\frac{1}{2}\Delta P_{min}$

$$\frac{E' V_s \sin\delta_1}{X_1+X_2-B_{svc}X_1X_2} - \frac{E' V_s \sin\delta_1}{X_1+X_2} = \frac{1}{2}\Delta P_{min} \tag{7}$$

By assuming $E'\cong1.0$, $V_s\cong1.0$ and $\delta_1\cong\delta_o$, from the above equation, the formula for setting the gain K_{svc} may be derived as follows :

$$K_{svc} = \frac{(X_1+X_2)^2}{2X_1X_2}\,\frac{1}{\sin\delta_o} \tag{8}$$

For practical applications the actual systems are more complicated than the system shown in Fig.1. If a study system can be equivalent to a two-area system with an SVC placed on the tie-line the SVC control gain may be set according to the above equation (see more discussions in Sec.7).

5. The Best SVC Location in a Power System

In the practical application of an SVC its effects on system P-δ curve is depending on its size as well as its location. The controllability factor as a function of the SVC location in a two-area system was computed in [8] based on many different runs of the load flow and eigenvalue calculation, and used to identify the best SVC location. The residues associated with the mode of interest at intermediate points along the transmission line of the same two-area system were used in [9] to determine the best SVC location. Their conclusion is that an SVC should be located near the mid-point of the transmission circuit to achieve the best damping effect.

As discussed before SVC providing damping to a power system is through the alterations of system P-δ curve. Therefore the best SVC location to increase damping should be at the place where an SVC would have the largest effect on system P-δ curve. In the one-machine system shown in Fig.1, when B_{svc} and X_1+X_2=X hold constant, the following derivative may be derived based on eqn(2):

$$\frac{\delta P_e}{\delta X_1} = \frac{E' V_s B_{svc}(X-2X_1)}{X_{12}^2}\sin\delta \tag{9}$$

By setting the derivative equal to zero, it is found that when $X_1=\frac{1}{2}X$ or X_1=X_2, an SVC has the largest effect on system P-δ curve. Therefore SVC should be placed at the electrical center point in a one-machine power system in order to achieve the maximum damping benefit. This also can serve as a guideline for SVC applications in multimachine power systems. The above analytical results are in accordance with [8,9], where the results were obtained by trial-and-error methods with many runs of numerical solutions.

6. A One-machine System Study

The one-machine system in Fig.1 with a more detailed model is simulated in the time domain to evaluate SVC performances. The system data for the simulation is shown in

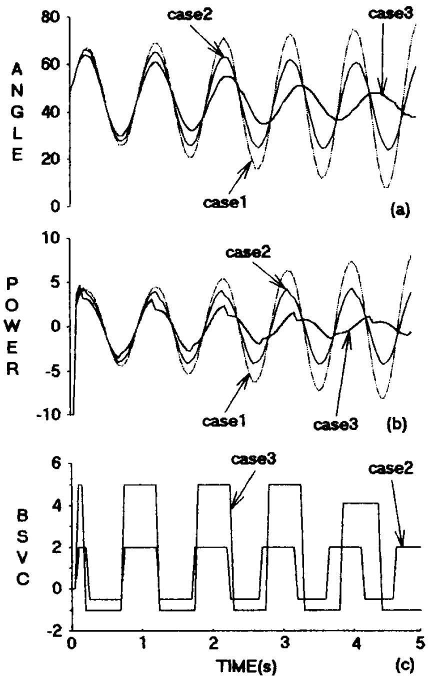

Fig.10 Time-domain simulation results

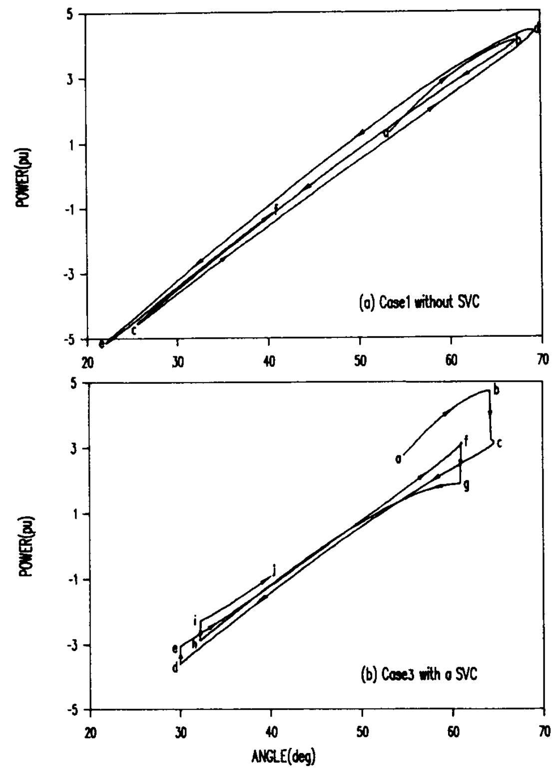

Fig.11 Post-fault power-angle trajectory

Table-1 System data for the simulation

M=108.0s	D=5.0pu	X_d=0.041pu	X_q=0.041pu
X_d'=0.017pu	X_1=0.021pu	X_2=0.039pu	$P_e^{(0)}$=10.0pu
K_e=20.0pu	T_e=0.05s	K_{svc}=2.65pu	

Table-1, where K_e, T_e are respectively the gain and time constant of the voltage regulator (AVR) on the machine, $P_e^{(0)}$ is the steady-state value of the power on the transmission line. The data are based on 100MVA. The fault simulated is a 0.06s 3-phase to ground fault at the generator terminal bus. Three cases have been studied. They are as follows :

Case1: without SVC in the system;

Case2: with an SVC in the system, B_{max}=2.0pu, B_{min}=-0.5pu;

Case3: with an SVC in the system, B_{max}=5.0pu, B_{min}=-1.0pu.

The simulation results are shown in Fig.10. Without SVC in the system (case1) the swing oscillation is negatively damped, the amplitudes of machine angle and line power oscillations are increasing with the time. When an SVC with the discontinuous $\Delta\omega$-control is in the system (case2, case3), the system damping has been improved. The SVC output B_{svc} changes at discrete points according to eqn(6) as shown in Fig.10(c). From the figure when ΔP_e reaches its maximum value the SVC changes its output B_{svc} from capacitive to inductive to "lower" the P-δ curve; when ΔP_e reaches its minimum value the SVC changes its output B_{svc} from inductive to capacitive to "raise" the P-δ curve. It is these dynamic alterations of the P-δ curve that result in the increase of the damping. Case3 has better damping than case2, the reason is that in case3 the SVC output B_{svc} has more dynamic change room ($5.0>B_{svc}>-1.0$pu) than case2 ($2.0>B_{svc}>-0.5$pu). K_{svc} (=2.65pu) is obtained by eqn(8). As can be seen in Fig.10, the disturbed system is far from settling in a new steady-state condition in "one-step" as predicted when eqn(8) is derived. The major reason is that the SVC output is limited by its rating (B_{max} and B_{min}) as shown in Fig.10(c). The other reason is that the simulated system is more complicated than the simple system in Fig.1 based on which eqn(8) is derived.

It is very interesting to examine the post-fault power-angle trajectory of the system as shown in Fig.11, which is obtained by combining the angle and power responses in Fig.10 together and being plotted on the power-angle coordinates. Only a portion of the responses in Fig.10 are plotted in Fig.11 (from t=0.1 to 2.0s), the trajectory move from point a to b ... to f ... with the increase of the time. In case1 without SVC, the trajectory in Fig.11(a) shows that the P-δ curve changes its position (up and down) slightly, due to the change of machine E_q', which is controlled by the excitation system of the machine. The machine has a high-speed AVR with T_e=0.05s (see Table-1), which was found providing negative damping to the system in [13]. Examining a cycle of the oscillation, for example c->d ->e in Fig.11(a), it can be seen that the AVR control actions "lower" the P-δ curve when the machine angle is increasing (c ->d in the figure) and "raise" the P-δ curve when the machine angle is decreasing (d->e). The alterations of the P-δ curve are in the opposite direction of improving system damping as explained in Fig.4, which has resulted in point e in the figure moving far away from the equilibrium point (δ_o=49°) of the system than point c, and the oscillation is negatively damped.

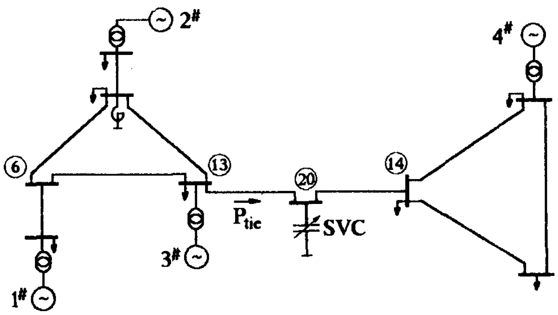

Fig.12 A 4-machine power system

Table-2 Machine and AVR data of the study system

M	MW	K_e	T_e
207.5	2200	20	0.05
198.6	3000	20	0.5
108.0	700	20	1.0
503.8	6000	20	0.5

In case3 with an SVC in the system, the trajectory in Fig.11(b) shows that the P-δ curve has sudden changes (b->c, d->e, f->g, h->i) due to the discontinuous control of the SVC reactive power output. The alterations of the P-δ curve are in the same manner as shown in Fig.4. At the point when the machine angle is turning from increasing to decreasing (point b or f in Fig.11(b)), the SVC changes its output B_{svc} (from 5.0 to -1.0pu as shown in Fig.10(c)) to "lower" the P-δ curve. At the point when the machine angle is turning from decreasing to increasing (point d or h), the SVC changes its output B_{svc} (from -1.0 to 5.0pu) to "raise" the P-δ curve. Examining a cycle of the oscillation, for example c->d->e->f in Fig.11(b), it can be seen that the alterations of the P-δ curve by the SVC control have brought the system closer to the equilibrium point, and the oscillation is positively damped.

7. A Multimachine System Study

It has been demonstrated in a one-machine power system by the theoretical analysis and the time-domain simulations that a discontinuously controlled SVC can increase system damping. The SVC output is controlled by the line power deviation according to eqn(6). In this section a 4-machine system representing a large interconnected power system is used as an example to study SVC behaviour in a multimachine environment. The study system is shown in Fig.12, where two areas are interconnected by a tie-line from bus #13 to bus #14. The tie-line is a 500KV, 480KM transmission line. 180KM from bus #13 there is a substation bus #20 with an SVC installed. At the steady-state (initial condition for the study) P_{tie}= 540MW. The machine data (inertia M in sec. and capacity in MW) and AVR data (time constant T_e in sec. and gain K_e in pu) are shown in table-2. The fault studied is a 3-phase to ground fault at bus #6 for 0.06s. As the same in Sec.6 three cases are studied. In case1 the system is without SVC. In case2 the system is with an SVC, B_{max}=2.0pu and B_{min}=-0.5pu. Case3 is the same as case2 except B_{max}=5.0pu and B_{min}=-1.0pu.

There is a low-frequency interarea oscillation mode (f≅0.5 hz) in the system. As indicated in the tie-line power response in

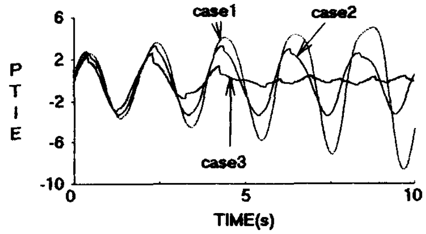

Fig.13 Tie-line power responses

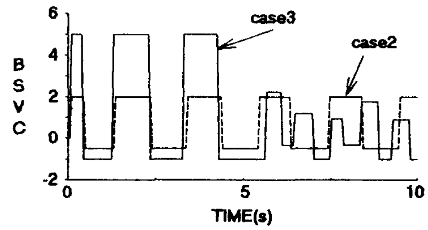

Fig.14 Responses of SVC output B_{svc}

Fig.13 (case1) the interarea mode is negatively damped and the system is unstable. When an SVC with the proposed control approach is placed at bus #20 the damping has been improved as shown in the figure (case2, case3). The SVC is discontinuously controlled according to the tie-line power deviation ΔP_{tie}. When ΔP_{tie} reaches its maximum or minimum value SVC changes its output B_{svc} according to eqn(6), the B_{svc} responses are shown in Fig.14. From the figures it is obvious that the SVC rating in case2 is too small. During the whole simulation process the SVC output B_{svc} is limited by its maximum or minimum value ($2.0>B_{svc}>-0.5$). The tie-line power oscillation is not well damped in case2. For case3 the SVC rating is larger ($5.0>B_{svc}>-1.0$). The low-frequency tie-line power oscillation is well damped in this case. About 5 sec. after the fault the interarea low-frequency mode is damped out (see Fig.13, case3) by the SVC, dynamically altering the transfer characteristics of the tie-line by changing its output B_{svc} (see Fig.14, case3). The system still has some active high-frequency local mode oscillations after the interarea mode diminishes, which the SVC, located on the tie-line, is not capable to provide any damping. Power system stabilizers may be used to solve local oscillation problems [12,14], this topic is out of the scope of this paper.

The SVC control gain K_{svc} is set according to eqn(8). First the short circuit KVAs at SVC bus #20 are computed. The short circuit KVA coming from the left-hand side system (from bus #13 to #20 in Fig.12) is 2641MW and from the right-hand side system (from bus #14 to #20) is 1733MW. From the obtained short circuit KVA values the equivalent reactances X_1 and X_2 in eqn(8) may be calculated, X_1=0.0379pu, X_2=0.0577 pu (based on 100MVA). By examining Fig.12 and Table-2 it is clear that machine #3 does not contribute to or participate in very much the low-frequency interarea oscillation because of its location in the system and its small inertia. At steady state the machine angle between machine #1 and #4 is $\delta_{14}^{(0)}=36.8^{o}$, and $\delta_{24}^{(0)}=44.4^{o}$. Averaging the angles by the machine inertias according to the following equation :

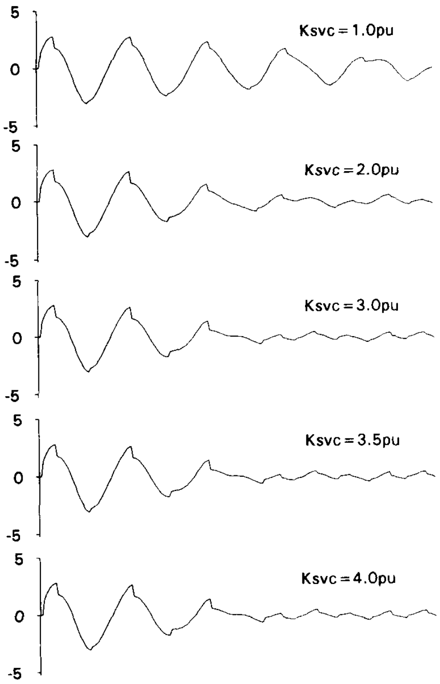

Fig.15 Tie-line power responses with different K_{svc}

$$\delta_o = \frac{M_1\,\delta_{14}^{(0)} + M_2\,\delta_{24}^{(0)}}{M_1 + M_2} \tag{10}$$

where δ_o is the machine angle to be used in eqn(8) to calculate K_{svc}. By substituting X_1, X_2 and δ_o (40.5^o obtained by eqn (10)) into eqn(8) the resulting K_{svc} is 3.2pu. The time-domain simulation results of the study system (use SVC data of case3) with different K_{svc} values are shown in Fig.15, where K_{svc} is varied from 1.0 to 4.0pu. The responses indicate that K_{svc}=1.0 or 2.0pu is too small. When K_{svc} is between 3.0~4.0pu the interarea oscillation is well damped. This is in accordance with the results obtained by eqn(8), where K_{svc} is calculated to be 3.2pu. The simulation results reveal an important characteristics of the proposed SVC control approach that the damping improvement is insensitive to the SVC control gain setting. The tie-line power oscillation is equally well damped when K_{svc} is equal to 3.0, 3.5 or 4.0pu.

8. Conclusions

A theory to analyze power system damping enhancement by the application of SVC has been developed. The development of the analysis theory is based on the well-known equal area criterion, which is very simple and easy to be understood. It is found that the SVC effect on a power system can be considered as dynamically altering system transfer characteristics (P-δ curve) by SVC changing its reactive power output B_{svc}. If an SVC is controlled in such a way that its output B_{svc} is proportional to or in phase with machine speed deviation $\Delta\omega$ in a one-machine power system, system damping can be improved by the application of the SVC. It has been shown by using the developed analysis theory that an SVC with the discontinuous control has better damping effect on power systems than the one with the continuous control. And the electrical center point in a one-machine system or in a two-area system is the best SVC location to achieve the maximum damping improvement.

A discontinuous SVC control approach has been proposed in which the change of SVC reactive power output at discrete points is determined by the power deviation on a transmission line. The time-domain simulations of the proposed SVC control approach in a one-machine system and in a 4-machine system representing a large interconnected power system demonstrate that the developed analysis theory and the proposed SVC control approach may be applied to solve practical power system damping problems. An equation for setting the SVC control gain K_{svc} has been derived and proved to be effective by the simulation results.

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