Enhancement of Transient Stability Using High-Speed Phase Shifters

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Enhancement of Transient Stability Using High-Speed Phase Shifters

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This paper presents an application of high-speed phase shifters (HSPSs) sited on AC interties to solve multimachine transient stability problem. The terminal characteristics of the HSPS are represented as node power injections, and its effects on the generators are obtained as additional bus power injections at the internal nodes. This treatment is useful and convenient for the transient and dynamic analysis of power system involving HSPSs. A control scheme which seeks to prevent power oscillations of machines has been investigated. The simulation of a system with 39 buses and 10 generators shows that HSPSs are very effective on enhancement of multimachine transient stability.

1. Introduction

Long-distance transmission lines play an important role in modern power systems because of the increased benefits of transmitting bulk energy over long distance. However, the fulfillment of stability conditions often results in transfer capability limitation. As well known, stabilizing measures associated with large interconnected power systems have been of increasing importance. In general, following faults, stabilizing action can be taken at the plant level and the system level[1]. Indeed, at the plant level considerable progress has been made on excitation control, governor control, etc. At the system level, the measures which are used to the transient stability are series capacitors, braking resistors and phase shifters etc.

The so-called FACTS (Flexible AC Transmission System) devices are intended to extend the capability of network controller and further improve the performance of existing power systems[2-3]. Since the advanced high power semiconductor devices and sophisticated electronic control technologies FACTS devices are capable of handling the power level and speed required for stability control. Recent investigations show that controllable series capacitors, static var compen-sators and braking resistors can enhance the stability bounds significantly[4-5].

Phase shifters have been used through the years as control equipment to control power flow under normal operations[6-7]. Conventional phase shifting transformers use mechanically switched tap changes which are suitable for slow operations. HSPS under the concept of FACTS, known as static phase-shifter or solid-state phase-shifter[3,8], provides power system with a novel way to handle dynamic system conditions rapidly, and may be one of the ultimate ac transmission system controllers. Attempts have been made to enhance transient stability using HSPS in two machine system[9-11]. In reference[12], a control algorithm using local measurements is developed to improve multimachine stability. Reference[13] shows a stabilizing control approach using optimal control method with locating HSPS at the terminals of generators. These investigations show that HSPS can enhance power system stability significatly.

In ordinary operation, HSPS fills the roles of controlling line powers to minimize system operation costs or solve the problems caused by unexpected loop flows and parallel flows. During the dynamic or transient period, HSPSs are expected to contribute system with recovery from contingency, by the aid of rapid power flow controls in one or more interties just like HVDC links do.

In this paper, a method to treat phase shifter is proposed which regards the terminal characteristics of

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phase shifter branch as node power injections. The effect of HSPS is represented as additional bus power injections at the internal buses of generators, which are depend on the dynamics of HSPS. The control scheme for multiple HSPS sited on AC interties uses both local measurement and the generator rotor speed deviations. The application results demonstrate that HSPSs are very effective on enhancement of multimachine transient stability.

2. Representation and Effect of HSPS

2.1 Power flow through HSPS branch

As depicted in Fig. 1 (a), HSPS is sited on the transmission line between buses l and k.

For convenience, assume that the HSPS is an ideal phase shifter that changes the transmission angle only, the voltage magnitude remains constant, that is,

$$\frac{V'_{sl}}{V_{sl}} = \exp^{j\alpha} \tag{1}$$

where α is the phase angle. Then the equations for real and reactive power flows at the corresponding buses are:

$$P_{lk} = V_{sl}^2 g_{slk} - V_{sl} V_{sk} [g_{slk} \cos(\delta_{slk} + \alpha) + b_{slk} \sin(\delta_{slk} + \alpha)] \tag{2}$$

$$Q_{lk} = -V_{sl}^2 (b_{shlo} + b_{slk}) - V_{sl} V_{sk} [g_{slk} \sin(\delta_{slk} + \alpha) - b_{slk} \cos(\delta_{slk} + \alpha)] \tag{3}$$

$$P_{kl} = V_{sl}^2 g_{slk} - V_{sl} V_{sk} [g_{slk} \cos(\delta_{slk} + \alpha) - b_{slk} \sin(\delta_{slk} + \alpha)] \tag{4}$$

$$Q_{kl} = -V_{sl}^2 (b_{shko} + b_{slk}) + V_{sl} V_{sk} [g_{slk} \sin(\delta_{slk} + \alpha) + b_{slk} \cos(\delta_{slk} + \alpha)] \tag{5}$$

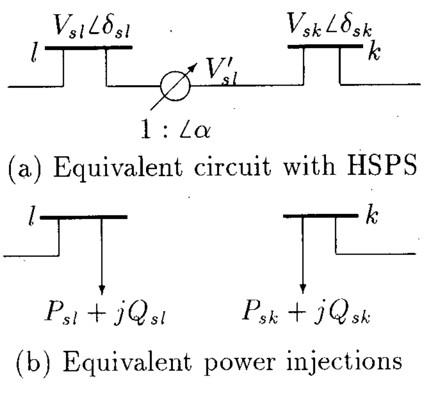


Fig. 1 Power flow through HSPS branch.
(a) Equivalent circuit with HSPS
(b) Equivalent power injections

where

$$\delta_{slk} = \delta_{sl} - \delta_{sk}$$
$$y_{slk} = g_{slk} + jb_{slk}$$

and V_{sl}, V_{sk} are bus voltage magnitudes, δ_{sl}, δ_{sk} indicate voltage phase angles, y_{slk}, b_{sklo} and b_{shko} are branch admittance and susceptance. It is seen that the structure of Eqs. (2) and (3) are asymmetrical to those of (4) and (5) respectively. Also they are functions of phase angle of HSPS and bus voltages.

For including the characteristics of HSPS, instead of using the equivalent curcuit Fig. 1 (a), the HSPS branch is treated as a pair of power injections at the terminal buses, as illustrated in Fig. 1 (b). The HSPS branch is removed from the network configuration.

The Power injections that depend upon the control dynamics of HSPS can be written as

$$P_{sl} + jQ_{sl} = P_{lk} + jQ_{lk} \tag{6}$$

$$P_{sk} + jQ_{sk} = P_{kl} + jQ_{kl} \tag{7}$$

As a result of this treatment, the dynamics of HSPS is incorporated into node power injections.

2.2 Interfacing HSPSs

For the transient a classical model is often used for the AC Power networks, that is, generators represented by constant voltage behind transient reactance, constant impedance loads, etc. Consider an n-machine power system which involves m HSPSs. When interface the HSPSs with such a system, all the nodes except the generator internal nodes ($\boldsymbol{V_G}$) and the nodes ($\boldsymbol{V_S}$) corresponding to HSPSs can be eliminated. The resulting reduced system equations may be represented as

$$\begin{Bmatrix} \boldsymbol{I_S} \\ \boldsymbol{I_G} \end{Bmatrix} = \begin{Bmatrix} \boldsymbol{Y_{SS}} & \boldsymbol{Y_{SG}} \\ \boldsymbol{Y_{GS}} & \boldsymbol{Y_{GG}} \end{Bmatrix} \begin{Bmatrix} \boldsymbol{V_S} \\ \boldsymbol{V_G} \end{Bmatrix} \tag{8}$$

where

$$\boldsymbol{I_S} = [I_{s1}\ I_{s2} \cdots I_{s2m}]^T$$
$$\boldsymbol{V_S} = [V_{s1}\ V_{s2} \cdots V_{s2m}]^T$$
$$\boldsymbol{I_G} = [I_{g1}\ I_{g2} \cdots I_{gn}]^T$$
$$\boldsymbol{V_G} = [V_{g1}\ V_{g2} \cdots V_{gn}]^T$$
$$I_{sj} = \frac{-P_{sj} + jQ_{sj}}{V_{sj}^*}$$

$\boldsymbol{V_S}$, $\boldsymbol{I_S}$ are vectors of voltages and current injections at the nodes to which HSPSs are connected, and $\boldsymbol{V_G}$, $\boldsymbol{I_G}$ are vectors of generator voltages and currents. The subscripts G and S in the $\boldsymbol{Y}$-matrix denote machine internal buses and HSPS branch buses respectively. Y_{SS}, Y_{SG}, Y_{GS}, Y_{GG}, are submatrices of dimensions $(2m\times 2m)$, $(2m\times n)$, $(n\times 2m)$ and $(n\times n)$ respectively. From Eq. (8), we get

$$I_G = Y_{red}\ V_G + D_S\ I_S \tag{9}$$

where

$$Y_{red} = Y_{GG} - Y_{GS}\ Y_{SS}^{-1}\ Y_{SG} = [G_{rik} + jB_{rik}]$$

$i=1, 2, \cdots, n$, $k=1, 2, \cdots, n$, is the reduced network admittance matrix excluding the HSPS branches.

$$D_S = Y_{GS}\ Y_{SS}^{-1} = [G_{slk} + jB_{slk}]$$

$i=1, 2, \cdots, n$, $k=1, 2, \cdots, 2m$, is the distribution factor matrix for HSPSs, which reflects the power flows through HSPS branches to generator internal buses. V_{red} and D_s are computed for both faulted and post-fault conditions by properly taking the corresponding network changes into account.

The effect of the HSPSs as additional bus power injections at the internal bus of the i-th generator is given as

$$\Delta\dot{S}_i = -\sum_{j=1}^{2m} \frac{V_{gj}}{\dot{V}_{sj}} (G_{sij} - jB_{sij})(P_{sj} + jQ_{sj}) \tag{10}$$

Since only active power is of interest in the swing equation, we get the total bus power injection at the i-th generator due to HSPSs as

$$\Delta P_i = -\sum_{j=1}^{2m} \frac{V_{gi}}{V_{sj}} (C_{ij}P_{sj} - D_{ij}Q_{sj}) \tag{11}$$

where

$$C_{ij} = G_{sij}\cos(\delta_i - \delta_{sj}) + B_{sij}\sin(\delta_i - \delta_{sj})$$
$$D_{ij} = G_{sij}\sin(\delta_i - \delta_{sj}) - B_{sij}\cos(\delta_i - \delta_{sj})$$

δ_i indicates the generator rotor angle. The effect of HSPSs is thus represented as the term that modifies the power input of generators. In other words, ΔP_i is the component of the i-th generator electric output power associated with power flows through HSPS branches. Therefore, the rapid control of intertie power flows will be an effective measure for transient stability problems.

2.3 Inclusion of HSPS dynamics

For the j-th HSPS, the dynamic equation is[13-14]

$$T_j\dot{\alpha}_j = -\alpha_j + G_ju_j \tag{12}$$

T_j, G_j are time constant and gain of the controller, u_j is external control signal obtained from system quantities according to control scheme. In this paper, a simple feedback control scheme is adopted.

For the simple case of one HSPS located between buses l and k, the resistance of the HSPS branch is neglect and the voltage magnitudes at buses l and k are assumed to be equal approximately. From Eq. (11), the effect of the HSPS on the i-th generator is described as

$$\Delta P'_i = -\frac{V_{gi}}{V_{sl}} [(C_{il} - C_{ik})\ P_{sl} - (D_{il} + D_{ik})\ Q_{sl}] \tag{13}$$

As seen, $C_{il} - C_{ik}$ means the degree at which the power flow of HSPS branch impacts the i-th generator. We call it effect degree. It is to be noted that besides the network configuration and loading levels, the effect degree is dependent on $\delta_i - \delta_{sj}$ both the local information and generator information. Thus, the effect degree should be incorporated in the control scheme.

On the external control signal, investigation confirmed that the generator rotor speed deviation, or an estimate provides the best control signal[15]. It is reasonable to take the rotor speed deviation (ω) of generators whose effect degrees are relatively big in absolute value as control signal. A proposed external control signal is

$$u_j = \sum_{j=1}^{n} |(C_{il} - C_{ik})|\ \omega_i \tag{14}$$

Therefore the rotor speed deviations of generators which are affected strongly by the HSPS are used as external control signal.

3. Application

For the system including HSPSs, the classical generator model in the center of angle reference (COA)[16] is

$$M_i\dot{\tilde{\omega}}_i = P_{mi} - \Delta P_i - P_{ei} - \frac{M_i}{M_t} P_{COA} \tag{15}$$

$$\dot{\theta}_i = \tilde{\omega}_i \tag{16}$$

for $i=1, 2, \cdots, n$. where

$$P_{ei}=\sum_{j=1}^{n} V_{gi}V_{gj}\,(B_{rij}\sin\theta_{ij}+G_{rij}\cos\theta_{ij})$$

$$P_{COA}=\sum_{j=1}^{n}(P_{mj}-\Delta P_j-P_{ej})$$

$$M_t=\sum_{j=1}^{n}M_j$$

$$\theta_{ij}=\theta_i-\theta_j$$

θ_i and $\tilde{\omega}_i$ are the rotor angle and the speed of the i-th generator relative to COA frame. P_{mi} and M_i are the mechanical input power and inertia constant of the i-th generator. P_{ei} is the electrical output power of the i-th generator without including HSPSs branch in network configuration. The equations concerning with HSPSs are rewritten as follows.

$$T_j\dot{\alpha}_j=-\alpha_j+G_ju_j \qquad (17)$$

$$\boldsymbol{I_S}=\boldsymbol{Y_{SS}}\,\boldsymbol{V_{SS}}+\boldsymbol{Y_{SG}}\,\boldsymbol{V_G} \qquad (18)$$

for $j=1, 2, \cdots, m$, where

$$u_j=\sum_{j=1}^{n}\mid(C_{lj}-C_{ik})\mid\tilde{\omega}_i$$

$$l=1, 3, \cdots, 2j-1$$

$$k=2, 4, \cdots, 2j$$

The phase angles of bus voltages are all converted to COA frame. Equations (15), (16), (17) and (18) constitute the total system equations. Iteration calculation of equation (18) is carried out at the same time of the integration in order to obtain bus voltages.

4. Simulation Results

A system shown in Fig. 2 is used for simulation[16]. The main loads are also shown in the figure. In this test system, more than half of the loads are connected in the area marked in Fig. 2, that is one of the main load center. Load flow studies show that relatively large power flows take place through the AC interties (transmission line 2-3, line 21-22, line 23-24, and line 28-29) which feed power into the load center area. Generators 2 and 3 are mainly meeting its local demand. The interconnecting between the generators 2, 3 area and the load center area is weak. Thus, based on the analysis above, it may be advantageous to install HSPS on the AC transmission line 2-3 and line 21-22, as shown in Fig. 2. Covering the simulation, three fault cases of three-phase fault at K_1, K_2 and K_3 have been studied. K_1 is located on the transmission line 23-24 which both close to generator area and is a major transmission line feed the load center area. K_2 is located on the transmission line 16-17 which is an important intertie in the load center area. And K_3 is near to generators 2 and 3.

The time constant of HSPS is assumed to be 0.1 s. The HSPSs are started after fault cleared.

4.1 Fault at K_1

At t=0.3s, the fault line is disconnected and HSPSs start to work. The gains of HSPSs are selected as

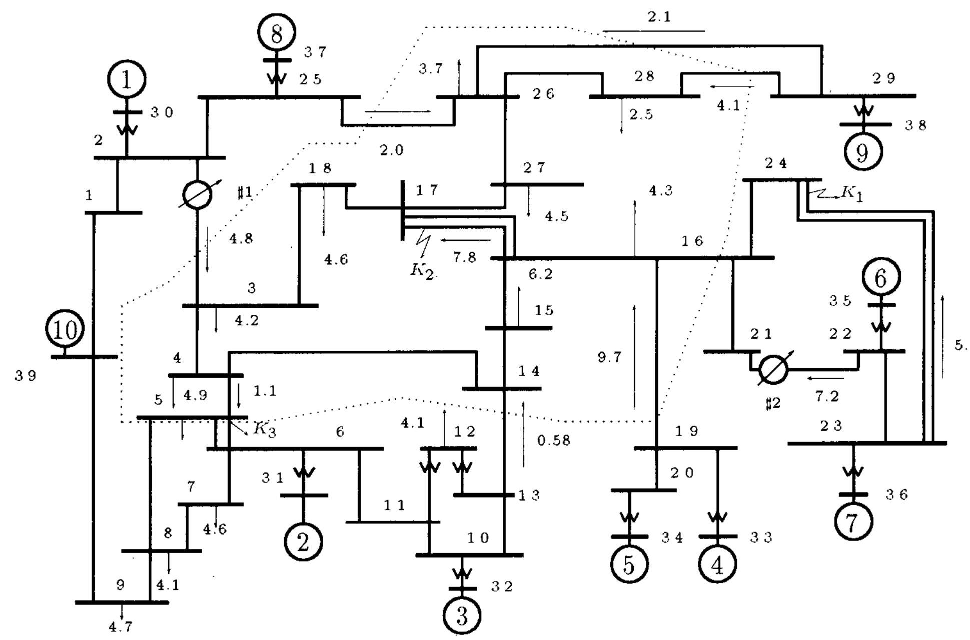
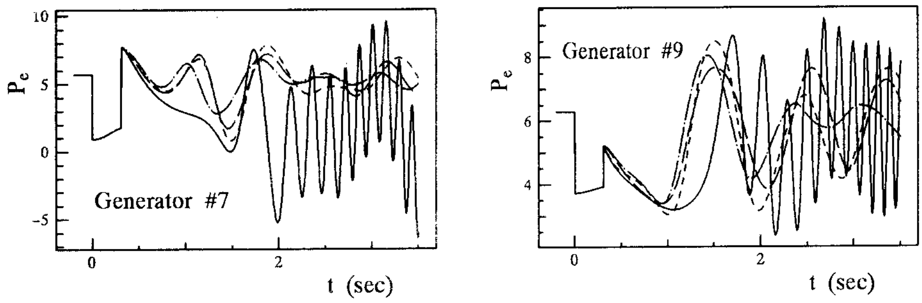


Fig. 2 Test System.

$G_1=0.3$, and $G_2=0.2$ using trial- and-error methods.

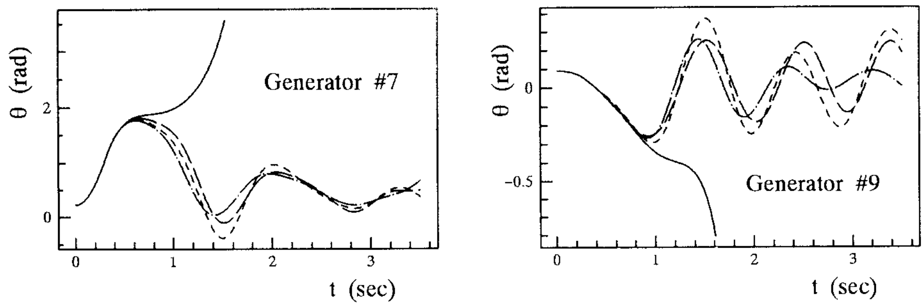
The relative rotor angles are shown in Fig. 3. It may be seen that following the fault the system is unstable without control. One HSPS only, either HSPS 1 or HSPS 2, could bring the system back to stable operation very soon, and provides good stabilizing to all generators. Although HSPS 1 is distant from the fault, it stabilizes the generators not only near to but also distant from it. Similarly, generators #9 also show good stabilization provided by HSPS 2 which is distant from them.

To illustrate the efficiency of multiple HSPS, the case using two HSPSs is presented as well. It should be noted that with two HSPSs, all generators are brought back to stable operation very well comparing with that with only one HSPS.



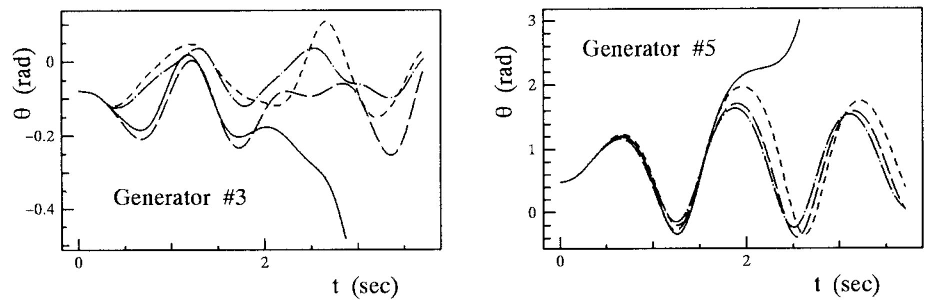
HSPS disabled
HSPS #1 in service
HSPS #2 in service
HSPS #1 and HSPS #2 in service

Fig. 3 Generator angles under disturbance K_1.



HSPS disabled
HSPS #1 in service
HSPS #2 in service
HSPS #1 and HSPS #2 in service

Fig. 4 Generator electric outputs under disturbance K_1.



HSPS disabled
HSPS #1 in service
HSPS #2 in service
HSPS #1 and HSPS #2 in service

Fig. 5 Generator angles under disturbance K_2.

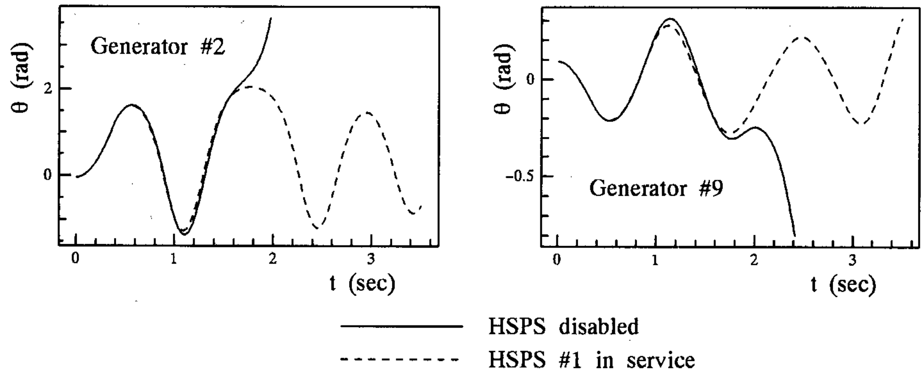


Fig. 6 Generator angles under disturbance K_3.

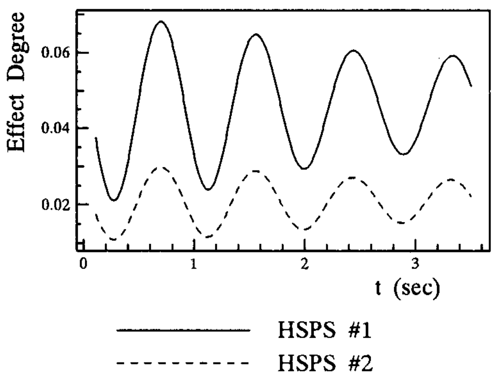


Fig. 7 Effect degree of HSPS 1 and HSPS 2.

The generator electric power outputs including the component associated with HSPS branches are shown in Fig. 4. It is very interest that HSPSs provides very good damping to power oscillation of generators and bring the power outputs back close to the mechanical inputs effectively. Similarly, the case with two HSPSs is better than that with one HSPS.

4.2 Fault at K_1

At t=0.25s, the fault line is disconnect and HSPSs start to work. The gains of HSPSs are selected as $G_1=0.35$ and $G_2=0.25$.

As mentioned, this is a fault on the most important transmission line in the load center area. The generators close to bus 16 will suffer a stronger shock due to the fault. The relative rotor angles are shown in Fig. 5. This fault drives generator 5 unstable at the second swing so that the whole system collapses. Under this kind of challenge, phase-shifter controls, using only one or two HSPSs both are able to stabilize the system. It may be seen that HSPS 1 better first-swing damping for generator 3 (also for generator 2) than HSPS 2 does though HSPS 2 is close to the fault. The HSPS 2 provides small negative first-swing damping for generator 3, but is able to make it stable.

4.3 Fault at K_3

At t=0.365s, the fault line is disconnect and HSPSs start to work. The gain of HSPS1 is selected as $G_1=0.20$.

This is the fault out of load center area but near to generators 2 and 3. The relative rotor angles are shown in Fig. 6. At the second swing, generator 2 firstly goes out of stable operation, and this drives the system into separation. HSPS 1 is able to bring the system back to stable operation as shown. But it is impossible to stabilize the system using HSPS 2. This is because the weak impact on generators 2 and 3 provided by the power flow through HSPS 2. Fig. 7 shows the effect degrees of HSPS 1 and HSPS 2 on generator 2 when the fault line is disconnected at t=0.1s and without phase-shifter control. As demonstrated, the effect degree of HSPS 2 is lower.

5. Conclusion

A method of handling HSPS is presented and the effect of HSPS is represented as the terms which modifies the power input of generators. It is useful and convenient for the transient analysis of power system. The so-called effect degree is used as the degree at which HSPS contribute generators. A simple feedback control scheme is tested which takes the local measures and generator rotor speed deviations into account.

The simulation work shows that HSPS located on the AC interties which feed bulk power into load center enhance system transient stability effectively. Even if the faults of concern are distant from the controller, HSPS is able to stabilize the system well. It is noted that using multiple HSPS provides good stabilizing control for system transient conditions. The validity of the simple feedback control scheme is also demonstrated. In addition, it is shown that for the fault close to the generator, the HSPS whose effect degree to the generator is lower does not stabilize the system well.

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