PSS PERFORMANCE AS AFFECTED BY ITS OUTPUT LIMITER

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Abstract — **The effects of control limits of power system stabilizers(PSS) have been studied using the Transient Stability Simulation Package(TSSP) and a real-time simulator. Extensive simulations were carried out for three different power systems with PSSs using either electrical power or speed deviation as input signal. Results from batch and real-time simulations are in agreement with each other for the cases studied. It has been concluded that higher PSS output limit settings can achieve added damping and enhance transient stability. They yield excellent PSS performance during major system disturbances.**

Keywords: power system stabilizer, PSS performance, control limits, transient stability

I. INTRODUCTION

The application of power system stabilizers (PSSs) has been a cost-efficient measure to suppress low-frequency oscillations in power systems. Considerable work on theoretical research and practical implementation of PSSs has been done over the last two decades[1]. New design techniques and methodology have been described in the literature, as summarized in [2]. Each design technique emphasizes certain important factors that affect the performance of the PSS to be designed. In this paper, however, no new design technique is introduced. Instead, a fundamental but very practical engineering issue is addressed. That is the control action of a PSS as affected by its output limits. In order to limit the amount of control action of a PSS during a major system disturbance, the output of the PSS is always confined within a certain range. As far as how to select this limit is concerned, there seems to be no written guide to setting the PSS limits. It is usually a compromise in sharing the excitation boost capability between the AVR voltage and VAR control and the PSS damping.

Results of studies on the effects of PSS limits may not have been widely reported in the literature. Some references suggest a PSS output limit at .10 or .20 per unit[3]. Actual PSS limits may be lower than this if an electrical utility has a conservative philosophy and limits the PSS to a fraction of AVR control capability. For small disturbance, this limit may never be reached and the excitation capability may not be fully utilized by PSS action. On the other hand, whenever there is a large system disturbance, the PSS limit is most likely hit again and again because of large oscillatory PSS input signals. This results in the exciter hitting its own upper and lower limits during the first few oscillations after the disturbance. In this case, an underdamped oscillatory torque is exerted on the generator shaft yielding increased mechanical stress. The PSS during these limit cycles is not providing enough damping torque to the generator thus it oscillates over a longer period of time. Another adverse effect of this hunting process between maximum and minimum limits is that the dynamic performance of the excitation system deteriorates.

In effect, the setting of these limits is system dependent and related to the selection of PSS parameters. It is beneficial to investigate the effects of limits on PSS performance by extensive simulations before field implementation.

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II. STUDY TOOLS AND SYSTEMS

The study reported in this paper includes both batch and real-time simulations. The software used in batch simulations is the Transient Stability Simulation Package (TSSP) [4]. A small signal eigenvalue program, which can simulate a synchronous machine up to eighteenth order, including its excitation system (AVR), speed governor (AGC) and power system stabilizer (PSS). Using this program, one can compute the eigenvalues of a system, identify the various low-frequency oscillation modes, their participating generators, and the best PSS installation sites.

Extensive batch simulations for three power systems were conducted in this study. They are a two-machine-infinite-bus system [5], the Athabasca-Points North Power System[2] and the New England Test System[6]. Both electrical power input PSS and speed deviation input PSS were utilized in the simulations. The following section will focus on discussing the results obtained in the studies. First, batch simulations of the two-machine infinite bus system are presented, followed by the results of its real-time simulations. Second, batch simulations of the other two systems are given. Finally conclusions are drawn from the studies.

III. SIMULATION RESULTS

A. *The Two-Machine Infinite Bus System*

This system consists of one test machine (G#1 - 175MVA), one equivalent machine (G#2 - 900MVA) and an infinite bus, as depicted by Figure 1. Each machine is equipped with an SCR excitation system and a standard hydro speed-governing system. The parameters of the network, machine and excitation systems are given in [5]. The parameters of the speed-governing system are listed in the Appendix of this paper. Both generators are modeled as salient rotor without subtransient circuits. A steady state stability study was carried out to identify the various oscillation modes. It is characterized by a 2 Hz local mode and a 1 Hz interarea mode. The design and tuning of power system stabilizers for each machine were then followed, based on the PSS design procedure given in [7]. The final settings of the PSSs, using the output electrical power of the generators as PSS input signal, are listed in Table I. Detailed IEEEST and IEEESN models are given in Appendix B.

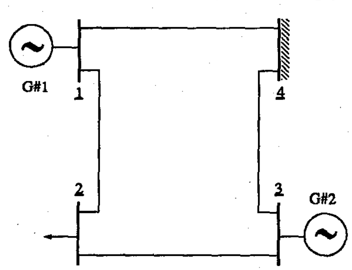

Fig. 1 Two machine infinite bus power system

TABLE I SETTINGS OF THE DESIGNED PSSS

Model	T_{A1}	T_1	T_2	T_3	T_4	T_5	T_6	K_s
IEEEST	.000	.100	.012	.25	.50	4.0	4.0	-1.8
IEEESN	.014	.003	.025	1.85	1.85	5.0	5.0	-.86

A. 1. *Electrical Power PSS on G#1*

An investigation of system stability was performed by simulating disturbances applied to the system, when each generator is at full load. To examine the effect of PSS limits (positive and negative limits in per unit are equal unless stated otherwise) on the performance of the electrical power PSS, IEEEST, given in Table I, two disturbances, a three-phase to ground fault for three cycles and a 4% increase of the terminal reference voltage, are applied to the terminal bus of generator #1, one at a time. Results from time domain simulations of the 3ϕ fault are shown in Figures 2a, 2b and 2c with different PSS output limits. The power oscillation with no PSS is also included for comparison purpose. It can be seen that the first swing is appreciably reduced when the limit increases from .10 to .40. Further increases do not produce significant improvement.

Figure 2b shows the terminal voltage of generator #1. It can be seen that with higher PSS limit, the oscillation of the terminal voltage is more attenuated. This trend of voltage damping is also observed in the simulations of the other two systems to follow. Figure 2c illustrates that with higher PSS limit, the field voltage hits its own limits less often than it does with lower PSS limit. The initial response from the PSS with increased limits results in less subsequent terminal voltage modulation compared to one with lower limits since the accelerating torque acting on the rotor is offset by the PSS robust action.

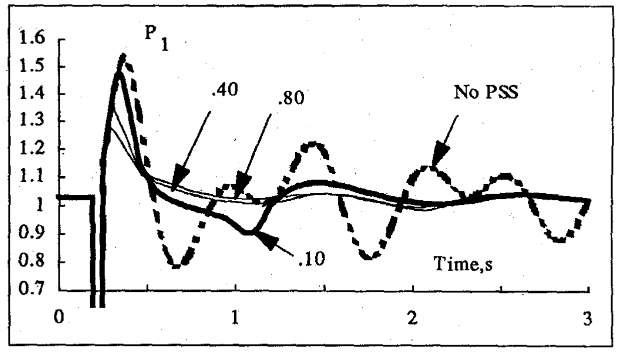

Fig. 2a Electrical power transients of G#1 for different PSS limits and a 3ϕ fault

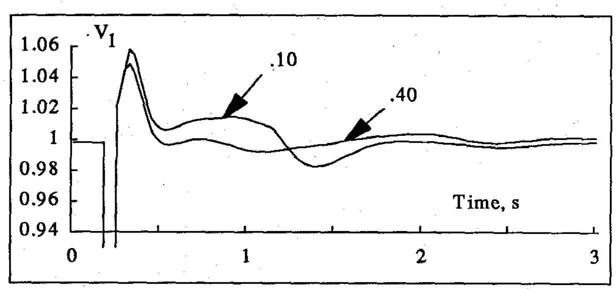

Fig. 2b Terminal voltage response of G#1 for different PSS limits and a 3ϕ fault

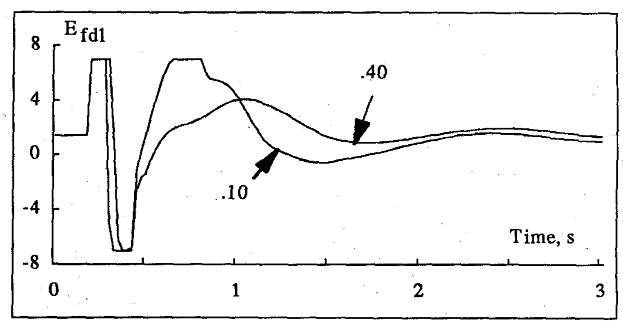

Fig. 2c Field voltage of G#1 for different PSS limits and a 3ϕ fault

A. 2. *Electrical Power PSS on G#1 and G#2*

Simulations were performed for the case where each of the two machines was equipped with PSSs as given in Table I. The three-phase fault was applied as in the previous section.

It was found that when the output limit of the PSS on G#1 and G#2 was increased to .40 and .20, respectively, the best performance of the PSSs is obtained with other conditions being unchanged(results not shown due to their similarity to those as obtained in A. 1).

For the case of a 4% reference voltage increase, Figures 3a and 3b show some of the results when the PSS output limits are .02, .04 and .08, respectively. When the PSS limit is greater than .04, the plots of electrical power transients overlap each other(not shown) and the PSS performs very well. These results were duplicated in our real-time simulations(see Section A.4). It can be seen that in both cases increasing the PSS output limits can provide more damping and at the same time enhance the transient stability of the system. Note that in the present case the PSS output limits are intentionally set lower as the disturbance is small.

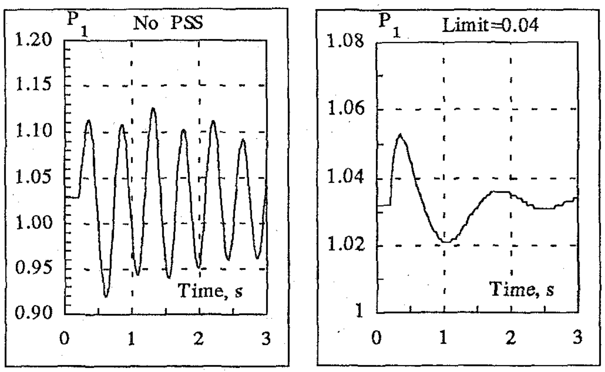

Fig. 3a Electrical power transients of G#1 with no PSS, with PSS for the limit being .04 and a 4% reference voltage increase, respectively

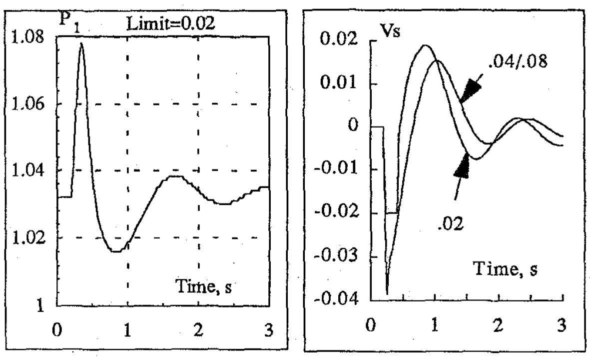

Fig. 3b PSS outputs, electrical power transients of G#1 for the limit being .02 and a 4% reference voltage increase

A. 3. No Output Limits on PSS

As pointed out in the beginning of the paper, the output of a PSS is always confined within a certain range, usually .10 - .20, in order to limit the participation of the PSS in the control action to the generator. In our simulation studies, experimental runs were carried out when the limiter of the PSS on G#1 was released(no limits were imposed on the output of the PSS) and no PSS was installed on G#2. Figure 4 illustrates this situation where the PSS provides maximum control action during the first swing for a 6-cycle three phase to ground fault at the terminal of generator #1.

When the limit is set at .40, the PSS output, V_s, from Fig. 4a, hits the upper limit again in the second swing, as does the field voltage, E_{fd1}, from Fig. 4b. This prolongs the saturation of the excitation system and renders it inactive for voltage regulation during saturation intervals. From Fig. 4c, it can be seen that the terminal voltage, V_t, is more attenuated when the PSS limit is released.

Normally the PSS output limit is set at a maximum allowable portion of the AVR field voltage maximum. This PSS limit is reached for severe system disturbances that yield large input signals to the PSS. It was observed for this case that higher PSS limits also result in the excitation system reaching its own limits less often than when the PSS limits are lower.

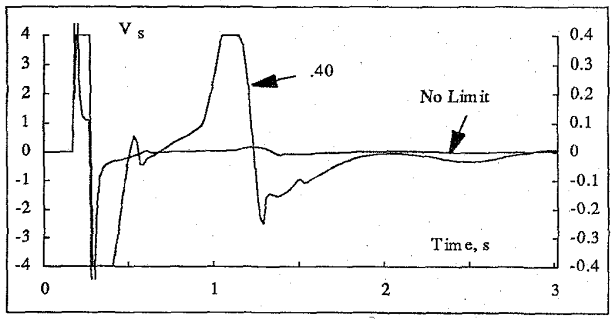

Fig. 4a PSS outputs of G#1 for different PSS limits and a 3ϕ fault

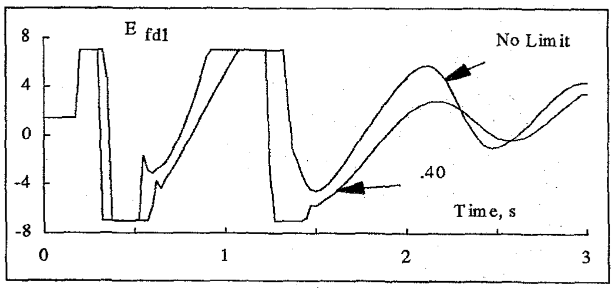

Fig. 4b Field voltage of G #1 for different PSS limits and a 3ϕ fault

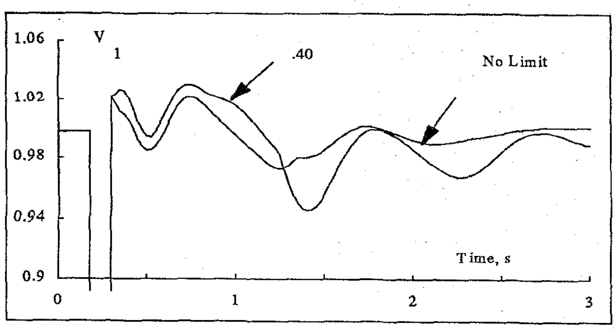

Fig. 4c Terminal voltage of G#1 for different PSS limits and a 3 ϕ fault

Further simulation studies have indicated that the above conclusions apply to both positive and negative limits, though for a particular machine and a specific disturbance, simulated results may be different(see Section B). On the other hand, the setting of the negative limit may be constrained by other factors[3].

A. 4. Results from Real-Time Simulator

The effects of PSS output limits were also investigated using a Real-Time Transient Stability Program (RTTSP). This program allows the multi-machine power system to run in a PC which is interfaced to external power plant controllers through A/D and D/A ports. In this application the two-machine-infinite-bus system was simulated on the RTTSP and the PSSs on external Digital PSS hardware. This is shown in the block diagram of Fig. 5 where it is noted that the RTTSP software allows keyboard control of all power system parameters in real-time,

The prime benefit of the RTTSP is that the power system is continuously running and external controllers can be configured and adjusted with flexibility limited only by the external control hardware and software. In this case the PSS transfer functions were programmed into a commercial Digital PSS(DPSS)[8] and limits were adjusted while applying a 4% step input to the AVR of G#1 with a signal generator. This test environment is similar to on-site testing at power plants where PSSs are tuned on-line.

Figure 6 shows transients obtained from a Brush recorder connected to the PSS input, P_e(electrical power), and output, V_s. The RTTSP software displays transients in real-time on the PC monitor and ports data to files for subsequent graphing to printers and plotters. In Fig. 6(a) the PSSs were not in service whereas in 6(b) they are in with PSS limits being .04 and parameters the same as indicated earlier. Figures 6(c), 6(d) and 6(e) show transients for decreased limit settings (.02, .01, .005 exactly) of the PSS's on G#1 and G#2. As noted the damping diminishes as the output of the PSS becomes more restricted. These results are in agreement with those obtained in batch-type simulations (compare with Figures 3a and 3b).

B. The Athabasca-Points North Power System

Computer simulations of a 69-bus 13-machine power system studied in earlier investigations were performed[2]. A portion of the system is shown in Fig. 7. It has been concluded in [2] that low frequency oscillations occur if one of the double circuits is out of service. A three-phase to ground fault for 6 cycles was applied to one of the double circuits between buses 1 and 2 near the Island Falls plant. The speed PSSs as given in [7] were installed on all the generators. Figure 8a shows electrical power oscillations of generator #1 for varying PSS output limits.

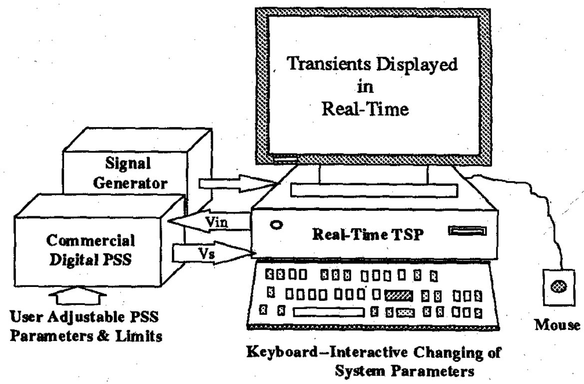

Fig. 5 Flow diagram showing main elements of real-time transient simulation programming and external digital PSS

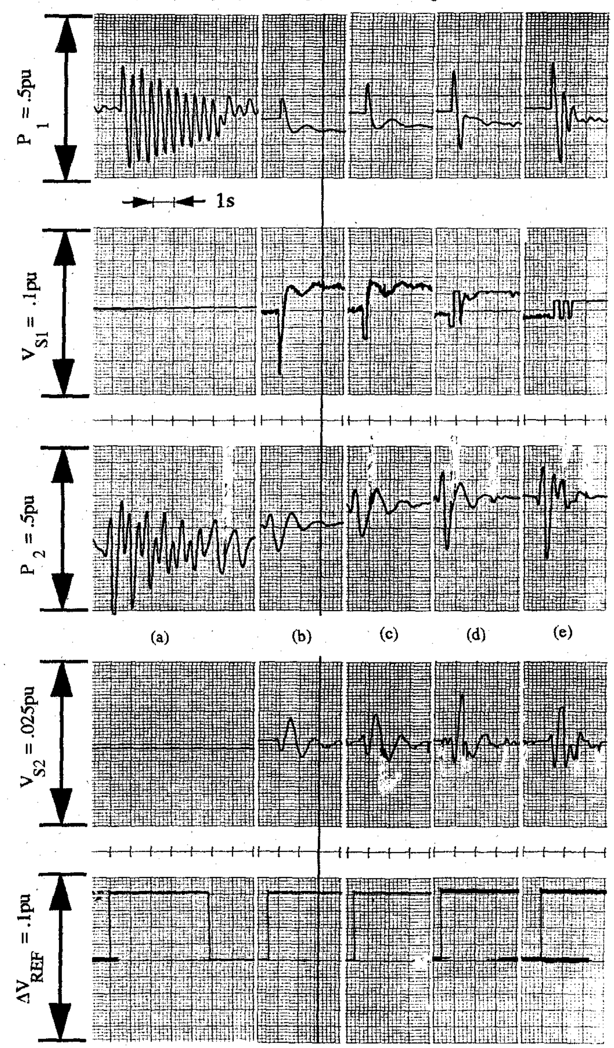

Fig. 6 Electrical power transients and PSS outputs of G#1 & G#2 for 4% reference voltage increase

Experimental runs were performed for the cases where either the upper limit or the lower limit changes in one direction. It was observed that when the upper limit is increased from 0.1 to a large value, the stability improves very little, and when the lower limit is decreased, the oscillation is damped out quickly, as shown in Fig. 8b. When both the upper and the lower limits are released, the oscillation curve is close to that of Fig. 8a with the limit set at .50 per unit.

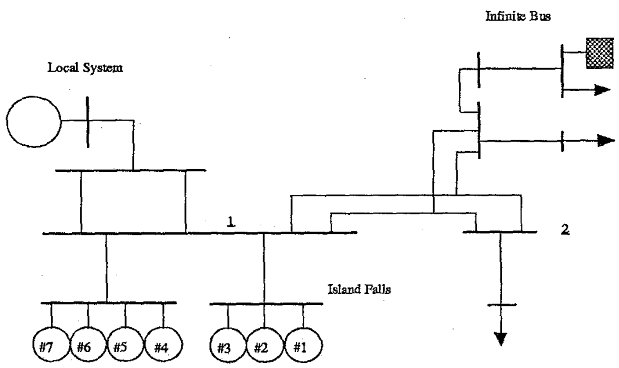

Fig. 7 Portion of the Athabasca-Points North Power System

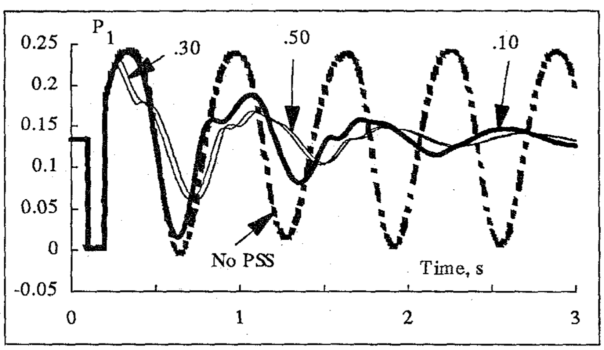

Fig. 8a Electrical power transients of G#1 for different PSS limits and a 3ϕ fault

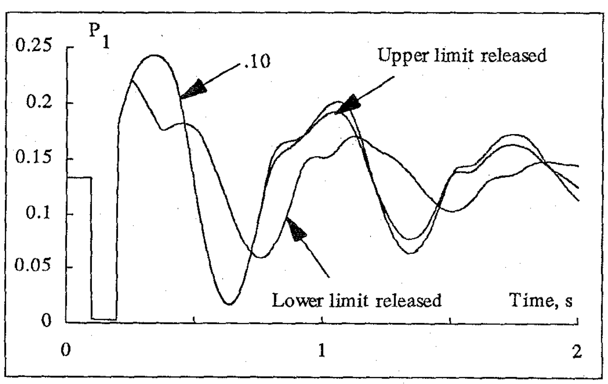

Fig. 8b Electrical power transients of G#1 for different PSS limits and a 3ϕ fault

C. *The New England Test System*

The New England Test System, as shown in Fig. 9, was also used in the study. Electrical power PSSs were designed using the procedure described in [7]. A 6-cycle three-phase to ground fault was applied to line 25-26 near bus 25 in the system. This fault caused severe power oscillations. The most affected generators are the ones close to the fault. Figures 10a and 10b show the electrical power oscillations of generators #8 and #9 which are located on either side of the faulted line. The limits of the PSSs installed on each of these generators were varied from zero to a very large value (equivalent to no limits). As shown in Fig. 10a, the oscillations of generator #8, which is close to the fault, are much more damped when the PSS limit is increased from .10 to .50 while further increases result in very little improvement. On the other hand, from Fig. 10b, the oscillations of generator #9, which has a large electrical distance due to the fault , are barely affected by increasing its PSS limit beyond the original setting which is .10 per unit.

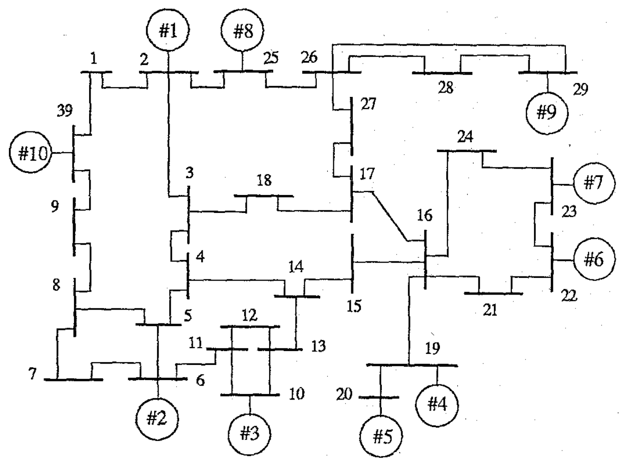

Fig. 9 Single line diagram of the New England Test System

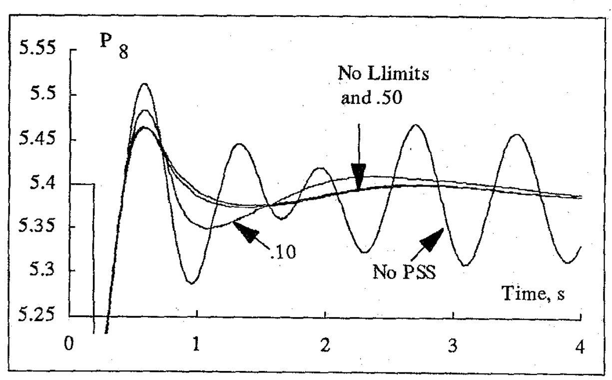

Fig. 10a Electrical power transients of G#8 for different PSS limits and a 3ϕ fault

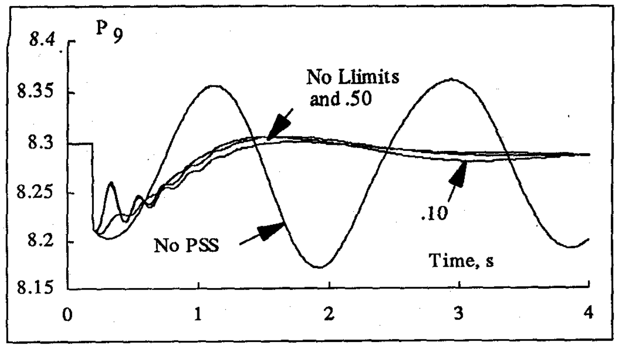

Fig. 10b Electrical power transients of G#9 for different PSS limits and a 3φ fault

VI. CONCLUSIONS

The effects of PSS output limits on its performance during system disturbances have been investigated using "batch" and "real-time" simulation software. Both large and small disturbances were applied (one at a time) in batch simulations to illustrate PSS performance when its output limits change. In real-time simulations, only small disturbances were applied. Results from both types of simulations for the two-machine-infinite-bus system agree with each other when a 4% reference voltage increase is imposed on the terminal bus of the test machine, as discussed in the paper. Computer simulations for other types of faults and for different power systems have shown similar results, from which the following general conclusions are drawn.

- Higher PSS output limits can improve the performance of PSSs and further enhance transient stability of a power system, especially following major system disturbances. This benefit is significant for those generators close to the disturbance. A normal high gain static excitation system with a gain of 200 per unit and a PSS with a 0.1 limit will reach the positive ceiling when the PSS is at limit on open loop. On closed loop the effective gain is reduced and transient stability enhancement can be increased with increased PSS limits.
- Higher PSS output limits can provide better voltage control and shorten the time period of saturation of the excitation system.

ACKNOWLEDGMENTS

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APPENDIX A

1. Parameters of the AVRs and exciters(Fig. A.1)

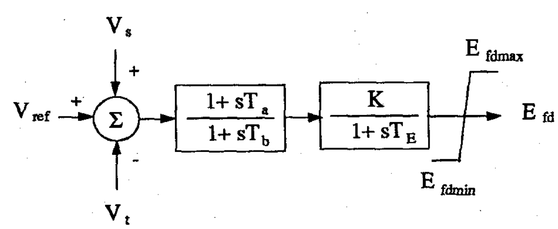

Fig. A.1 SCR Excitation System

For generator #1,

$$T_a = 1, T_b = 1, T_E = 0.05$$
$$K = 115$$
$$E_{fd\min} = -7.0, E_{fd\max} = 7.0$$

For generator #2,

$$T_a = 1, T_b = 1, T_E = 0.05$$
$$K = 60$$
$$E_{fd\min} = -7.0, E_{fd\max} = 7.0$$

2. Parameters of the speed-governing systems

For generator #1,

$$T_s = 0.10, T_r = 10.3, T_w = 2.2$$
$$\sigma = 0.05, \delta = 0.32, \dot{G}_{\min} = -0.10, \dot{G}_{\max} = +0.10$$
$$G_{\min} = 0.0, G_{\max} = 1.1$$

For generator #2:

$$T_s = 0.10, T_r = 10.3, T_w = 1.9$$
$$\sigma = 0.05, \delta = 0.40, \dot{G}_{\min} = -0.10, \dot{G}_{\max} = +0.10$$
$$G_{\min} = 0.0, G_{\max} = 1.1$$

3. Network Data

Network data in Table A.1 are in per unit on a system base of 100 MVA, where *i, j, R, X,* and *b/2* denote line connecting bus *i* to bus *j*, resistance, reactance, and half of line charge, respectively.

TABLE A.1 NETWORK DATA

i	*j*	*R*	*X*	*b/2*
1	*2*	*.0005*	*.0020*	*0.0*
2	*3*	*.0005*	*.0020*	*0.0*
3	*4*	*.0500*	*.2800*	*0.0*
1	*4*	*.0070*	*.0800*	*0.0*

4. Machine Data

Machine data are given as follows. Machine inertial constant H is in second based on machine - rated MVA. Resistance, reactance, and damping Coefficient (D) are in per unit based on machine - rated MVA. Time constants are in second.

For generator #1,

$$H = 3.91, r_a = .0032, x_l = .22$$
$$x_d = .74, x_d' = .27, x_q = .45, x_q'' = .43$$
$$\tau_{do}' = 4.73, \tau_{qo}' = 1.74$$
$$D = 2.5, A_G = .00003, B_G = 6.0$$

For generator #2,

$$H = 4.0, r_a = 0, x_l = .24$$
$$x_d = .74, x_d' = .27, x_q = .48, x_q'' = .44$$
$$\tau_{do}' = 4.6, \tau_{qo}' = 1.74$$
$$D = 16.5, A_G = .00003, B_G = 6.0$$

APPENDIX B

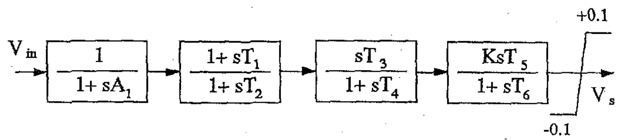

Fig. A.1 IEEESN PSS Model

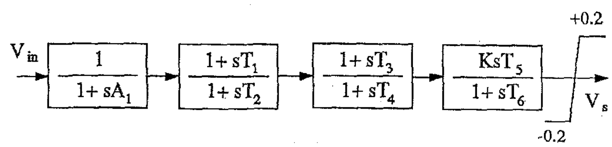

Fig. A.2 IEEEST PSS Model

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