REC-ERC-92-1

POWER SYSTEM STABILIZER COMPARISON: LOCAL MODE DAMPING PERFORMANCE

September 1992

Denver Office

U. S. Department of the Interior

Bureau of Reclamation

7-2090 (4-81)
Bureau of Reclamation

TECHNICAL REPORT STANDARD TITLE PAGE

1. REPORT NO.
REC-ERC-92-1

2. GOVERNMENT ACCESSION NO.

3. RECIPIENT'S CATALOG NO.

4. TITLE AND SUBTITLE

Power System Stabilizer Comparison:
Local Mode Damping Performance

5. REPORT DATE
September 1992

6. PERFORMING ORGANIZATION CODE
D-3772

7. AUTHOR(S)
Hoa D. Vu
J. C. Agee

8. PERFORMING ORGANIZATION REPORT NO.
REC-ERC-92-1

9. PERFORMING ORGANIZATION NAME AND ADDRESS
Bureau of Reclamation
Denver Office
Denver CO 80225

10. WORK UNIT NO.

11. CONTRACT OR GRANT NO.

12. SPONSORING AGENCY NAME AND ADDRESS
Same

13. TYPE OF REPORT AND PERIOD COVERED

14. SPONSORING AGENCY CODE
DIBR

15. SUPPLEMENTARY NOTES
Microfiche and hard copy available from Denver Office, Denver, Colorado. Ed: RNW

16. ABSTRACT

Several types of power system stabilizers are being investigated as part of the Bureau of Reclamation's Electric Power System Stability Enhancement research project. The focus of this phase of the project is to evaluate the local mode damping performance of three different types of power system stabilizers. The types used speed, electric power, or accelerating power as an input signal and conventional lead-lag compensation in the signal path. Comparisons of operating characteristics such as PSS output noise and sensitivity to load changes are included. Results are based on the analysis of field test data and analog computer simulation. Methods that can be used at remote sites during PSS alignment tests have been employed.

a. *DESCRIPTORS*-- power system stability/ local mode oscillation/ excitation control system

b. *IDENTIFIERS*-- Blue Mesa Powerplant

c. *COSATI Field/Group* 09C *COWR*: 0901 *SRIM*:

18. DISTRIBUTION STATEMENT
Available freom the National Technical Information Service, Operations Division, 5285 Port Royal Road, Springfield, Virginia 22161

19. SECURITY CLASS (THIS REPORT)
UNCLASSIFIED

20. SECUTIY CLASS (THIS PAGE)
UNCLASSIFIED

21. NO. OF PAGES
17

22. PRICE

REC-ERC-92-1

POWER SYSTEM STABILIZER COMPARISON: LOCAL MODE DAMPING PERFORMANCE

by

Hoa D. Vu
and
J. C. Agee

September 1992

Electric Power Branch
Research and Laboratory Services Division
Denver Office
Denver, Colorado

SI METRIC

UNITED STATES DEPARTMENT OF THE INTERIOR ★ BUREAU OF RECLAMATION

Mission: As the Nation's principal conservation agency, the Department of the Interior has responsibility for most of our nationally-owned public lands and natural and cultural resources. This includes fostering wise use of our land and water resources, protecting our fish and wildlife, preserving the environmental and cultural values of our national parks and historical places, and providing for the enjoyment of life through outdoor recreation. The Department assesses our energy and mineral resources and works to assure that their development is in the best interests of all our people. The Department also promotes the goals of the Take Pride in America campaign by encouraging stewardship and citizen responsibility for the public lands and promoting citizen participation in their care. The Department also has a major responsibility for American Indian reservation communities and for people who live in Island Territories under U.S. Administration.

Mission

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

CONTENTS

	Page
Introduction	1
Conclusions	1
Power system stabilizer adjustment criteria	1
Basic principles	1
Frequency input PSS	2
Electrical power input PSS	3
Accelerating power input PSS	3
Gain and phase criteria	4
Field test data	4
Frequency input PSS	5
Electrical power input PSS	5
Accelerating power input PSS	6
Observations from field test data	7
Analog computer simulation	7
Simulation case 1: Field test compensation	7
Frequency input PSS	7
Electrical power input PSS	9
Accelerating power input PSS	10
Simulation case 2: optimum phase compensation	10
Frequency input PSS	11
Electrical power input PSS	12
Accelerating power input PSS	12
Appendix—Analog Computer Model	14

FIGURES

No.		
1	Speed (internal frequency), acceleration power, and electrical power relationship	2
2	Accelerating power PSS block diagram	2
3	Impulse response with PSS off—field test data	4
4	Signal conditioning frequency responses, case 1	4
5	Signal conditioning frequency responses, case 1 (without 90° phase shift)	5
6	Impulse response with internal frequency PSS—field test data: (a) PSS gain 1.5 pu, and (b) PSS gain 2.5 pu	5
7	Impulses with PSS gain = 15 pu—field test data: (a) Electrical power PSS, and (b) Accelerating power PSS	6
8	Load change test with electrical power PSS	6
9	Unstable system with accelerating power PSS, PSS gain of 30 pu	6
10	Load change test with accelerating power PSS	7
11	Gain comparison	7
12	Frequency responses with PSS open-loop compensation, case 1	8
13	Diagram of PSS compensation: (a) Open loop, and (b) Closed loop	8
14	Root locus with varying PSS gain, case 1	8
15	Step response, case 1 with: (a) PSS off, (b) Frequency PSS, gain 1.9 pu, and (c) Frequency PSS, gain 4.5 pu	9
16	Frequency responses with and without PSS, case 1	9
17	Step response with PSS gain = 12 pu, case 1: (a) Electrical power PSS, and (b) Accelerating power PSS	9
18	Signal conditioning frequency responses, case 2	10
19	Signal conditioning frequency responses, case 2 (without 90° phase shift)	10
20	Signal conditioning frequency responses with frequency PSS for cases 1 and 2	10
21	Frequency responses with PSS open-loop compensation, case 2	11

CONTENTS — Continued

No. Page

22 Root locus with varying PSS gain, case 2 11
23 Step response, case 2, with: (a) Frequency PSS, gain = 2.1 pu, (b) Electrical power PSS, gain = 16 pu, and (c) Accelerating power PSS, gain = 16 pu 11
24 Frequency responses with and without PSS, case 2 12
25 Step response with frequency PSS, case 2: (a) PSS gain = 4.0 pu, and (b) PSS gain = 5.0 pu 12

INTRODUCTION

The Bureau of Reclamation has used power system stabilizers (PSS) with internal or terminal frequency as their input for many years [1,2,3].[1] In certain situations, the PSS gain of these stabilizer types cannot be optimized because of high noise amplitude at the stabilizer output. This noise arises from a large amount of phase lead compensation and the susceptibility of frequency transducers to noise on the system. A large amount of phase lead compensation is required because many generators equipped with PSS have rotating exciters or have been tuned with enough transient gain reduction to permit operation with the PSS out of service.

Power type stabilizers should produce less noise because they require less phase compensation [4]. Therefore, an effort was initiated to investigate this solution to the PSS noise problem. As a part of this effort, the local mode damping performance and load change sensitivity of three PSS types were investigated. The three PSS types are: (1) internal frequency (*FREQ*) input, (2) electrical power (P_e) input, and (3) accelerating power (P_{acc}) input.

The comparison of the three PSS types is based on equivalent phase response of the signal conditioning circuits. The local mode damping performance evaluation is based on the root locus of the system local mode with varying PSS gain as measured from time domain records. Other analytical tools have been described in the literature [4,5,6,7,8]; however, this technique was selected because it can be used at remote sites during PSS tuning tests. Results are based on the analysis of field test data and analog computer simulation.

Field testing was performed on unit 1 at Blue Mesa Powerplant. The unit is rated 48 MV•A and 11.5 kV, and equipped with a high-initial response static excitation system. Two stabilizers were used for testing. One was a digital power system stabilizer that used potential transformer (PT) and current transformer (CT) signals to produce frequency, electrical power, and accelerating power signals. The other was a standard frequency input PSS.

The appendix contains the description of the analog computer model (for simulation), and a list of generator and excitation system parameters. The analog computer model includes the model of unit 1 at Blue Mesa Powerplant and a PSS model that simulates the algorithm of the digital PSS.

[1] Number in brackets refers to bibliography.

CONCLUSIONS

All three PSS types can be tuned to damp local mode oscillations. The power PSS types have higher per unit (pu) gain than the frequency PSS type for the same local mode damping ratio. However, if the machine inertia and signal conditioning gains are evaluated at the local mode frequency, the gain of all three types is equal.

To achieve optimum phase compensation for local mode oscillations, the phase response of the signal conditioning should provide increasing phase lead that peaks at the local mode frequency and then decreases at higher frequencies. The peak value depends on the excitation-control-system phase lag at the local mode frequency.

With adequate phase compensation, the frequency PSS produces high noise amplitude at its output, while the outputs of both power type PSSs are nearly noise free. The electrical power PSS produces large voltage variations during normal load changes, but the accelerating power PSS gives an acceptable response.

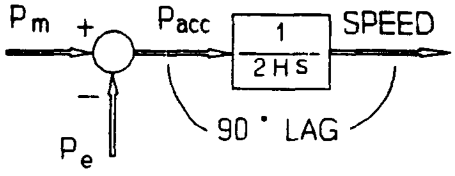
Therefore, it is our opinion that the accelerating power PSS is the preferred stabilizer of the three types evaluated. This is, of course, based on local mode oscillation damping, PSS output noise, and load change sensitivity evaluation criteria.

POWER SYSTEM STABILIZER ADJUSTMENT CRITERIA

Basic Principles

The relationship between shaft speed (or internal frequency), accelerating power, and electrical power is illustrated on figure 1. If the mechanical power (P_m) is constant, negative changes in electrical power (P_e) precede positive changes in speed by 90°. Also, changes in accelerating power precede changes in speed by 90°. Using accelerating power or electrical power as a PSS input results in an extra 90° of phase lead with respect to a speed or internal frequency input PSS. Therefore, a power input PSS will require less phase lead compensation from signal conditioning lead/lag time constants. Less phase lead compensation should help reduce PSS output noise.

A local mode oscillation is an oscillation of the rotor of an electric generator against a power system. To provide oscillation damping, the PSS signal should force electrical torque changes that are in phase with rotor speed changes [4]. Field tuning techniques approximate the electrical torque signal with the



P_{acc}: Accelerating power
P_e: Electrical power
P_m: Mechanical power

Figure 1.–Speed (internal frequency), accelerating power, and electrical power relationship.

terminal voltage signal; therefore, a PSS signal should force terminal voltage changes that are in phase with speed changes and, thus, lag accelerating power changes by 90°.

The block diagram of the accelerating power PSS used at Blue Mesa is shown on figure 2. An electrical power PSS can be implemented with this hardware by setting M to zero to remove the frequency input signal. Simplification of the block diagram leads to an electrical power input PSS with washout and signal conditioning stages.

This hardware can also implement a speed input (actually internal frequency) PSS by setting T_p to zero and M equal to T_f. These adjustments remove the electrical power signal and produce a washout for the internal frequency signal.

Frequency Input PSS

Internal frequency is the frequency of the machine internal voltage (E_q) and, therefore, the speed of the rotor poles. The internal voltage can be obtained by adding a terminal voltage phasor (from PTs) to the product of the machine quadrature impedance and a machine current phasor (from CTs) that is shifted by 90°. The internal frequency is more sensitive to rotor speed changes than the generator terminal frequency. Therefore, internal frequency is more effective as a frequency input to a PSS as far as local mode damping is concerned [6]. The internal frequency signal is used instead of a rotor speed signal because a rotor speed signal would require additional transducers that are not present in a typical voltage regulator.

The frequency input signal goes through a washout block to remove its direct current (d–c) component. Then, it is phase compensated by the signal conditioning function. The phase compensation is required to compensate for the excitation-control-system phase lag. The PSS output goes to the regulator summing junction.

To be consistent with adjustment procedures used for many years by WSCC (Western Systems Coordinating Council), the washout time constant, T_f, should be about 30 seconds (0.0053 Hz). This adjustment eliminates significant phase lead at frequencies above 0.05 Hz and allows the PSS to contribute damping for the lowest known system modes of oscillation. With the time constant, T_f, of 30 seconds, the *washout* block is a high-pass filter with a corner frequency at 0.0053 Hz and high frequency gain of 1.

Phase compensation is not needed at low frequencies (0.1 to 0.4 Hz) because excitation-control-system phase lag is small. The lead time constants, T_1 and T_3 (zeros), are set to compensate the excitation-control-system phase lag at the local mode frequency. The lag time constants, T_2 and T_4 (poles), are set about 8 to 10 times smaller than T_1 and T_3.

The optimum adjustment of the signal conditioning time constants should produce a phase response that starts with zero degree phase lag at low frequency (0.1 Hz), provides increasing phase lead that peaks at the local mode frequency, and then decreases at higher frequencies. The peak should provide 60 to 100 degrees of phase lead. The exact value of the peak depends on the amount of the excitation-control-system phase lag at the local mode frequency. If the phase lag at the local mode frequency is 90°, then the peak should be about 90°.

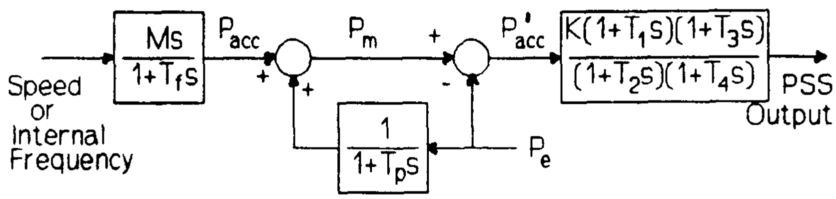


Figure 2.–Accelerating power PSS block diagram.

The optimum ajustment may require more than one attempt to set. Initially, locate the frequency where excitation-control-system phase lag is about 90°; then, set the zeros at about 1/10 to 3/10 of a decade smaller than the located frequency. The poles are set to a frequency about 8 to 10 times larger than the zeros. After the above adjustments are made, check for the following:

- Does the PSS phase response have enough phase lead at the peak?
- Does the PSS phase response have its peak at the local mode frequency?

If the above two criteria are satisfied, the signal conditioning time constants are set properly. If the PSS phase response does not have correct phase lead at the peak, then increase the corner frequency of the poles to provide more phase lead or decrease it to obtain less phase lead.

After adjusting the poles to provide the right amount of phase lead, check the PSS phase response again for the peak location. If the peak occurs at a lower frequency than the local mode frequency, then increase the corner frequencies of all zeros and poles. If the peak occurs at a higher frequency, decrease the corner frequencies of all zeros and poles. When adjusting the peak location, keep the zero/pole ratio the same.

Electrical Power Input PSS

An electrical power PSS must use negative electrical power changes because increases in electrical power output of a generator decrease its speed if mechanical power is constant. The power washout circuit shown on figure 2 provides this signal inversion. The washout time constant, T_p, should be about 30 seconds for comparison with the frequency input PSS case.

The extra 90° of phase lead provided by the electrical power PSS is not needed at low frequency (below 0.4 Hz) because excitation-control-system phase lag is near zero. Therefore, the time constant, T_2 (pole), is used to cancel this 90° phase lead. Setting this pole at 30 seconds (0.0053 Hz) provides 90° of phase lag above 0.053 Hz.

The lead time constants, T_1 and T_3 (zeros), are set to compensate for the excitation-control-system phase lag at the local mode. The lag time constant, T_4 (pole), is set about 8 to 10 times smaller than T_3.

The optimal adjustment of the signal conditioning time constants should produce a phase response that starts with 90° phase lag at low frequency (0.1 Hz), provides decreasing phase lag peaking at the local mode frequency, and increasing lag at higher frequencies. The peak should produce about 60 to 100 degrees of phase lead with respect to the phase response at low frequencies (0.1 to 0.4 Hz). Since the phase at low frequencies is near 90° lagging, the phase at the peak should be near zero degrees. The exact value of the peak depends on the excitation-control-system phase lag at the local mode frequency. If the phase lag at the local mode frequency is about 90° then the peak should be about zero degrees.

Again, the optimum adjustment may require more than one attempt to set. Initially, a pole is set at a frequency of 0.0053 Hz (30 seconds). Locate the frequency where the excitation-control-system phase lag is about 90°; then, set zeros at about 1/10 to 3/10 of a decade smaller than the located frequency. The second pole is set at a frequency about 8 to 10 times larger than the zeros. After the above adjustments are made, check for the following:

- Does the PSS phase response have enough phase lead at the peak?
- Does the PSS phase response have its peak at the local mode frequency?

If the above two criteria are satisfied, the signal conditioning time constants are set properly. If the PSS phase response does not have enough phase lead and the peak frequency is higher than the local mode frequency, then decrease the corner frequency of the zeros. If the phase response does not have enough phase lead and the peak frequency is lower than the local mode frequency, increase the corner frequency of pole T_4 to provide more phase lead.

Check the PSS phase response again for the peak location. If the peak frequency is higher than the local mode frequency, decrease the corner frequency of the zeros and pole T_4 (keep the lead/lag ratio of T_3 and T_4 the same). If the peak frequency is lower than the local mode frequency, increase the corner frequency of the zeros and pole T_4 (keep the lead/lag ratio of T_3 and T_4 the same).

Accelerating Power Input PSS

An accelerating power PSS can be obtained using a PSS with the structure shown on figure 2 by adjusting M equal to twice the machine inertia (2H) and T_f and T_p to 0.2 second. The internal frequency signal is applied to the differentiator with gain M and becomes filtered accelerating power with a filter time constant T_f. Adding the filtered electrical power signal, with a filter time constant (T_p) to the filtered accelerating power produces filtered mechanical power (P_m). This signal should represent the mechanical power exactly if the governor only permits slow changes and turbine damping effects are small. Subtracting the electrical power signal from this filtered mechanical power produces a full spectrum accelerating power signal. Additional washout is not needed to drive the steady-state value to zero, since the accelerating power must be zero unless the machine speed is changing [5].

The load change sensitivity of an accelerating power PSS depends on the governor's response time. The description in the above paragraph requires the governor response time to be slower than 0.2 second (0.7 Hz). Time constants (T_f and T_p) set smaller than 0.2 second results in a PSS that is more susceptible to noise. This result is related to the derivative of the frequency signal. Therefore, these time constants should be as large as possible, but shorter than the governor response time.

The adjustment criteria of the lead/lag time constants T_1, T_2, T_3, and T_4 is identical to the electrical power input case.

Gain and Phase Criteria

Power system stabilizer performance is sensitive to the phase compensation established by the signal conditioning circuits. Therefore, a performance comparison between various PSS types should be based on equivalent phase compensation.

With equivalent phase compensation, all three PSS types have the same root locus characteristic path for the local mode. However, at the same point on the root locus, the per unit gain of a power type PSS is typically higher than that of a frequency type PSS; that is, with the same damping ratio and frequency, a power type PSS has higher per unit gain than a frequency type PSS. But if the gain of the signal conditioning stage and the machine inertia (M) are evaluated at the oscillation frequency, the overall gain of the three PSS types calculated from the speed signal to the PSS output is equal at common points on the root locus.

FIELD TEST DATA

Field test data were recorded during a test of unit 1 at Blue Mesa Powerplant. The excitation-control-system without PSS has a bandwidth of 0.6 Hz and a significant local mode resonant near 1.8 Hz. The system impulse response without PSS, on figure 3, indicates the system is stable, but the damping factor is low.

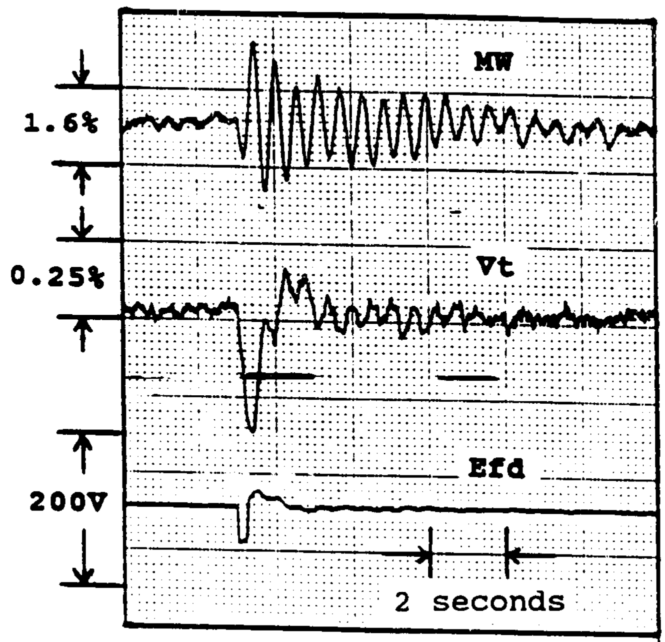


Figure 3.-Impulse response with PSS off—field test data.

Experimental tests were conducted using a digital PSS of the type shown on figure 2. Unfortunately, the slow cycle time of this digital PSS prevented implementation of time constants smaller than 50 milliseconds (3 Hz). This limitation prevented optimal setting of the digital PSS lead/lag time constants.

Frequency responses of the digital PSS were measured using the electrical power and frequency inputs; then Bode plots were drawn. The phase curves had the same shape but were 90° out of phase as shown on figure 4. Subtracting the 90° phase shift from the electrical power PSS plot resulted in phase curves that were identical above 0.1 Hz. This can be seen on figure 5.

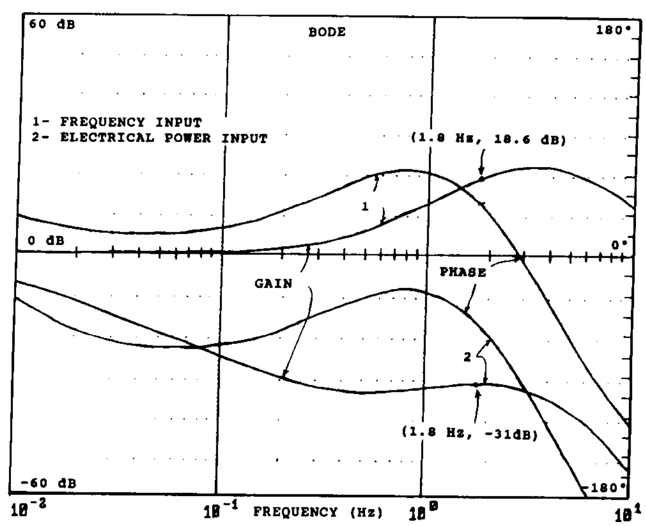


Figure 4.-Signal conditioning frequency responses, case 1.

The phase response of the accelerating power PSS is not shown, because it is impossible to measure a frequency response of a single-output, multiple-input system. However, because electrical power and accelerating power PSSs use the same adjustment criteria, their signal conditioning phase responses should be identical. This is accomplished by setting the lead/lag time constants to the same values.

Figure 5 indicates that the shapes of the phase curves are the same, but the gain curves are different. The frequency PSS gain curve is higher than the power PSS in the high frequency region. This indicates that the frequency PSS is more susceptible to high frequency noise than the power type PSS.

Frequency Input PSS

The Blue Mesa Powerplant analog PSS was used for this case, because the digital PSS program contained a software error, thereby preventing its use as a frequency PSS. The original parameters of the signal conditioning were retained as follows:

$$M = T_f = 30 \text{ s}$$
$$T_p = 0.0$$
$$T_1 = T_3 = 0.3183 \text{ s}$$
$$T_2 = T_4 = 0.05 \text{ s}$$

Two low-pass filters, each with a time constant of 0.04 second, were added to compensate for additional phase lags present in the digital PSS.

The system impulse responses with PSS gains of 1.5 and 2.5 per unit are shown on figure 6. PSS output noise amplitude increases as the PSS gain increases. The PSS provides damping of the local mode oscillation; however, the results are difficult to interpret because of the noise. With the gain at 2.5 per unit, the noise amplitude is large enough to be coupled into the regulator and reproduced in the main field voltage (E_{fd}), terminal voltage (V_t), and megawatt (MW) signals.

A normal load change was conducted by a powerplant operator with the frequency input PSS in service. During this load change period, the PSS did not affect terminal voltage.

Electrical Power Input PSS

The digital PSS was used to implement the electrical power PSS. To achieve the frequency response shown on figure 4, the PSS time constants were set as follows:

$$T_p = 30 \text{ s} \rightarrow 0.0053 \text{ Hz}$$
$$M = 0.0$$
$$T_f = 1000 \text{ s}$$
$$T_1 = 0.3183 \text{ s} \rightarrow 0.5 \text{ Hz}$$
$$T_2 = 30.0 \text{ s} \rightarrow 0.0053 \text{ Hz}$$
$$T_3 = 0.2652 \text{ s} \rightarrow 0.6 \text{ Hz}$$
$$T_4 = 0.05 \text{ s} \rightarrow 3.183 \text{ Hz}$$

A third lead/lag pair was added to exactly match the characteristics of the digital PSS when operating as a frequency type PSS. This third pair was set as follows:

$$T_5 = 0.06365 \text{ s} \rightarrow 2.5 \text{ Hz}$$
$$T_6 = 0.05 \text{ s} \rightarrow 3.183 \text{ Hz}$$

The system impulse response with PSS gain of 15 per unit is shown on figure 7a. The PSS provides

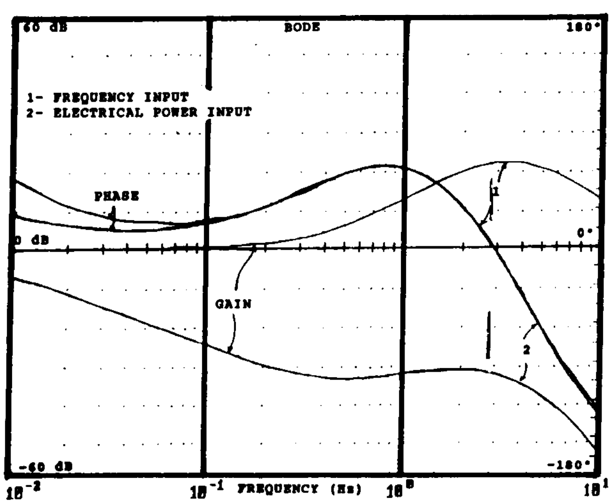


Figure 5.-Signal conditioning frequency responses, case 1 (without 90° phase shift).

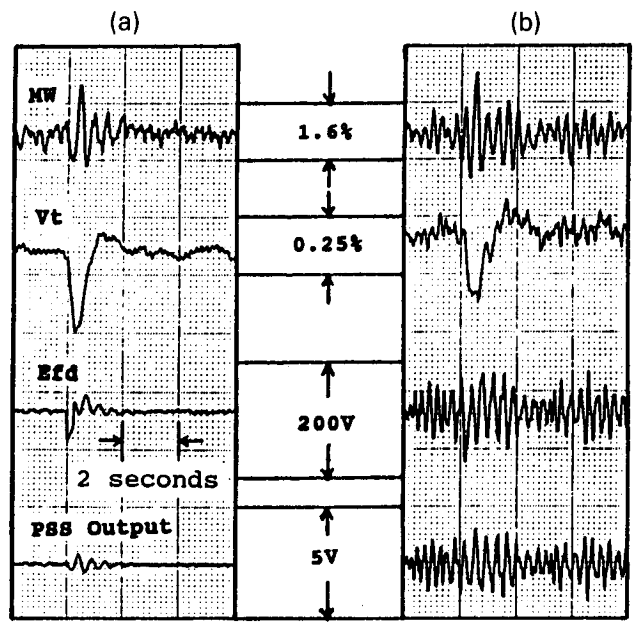


Figure 6.-Impulse response with internal frequency PSS, field test data: (a) PSS gain = 1.5 pu, and (b) PSS gain = 2.5 pu.

damping of the local mode oscillation while the PSS output shows a very small amplitude of high frequency noise.

During a load-change response test with the electrical power PSS, the PSS output went to its maximum limit as the load changed. The PSS output was disconnected from the regulator to prevent terminal voltage change. If it had been connected, the terminal voltage would have been forced to change by 10 percent. With these parameters, the PSS was too sensitive to a normal operator-effected load change.

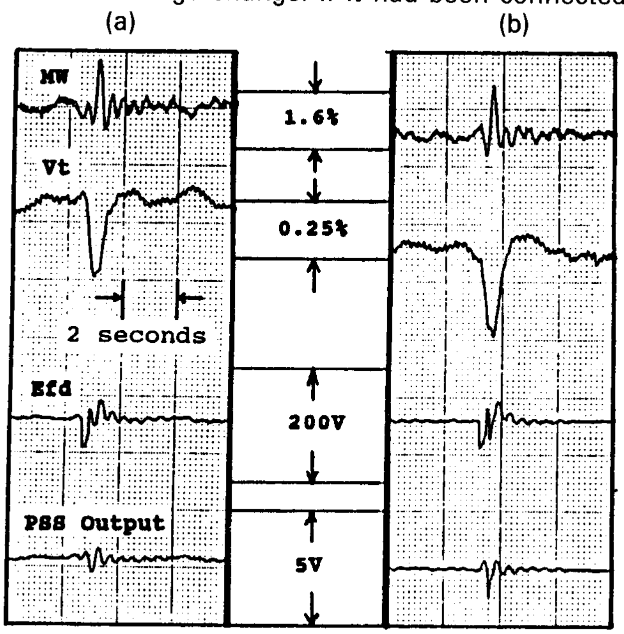


Figure 7.-Impulse response with PSS gain = 15 pu, field test data: (a) Electrical power PSS, and (b) Accelerating power PSS.

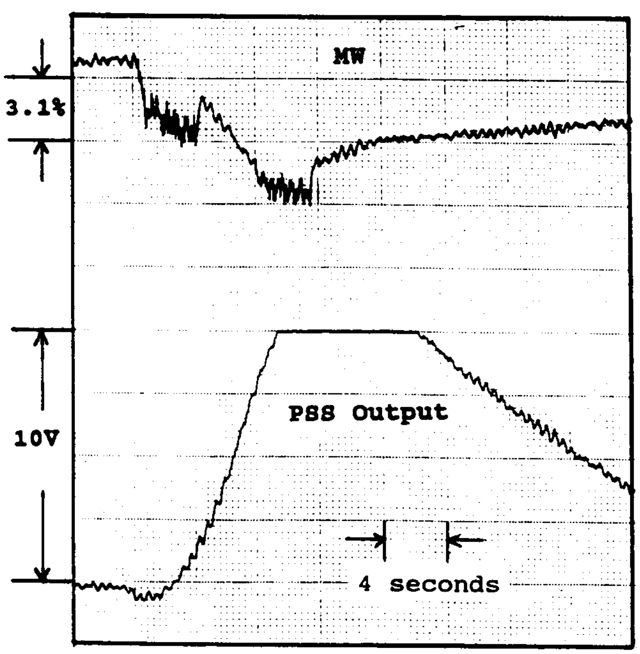


Figure 8.-Load change test with electrical power PSS.

Repeating the load-change test, with the value of T_p changed to a more traditional power type PSS value of 5 seconds, found the PSS still too sensitive, as shown on figure 8. In addition, if the value of T_p is less than 10 seconds (0.016 Hz), the PSS would be overcompensated at low frequency [7].

Accelerating Power Input PSS

The digital PSS was also used to implement the accelerating power PSS. The tuning concept used for an accelerating power PSS is similar to that used for an electrical power PSS; therefore, the parameters were set as follows:

$$T_p = 0.2\text{ s} \rightarrow 0.8\text{ Hz}$$
$$T_f = 0.2\text{ s} \rightarrow 0.8\text{ Hz}$$
$$M = 3.89$$

The lead/lag time constants were set the same as in the electrical power case.

The system impulse response with PSS gain of 15 per unit is shown on figure 7b. Again, PSS output noise amplitude is small while the local mode oscillation is well damped and the system is stable. The control system became unstable as the PSS gain was increased to 30 per unit as shown on figure 9.

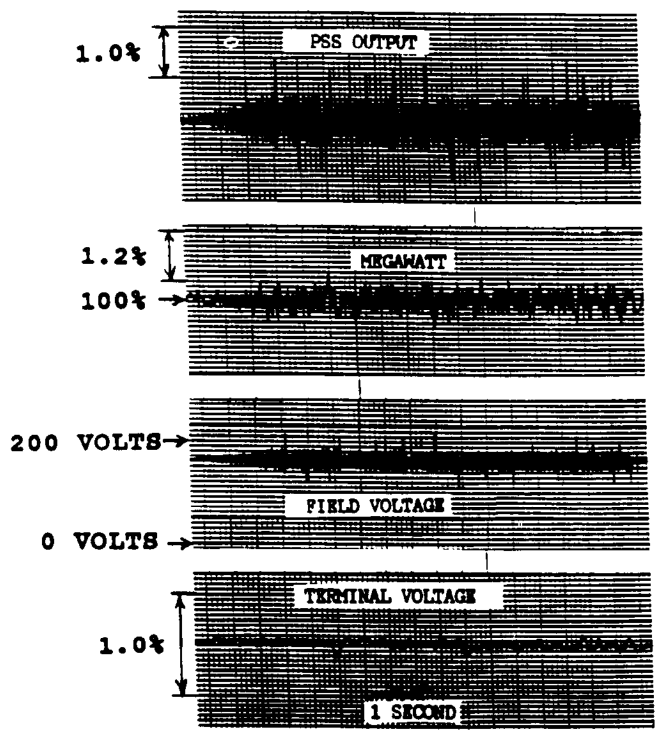


Figure 9.-Unstable system with accelerating power PSS, PSS gain of 30 pu.

The result of a load-change test with the accelerating power PSS is shown on figure 10. The PSS output changed slightly in response to a normal load change. The terminal voltage also changed slightly (less than 0.5 percent). Therefore, this type of PSS has low sensitivity to a normal load change.

Observations From Field Test Data

Noise in the megawatt signal prevented accurate extraction of the damping ratio from the field test data, preventing a direct comparison of the local mode damping performance of the three PSS types. However, an approximation can be made as follows.

At approximately the same damping ratio (from observation of field test data), the frequency PSS has a gain of about 2.0 per unit, while the power types PSS have a gain of about 15 per unit. However, if the gain of the signal conditioning stage and the machine inertia (*M*) are evaluated at the local mode frequency and taken into account, then the gain of the three PSS types from the speed signal to the PSS output is approximately the same for each corresponding damping ratio.

For frequency PSS, the signal conditioning gain is 18.6 dB at the local mode frequency, which is 8.5 per unit. Therefore, the overall gain for 1.8-Hz signals is 17 per unit (fig. 11).

For the power type PSS, the machine inertia block has a gain of 44 per unit at the local mode frequency (2 Hs) while the signal conditioning circuit has a gain of minus 31 dB, which is 0.0282 per unit.

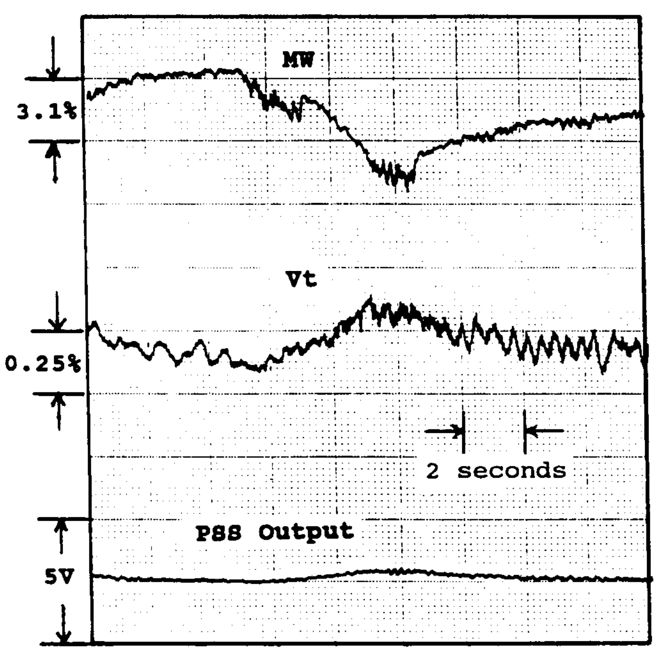


Figure. 10.-Load change test with accelerating power PSS.

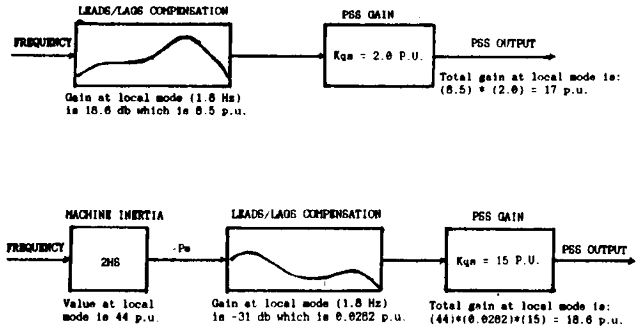


Figure 11.-Gain comparison.

Therefore, the overall gain for 1.8-Hz signals is 18.6 per unit (fig. 11) from an equivalent frequency input.

For a more accurate comparison of local mode damping performance, the following sections describe an analog computer simulation of these systems.

ANALOG COMPUTER SIMULATION

An analog computer was used to simulate unit 1 at Blue Mesa Powerplant as a single-machine-infinite-bus system. The simulation also included the accelerating power PSS algorithm shown on figure 2. Simulation was employed because: (1) the field data was embedded in noise, preventing direct retrieval of a root locus and (2) the digital PSS could not provide optimal signal conditioning.

Two major cases of analog computer simulation were examined. Each major case had three subcases for the three different PSS types. The first major case involved undercompensation of the signal conditioning. This case was simulated because the field test data was produced with undercompensation of the signal conditioning. This condition was caused by limitations of the PSS hardware used during field tests. The second case has optimum phase compensation of the signal conditioning. The second case study was necessary to study the optimum performance of the three PSS types.

Simulation Case 1: Field Test Compensation

Frequency Input PSS

To achieve the frequency response, as shown on figure 4 (field test data), the PSS time constants were set as follows:

$$\begin{aligned} T_q &= 30.0 \text{ s} \rightarrow 0.0053 \text{ Hz} \\ T_1 \;\&\; T_3 &= 0.3183 \text{ s} \rightarrow 0.5 \text{ Hz} \\ T_2 \;\&\; T_4 &= 0.05 \text{ s} \rightarrow 3.183 \text{ Hz} \end{aligned}$$

To exactly match the phase response shown on figure 4, one additional lead/lag pair with time constants, T_5 and T_6, and a low-pass filter with time constant, T_{c1}, were added to the signal conditioning. The analog computer model is shown in the appendix.

$$T_5 = 0.00796 \text{ s} \rightarrow 20.0 \text{ Hz}$$
$$T_6 = 0.03979 \text{ s} \rightarrow 4.0 \text{ Hz}$$
$$T_{c1} = 0.03979 \text{ s} \rightarrow 4.0 \text{ Hz}$$

Curve 1, on figure 12, is a bode plot of the unity-gain, open-loop compensated PSS control system (V_t/change in frequency). This open-loop system in block diagram form is shown on figure 13a. The bode plot shows that at the local mode frequency (1.8 Hz), the phase is about 70° lagging. This compensation is not optimum, but provides less than 90° phase lag. Therefore, the PSS will provide damping of the local mode oscillation. However, the damping is not maximized.

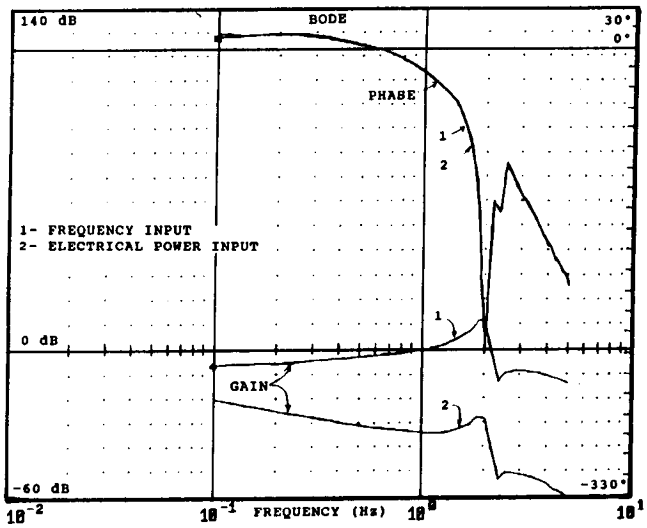


Figure 12.-Frequency responses with PSS open-loop compensation, case 1.

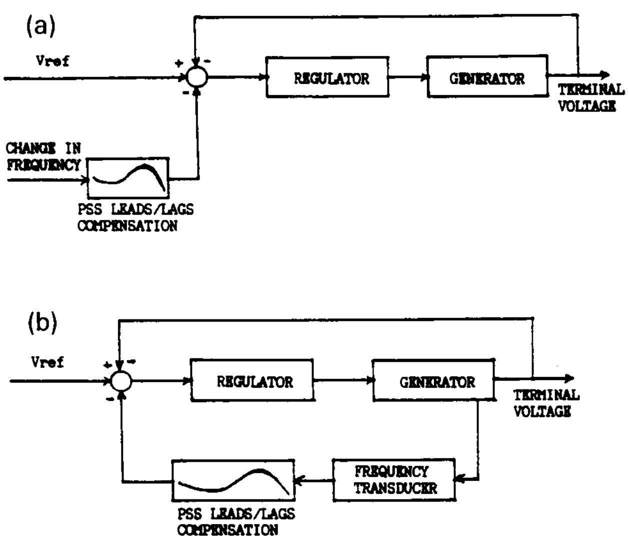


Figure 13.-Diagram of PSS compensation: (a) Open loop, and (b) Closed loop.

The local mode root locus with varying PSS gain is shown on figure 14, trace 1. This root locus curves up and turns to the right, as expected, because of system undercompensation. If the root locus goes straight to the left, the system is optimally compensated for the local mode root. If the root locus goes to the left and then curves down, the system is overcompensated. As the root locus goes to the right, the system will be less stable. The system will be unstable if the roots cross the jw-axis into the right half-plane.

The root locus indicates that the best damping ratio for this frequency PSS compensation comes with PSS gain of 1.9 per unit. Increasing gain with this compensation does not appreciably improve the damping ratio. Therefore, a different compensation should be chosen which produces less overall phase lag at the local mode (case 2).

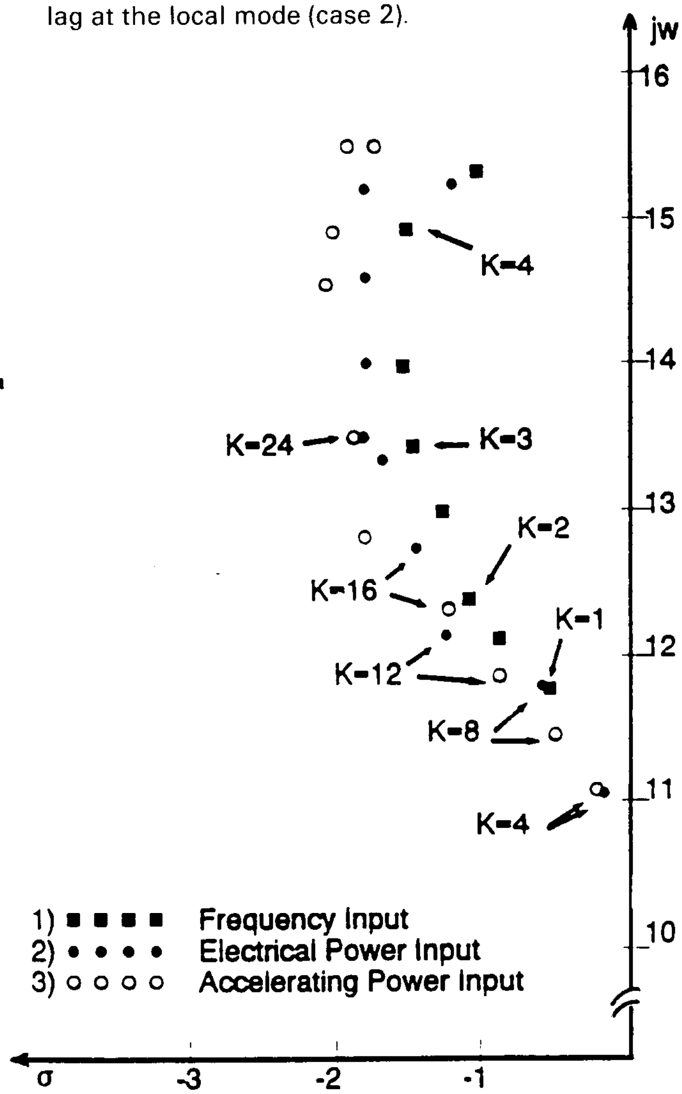


Figure 14.-Root locus with varying PSS gain, case 1.

Step responses without PSS and with PSS gains of 1.9 and 4.5 per unit are shown on figure 15. As in the field data case, the gain should be multiplied by 8.5 to obtain the overall gain at 1.8 Hz. Therefore, PSS gain of 1.9 pu results in a gain of 16 per unit for signals at this frequency.

Curve 2, on figure 16, is a bode plot of the closed-loop compensated frequency input PSS control system with PSS gain equal to 1.9 pu. The block diagram of this closed-loop control system is shown on figure 13b (V_t/V_{ref}). The bode plot shows that the local mode peak is damped with respect to the case without PSS (curve 1).

Electrical Power Input PSS

To achieve the frequency response, as shown on figure 4, the PSS time constants were set as follows:

$$
\begin{aligned}
M &= 0.0 \\
T_p &= 30.0 \text{ s} \rightarrow 0.0053 \text{ Hz} \\
T_1 &= 0.3183 \text{ s} \rightarrow 0.5 \text{ Hz} \\
T_2 &= 30.0 \text{ s} \rightarrow 0.0053 \text{ Hz} \\
T_3 &= 0.3183 \text{ s} \rightarrow 0.5 \text{ Hz} \\
T_4 &= 0.05 \text{ s} \rightarrow 3.183 \text{ Hz}
\end{aligned}
$$

(a) (b) (c)

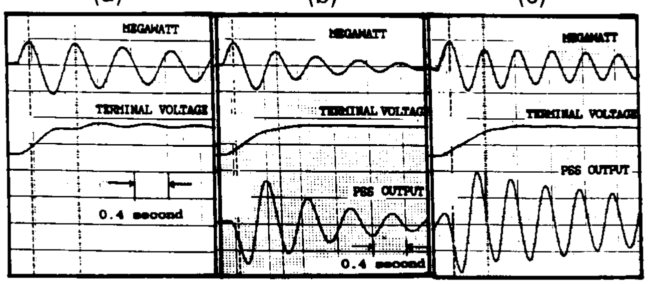


Figure 15.-Step response, case 1, with: (a) PSS off, (b) Frequency PSS, gain = 1.9 pu, and (c) Frequency PSS, gain = 4.5 pu.

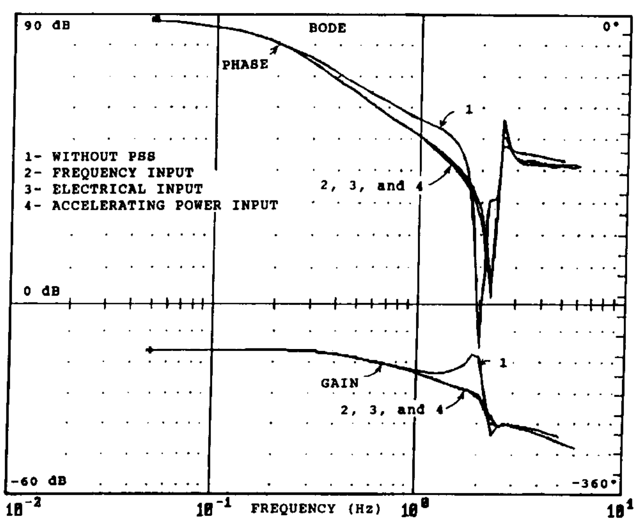


Figure 16.-Frequency responses with and without PSS, case 1.

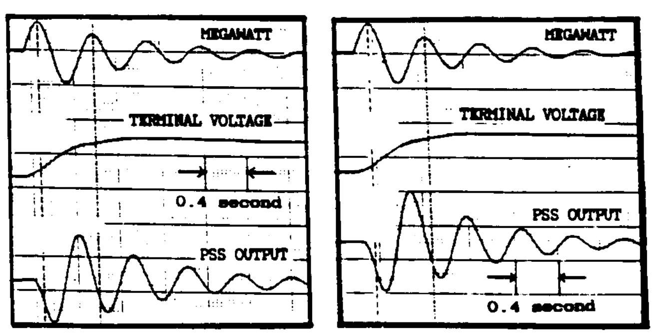
A third lead/lag pair (T_5, T_6) and three low-pass filters were added to exactly match the characteristics of the frequency input PSS. The time constants of these circuits were set as follows:

$$
\begin{aligned}
T_5 &= 0.00796 \text{ s} \rightarrow 20.0 \text{ Hz} \\
T_6 &= 0.03537 \text{ s} \rightarrow 4.5 \text{ Hz} \\
T_{c1} &= 0.03979 \text{ s} \rightarrow 4.0 \text{ Hz} \\
T_{c2} &= 0.03121 \text{ s} \rightarrow 5.1 \text{ Hz} \\
T_{c4} &= 0.03183 \text{ s} \rightarrow 5.0 \text{ Hz}
\end{aligned}
$$

The open-loop compensation phase responses of the electrical power and frequency PSS have the same shape but are 90° out of phase. Without the 90° phase shift, the shapes of the two open-loop compensation phase responses are about the same. Figure 12 was produced to illustrate this by subtracting 90° from the original electrical power PSS phase curve. The bode plot indicates that, at local mode frequency (1.8 Hz), the equivalent phase is about 70° lagging. This compensation is also not optimum, but will provide damping of the local mode oscillation.

The local mode root locus with varying PSS gain is shown on figure 14, trace 2. This root locus also curves up and turns to the right. The best damping ratio for this compensation is obtained with a PSS gain of 12 per unit. The step response with a PSS gain of 12 per unit is shown on figure 17a. As in the field data case, the gain should be multiplied by 44 and 0.0282 to obtain the overall gain at 1.8 Hz, thereby resulting in a gain of 15 per unit for signals at this frequency.

Curve 3, on figure 16, is a bode plot of the closed-loop compensated electrical power input PSS control system with a PSS gain of 12 per unit. The bode plot indicates that the local mode peak is damped with respect to the case without PSS. Also, it shows that the PSS control system has about the same damping factor as in the frequency input case (curve 2).



(a) (b)

Figure 17.-Step response with PSS gain = 12, case 1: (a) Electrical power PSS, and (b) Accelerating power PSS.

Accelerating Power Input PSS

The accelerating power PSS was adjusted with the same lead/lag time constants as in the electrical power case. The value of *M*, twice the machine inertia, was 3.89, while the values of T_f and T_p were 0.2 second.

The local mode root locus with varying PSS gain is shown on figure 14, trace 3. This root locus also curves up and turns to the right. Again, damping ratio is obtained with a PSS gain of 12 per unit. The corresponding step response is shown on figure 17b. The gain at 1.8 Hz for this PSS is the same as in the electrical power input case.

On figure 16, curve 4 is a bode plot of the closed-loop compensated accelerating power input PSS control system with a PSS gain of 12 per unit. The bode plot indicates that the local mode peak is damped with respect to the case without PSS and very similar to the other PSS input types.

Simulation Case 2: Optimum Phase Compensation

In this case, the parameters of the PSS signal conditioning were set so that the phase responses peaked at the local mode frequency. The peak value of about 85° was provided as shown on figure 18. The simulation of this second case was necessary to examine the optimum phase compensation performance of the stabilizers. Unfortunately, the apparatus used for the field test did not allow this option.

The concept of equivalent phase responses is again applied. That is the signal conditioning phase responses will have the same shape for all three PSS types. Since the electrical power and the accelerating power PSS have identical adjustment criteria, their signal conditioning phase responses will be the same. The phase responses of the frequency and power stabilizers are 90° out of phase, as shown on figure 18. Removing the 90° phase shift results in identical phase responses (above 0.1 Hz). This is shown on figure 19 by subtracting 90° from the original electrical power phase curve.

The signal conditioning frequency responses, for cases 1 and 2, with a frequency input PSS are shown on figure 20. Case 2 has more phase advance at local mode frequency. This will improve damping of the local mode oscillation. It also has higher gain at the high frequency end (3 to 60 Hz) which will produce larger noise amplitude at the PSS output.

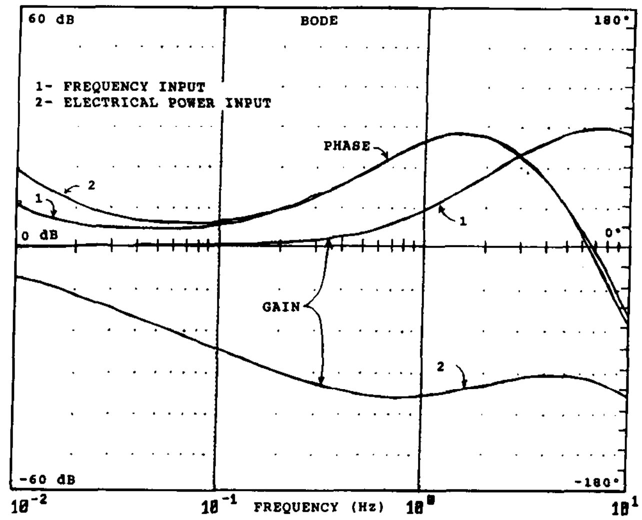


Figure 19.-Signal conditioning frequency responses, case 2 (without 90° phase shift).

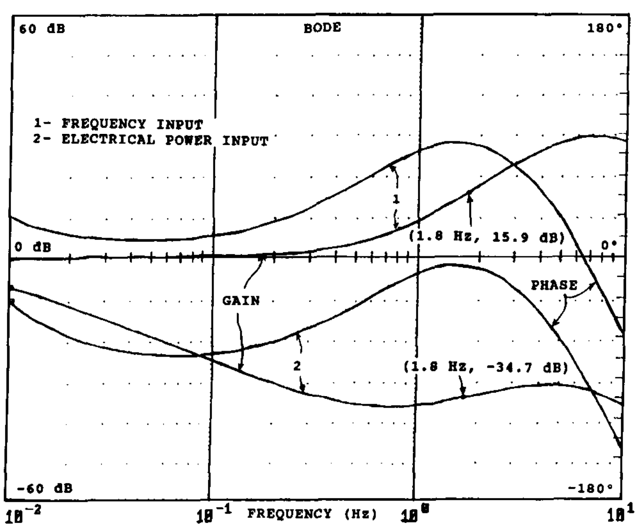


Figure 18.-Signal conditioning frequency responses, case 2.

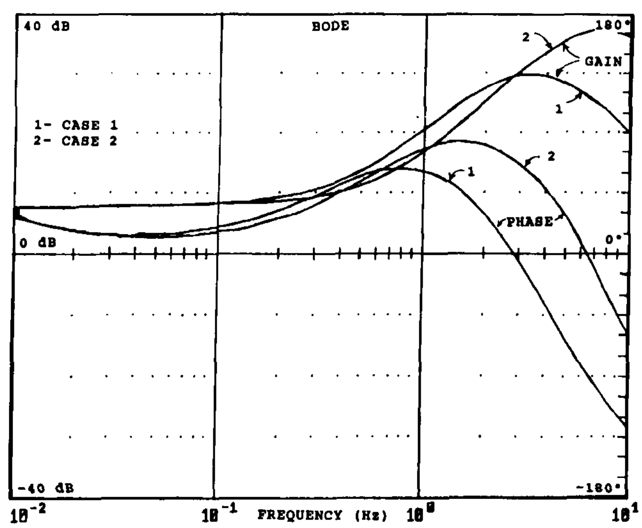


Figure 20.-Signal conditioning frequency responses with frequency PSS for cases 1 and 2.

Frequency Input PSS

To obtain the frequency response shown on figure 18, trace 1, the frequency PSS time constants were set as follows:

$$\begin{aligned}
T_f = M &= 30.0 \text{ s} \rightarrow 0.0053 \text{ Hz}\\
T_1 &= 0.2120 \text{ s} \rightarrow 0.75 \text{ Hz}\\
T_2 &= 0.0212 \text{ s} \rightarrow 7.5 \text{ Hz}\\
T_3 &= 0.2053 \text{ s} \rightarrow 0.775 \text{ Hz}\\
T_4 &= 0.0227 \text{ s} \rightarrow 7.0 \text{ Hz}
\end{aligned}$$

To be practical, as in real circuit design, high-frequency filters were added to the signal conditioning phase response. One came from implementation of a lead/lag pair with time constants of T_5 and T_6. Two others came from the addition of two low-pass filters with time constants of T_{c1} and T_{c3}.

$$\begin{aligned}
T_5 &= 0.007924 \text{ s} \rightarrow 20.0 \text{ Hz}\\
T_6 &= 0.018295 \text{ s} \rightarrow 8.7 \text{ Hz}\\
T_{c1} &= 0.015915 \text{ s} \rightarrow 10.0 \text{ Hz}\\
T_{c3} &= 0.015915 \text{ s} \rightarrow 10.0 \text{ Hz}
\end{aligned}$$

On figure 21, curve 1 is the bode plot of the unity-gain, open-loop compensated PSS control system. At the local mode frequency, the phase is about 15° lagging. This is a moderate phase compensation as V_t is much in phase with change-in-frequency in the frequency range of interest, 0.1 to 3 Hz. Therefore, this PSS compensation will have excellent damping of the local mode oscillation as well as damping of other system oscillation modes [7].

The local mode root locus with varying PSS gain is shown on figure 22, trace 1. This root locus goes straight to the left, indicating the system has optimal phase compensation for the local mode. To obtain optimal PSS gain, other system modes of oscillation must be considered. However, a PSS gain of 2.1 per unit was chosen for analysis and comparison. The corresponding step response is shown on figure 23a.

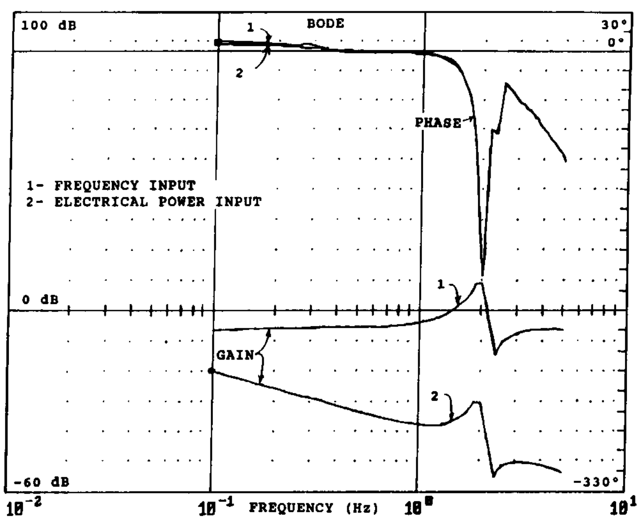


Figure 21.–Frequency responses with PSS open-loop compensation, case 2.

Again, for gain comparison with other PSS types, the signal conditioning gain should be considered. The compensation gain is 15.9 dB at the local mode frequency, which is a gain of 6.24 per unit. Therefore, the overall gain evaluated at 1.8 Hz is 13.1 per unit.

On figure 24, curve 2 is the bode plot of the closed-loop compensated PSS control system with a PSS gain of 2.1 per unit. This figure shows that the local

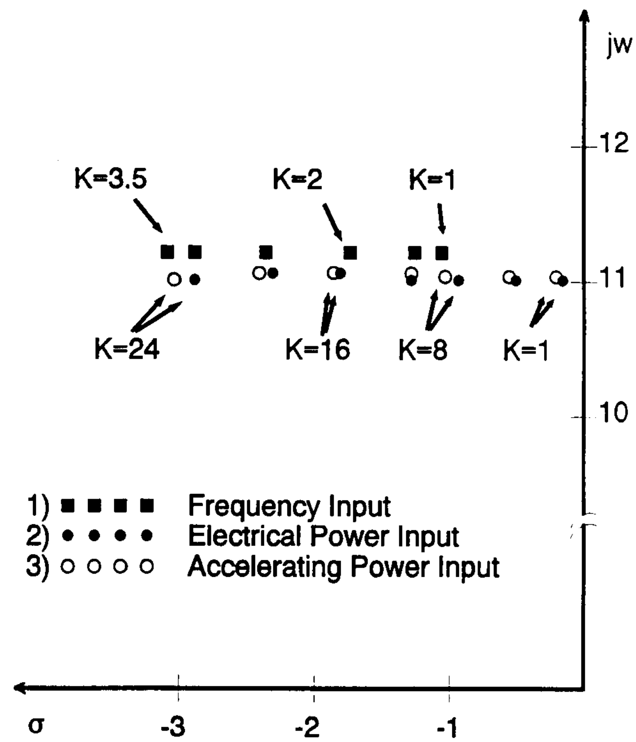
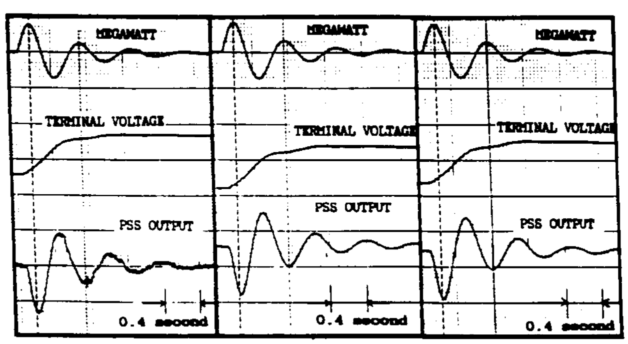


Figure 22.–Root locus with varying PSS gain, case 2.



(a) (b) (c)

Figure 23–Step responses, case 2, with: (a) Frequency PSS, gain = 2.1 pu, (b) Electrical power PSS, gain = 16 pu, and (c) Accelerating power PSS, gain = 16 pu.

mode peak is very well damped with respect to the case without PSS (curve 1).

Figure 25 indicates that as the PSS gain increases, the magnitude of high frequency noise at the PSS output also increases. If the magnitude of the noise is high enough, it is coupled into the regulator and reproduced in generator terminal voltage and generator megawatts. The PSS gain of 2.1 per unit is the gain that is a good compromise between the MW swing damping (local mode damping) and PSS output noise. In actual field environment, the noise is typically much larger and may restrict PSS gain to a lower level.

Electrical Power Input PSS

To obtain the frequency response shown on figure 18, trace 2, the PSS time constants were set as follows:

$$M = 0.0$$
$$T_p = 30.0 \text{ s} \rightarrow 0.0053 \text{ Hz}$$

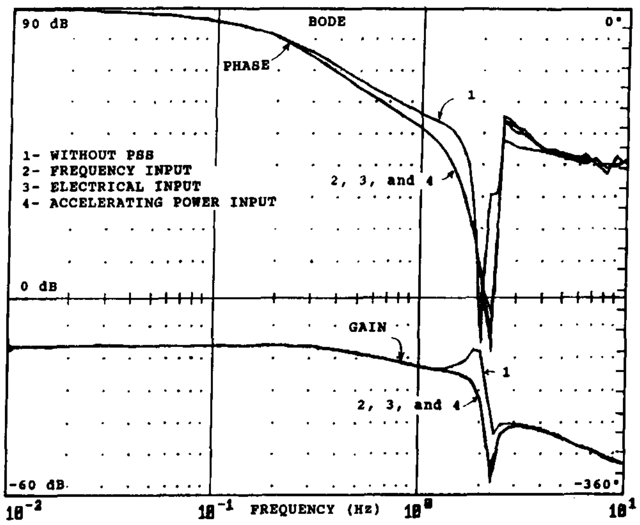


Figure 24.–Frequency responses with and without PSS, case 2.

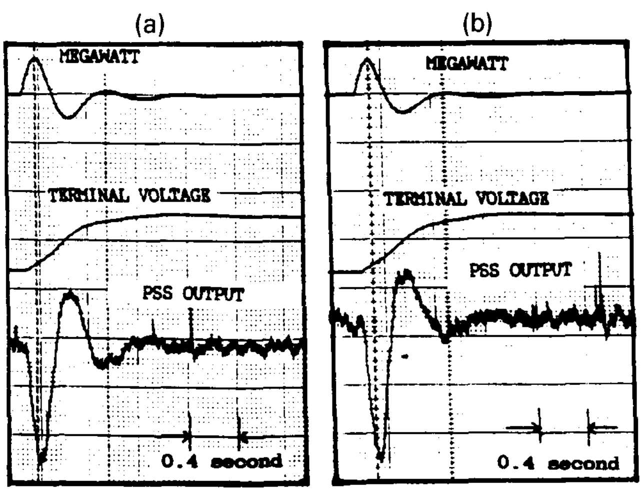


Figure 25.–Step response with frequency PSS, case 2: (a) PSS gain = 4.0 pu, and (b) PSS gain = 5.0 pu.

$$T_1 = 0.20536 \text{ s} \rightarrow 0.775 \text{ Hz}$$
$$T_2 = 30.0 \text{ s} \rightarrow 0.0053 \text{ Hz}$$
$$T_3 = 0.20536 \text{ s} \rightarrow 0.775 \text{ Hz}$$
$$T_4 = 0.02274 \text{ s} \rightarrow 7.00 \text{ Hz}$$

Four additional phase lag circuits were added to exactly match the characteristic of the frequency PSS. One came from implementation of a lead/lag pair with time constants of T_5 and T_6. Three others came from three low-pass filters with time constants of T_{c1}, T_{c2}, and T_{c4}.

$$T_5 = 0.002274 \text{ s} \rightarrow 20.0 \text{ Hz}$$
$$T_6 = 0.018294 \text{ s} \rightarrow 8.7 \text{ Hz}$$
$$T_{c1} = 0.015915 \text{ s} \rightarrow 10.0 \text{ Hz}$$
$$T_{c2} = 0.01384 \text{ s} \rightarrow 11.5 \text{ Hz}$$
$$T_{c4} = 0.01384 \text{ s} \rightarrow 11.5 \text{ Hz}$$

As in the other cases, the open-loop compensation phase responses of the electrical power and frequency PSS have the same shape but are 90° out of phase. This is shown on figure 21 by subtracting 90° from the original electrical power PSS phase curve. The bode plot shows that at the local mode frequency, the phase is about 15° lagging. With the 90° phase shift, V_t should lag P_e about 105° at the local mode frequency. This is a moderate phase compensation as V_t is very close to 90° phase lag of P_e in the frequency range of interest, 0.1 to 3.0 Hz. Therefore, a control system with this PSS will have excellent damping of the local and other system oscillation modes.

The local mode root locus with varying PSS gain is shown on figure 22, trace 2. This root locus also goes to the left as the PSS gain increases. To achieve the same damping ratio as in frequency input case, the electrical power PSS requires a gain of about 16 per unit. The corresponding step response is shown on figure 23b.

For gain comparison, the signal conditioning gain and machine inertia should again be considered. At the local mode frequency, the compensation gain is minus 34.7 dB, which is 0.0184 per unit, and the machine inertia gain is about 44 per unit. Therefore, the overall gain evaluated at 1.8 Hz is 13.0 per unit.

On figure 24, curve 3 is the bode plot of the closed-loop compensated PSS control system with a PSS gain of 16 per unit. This shows that the local mode peak is well damped. It also shows that the PSS control system has about the same damping factor as in the frequency input case.

Accelerating Power Input PSS

To achieve the same compensation as in the electrical power input case, the PSS parameters were set as follows:

$$M = 3.89$$
$$T_f = 0.2 \text{ s} \rightarrow 0.8 \text{ Hz}$$
$$T_p = 0.2 \text{ s} \rightarrow 0.8 \text{ Hz}$$
$$T_1 - T_6,\ T_{c1},\ T_{c2},\ T_{c4} = \text{same as } P_e \text{ input case}$$

The local mode root locus with varying PSS gain is shown on figure 22, trace 3. This root locus also goes to the left as the PSS gain increases. To achieve the same damping ratio as in the electrical power case, the accelerating power PSS also requires a gain of about 16 per unit. The corresponding step response is shown on figure 23c. The gain comparison for this PSS is the same as in the electrical power case.

On figure 24, curve 4 is the bode plot of the closed-loop compensated PSS control system with a PSS gain of 16 per unit. This shows that the local mode peak is damped. It also shows that the PSS control system has about the same damping factor as in the electrical power and frequency input cases.

BIBLIOGRAPHY

[1] Schleif, F. R. and J. H. White, "Damping for the Northwest-Southwest Tie Line Oscillations—An analog study," IEEE Transactions on Power Apparatus and System, vol. PAS-85, pp. 1239-1246, December 1966.

[2] Schleif, F. R., G. E. Martin, and R. R. Angell, "Damping of System Oscillations With a Hydrogenerating Unit," IEEE Transactions on Power Apparatus and System, vol. PAS-86, pp. 438-442, April 1967.

[3] Schleif, F. R., H. D. Hunkins, E. E. Hattan, and W. B. Gish, "Control of Rotating Exciters for Power System Damping: Pilot Applications and Experience," IEEE Transactions on Power Apparatus and System, vol. PAS-88, pp. 1259-1266, August 1969.

[4] Larsen, E. V. and D. A. Swann, "Applying Power System Stabilizers, IEEE Transactions on Power Apparatus and Systems, vol. PAS-100, pp. 3017-3041, June 1981.

[5] de Mello, F. P., L. N. Hannett, and J. M. Undrill, "Practical Approaches to Supplementary Stabilizing From Accelerating Power," IEEE Transactions on Power Apparatus and Systems, vol. PAS-97, pp. 1515-1522, September/October 1978.

[6] IEEE Tutorial Course, "Power System Stabilization via Excitation Control," Sponsored by IEEE Power Engineering Education Committee and the Excitation System Subcommittee of the Power Generation Committee, IEEE Service Center, Piscataway NJ.

[7] Kundur, P., M. Klein, G. J. Rogers, and M. S. Zywno, "Application of Power System Stabilizers for Enhancement of Overall System Stability," IEEE Transactions on Power Systems, vol. 4, May 1989.

[8] Bollinger, K. E., W. Gu, and E. Norum, "Accelerating Power Versus Electrical Power as Input Signals to Power System Stabilizers," IEEE Transactions on Energy Conversion, vol. 6, pp. 620-626, December 1991.

APPENDIX A

The analog computer simulation has three main parts. The first part is the regulator (excitation system model). It is shown on figure A-1. The regulator model includes the following functions:

- Terminal voltage feed back (V_t) and its transducer pole
- A summing junction
- A transient gain reduction (*TGR*)
- A bridge pole
- A regulator pole
- A regulator gain K_a
- A switch for auto/manual regulator

The second part is shown on figure A-2. It consists of the machine D- & Q-axis, swing equation, and infinite bus models. The machine D- & Q-axis models also include the machine saturation curve. The saturation curve is modeled backward and upside down. The input is the equivalent terminal voltage (10 volt per unit), and the output is field voltage (2 volt per unit). When the output of A44 is zero, the output of A47 is 10 volts, and the input into F00 is zero per unit. When the output of A44 is 5 volts (one per unit), the output of A47 is zero volts, and the input into F00 is one per unit.

The swing equation and infinite bus models also have off-line and on-line switches, reference for mechanical power (load), and algebraic loop oscillation prevention. The algebraic loop is a loop that has only algebraic functions (no integration). Since the loop has high-frequency poles (from amplifiers) and the loop gain is high enough, the loop system will be unstable or oscillate. To prevent the instability or oscillation, a filter is added in the loop. This filter will reduce the loop gain at high frequency to prevent the instability or oscillation situations.

The third main part of the simulation is shown on figure A-3. It consists of the PSS model and electrical power model. The PSS model is based on the block diagram shown on figure 2 in the text. The PSS gain is the value of the potentiometer 37. One per unit gain corresponds to a value of 0.05; two per unit gain corresponds to a 0.1 value.

The electrical power input was implemented with an electrical power deviation signal because changing the per unit value of P_e from 2.5 volt per unit to 50 volt per unit would saturate the analog computer amplifiers. Therefore, a constant d-c voltage was subtracted from the electrical power signal to create the power deviation signal.

Machine saturation curve data is shown on figure A-2. These data represent the saturation of unit 1 at Blue Mesa Powerplant.

The parameters of unit 1 at Blue Mesa Powerplant are as follows:

$$X_d = 1.515 \qquad X'_d = 0.53 \qquad X''_d = 0.43$$
$$X_q = 1.02 \qquad X''_q = 0.46 \qquad X_l = 0.34$$
$$T'_{do} = 5.9 \qquad T''_{do} = 0.05 \qquad T''_{qo} = 0.095$$
$$M = 2H = 3.89$$

The parameters of the excitation system of unit 1 at Blue Mesa powerplant are as follows (IEEE type ST1):

$$K_a = 200 \qquad T_a = 0.042$$
$$T_b = 2.4 \qquad T_c = 0.55$$

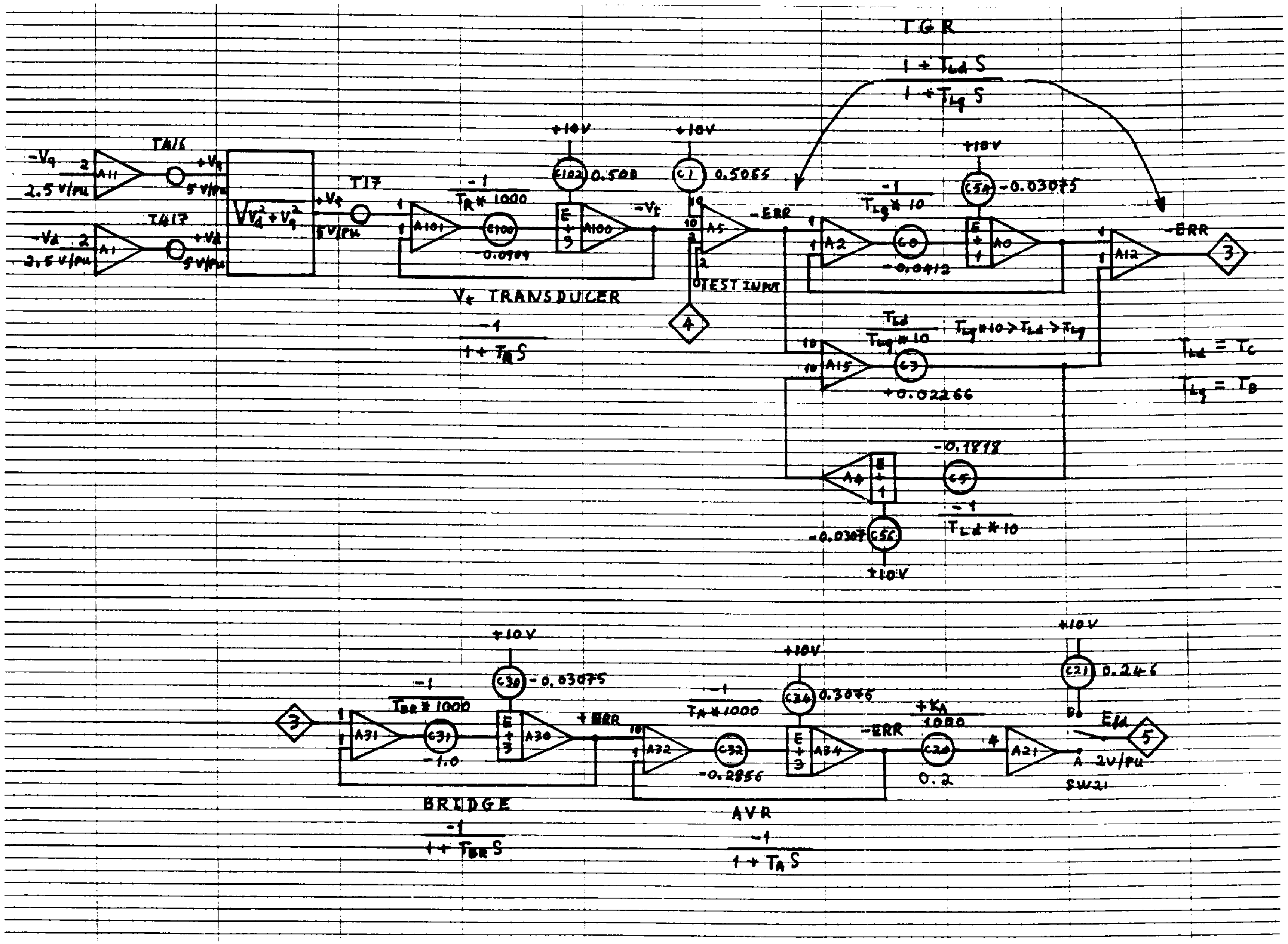
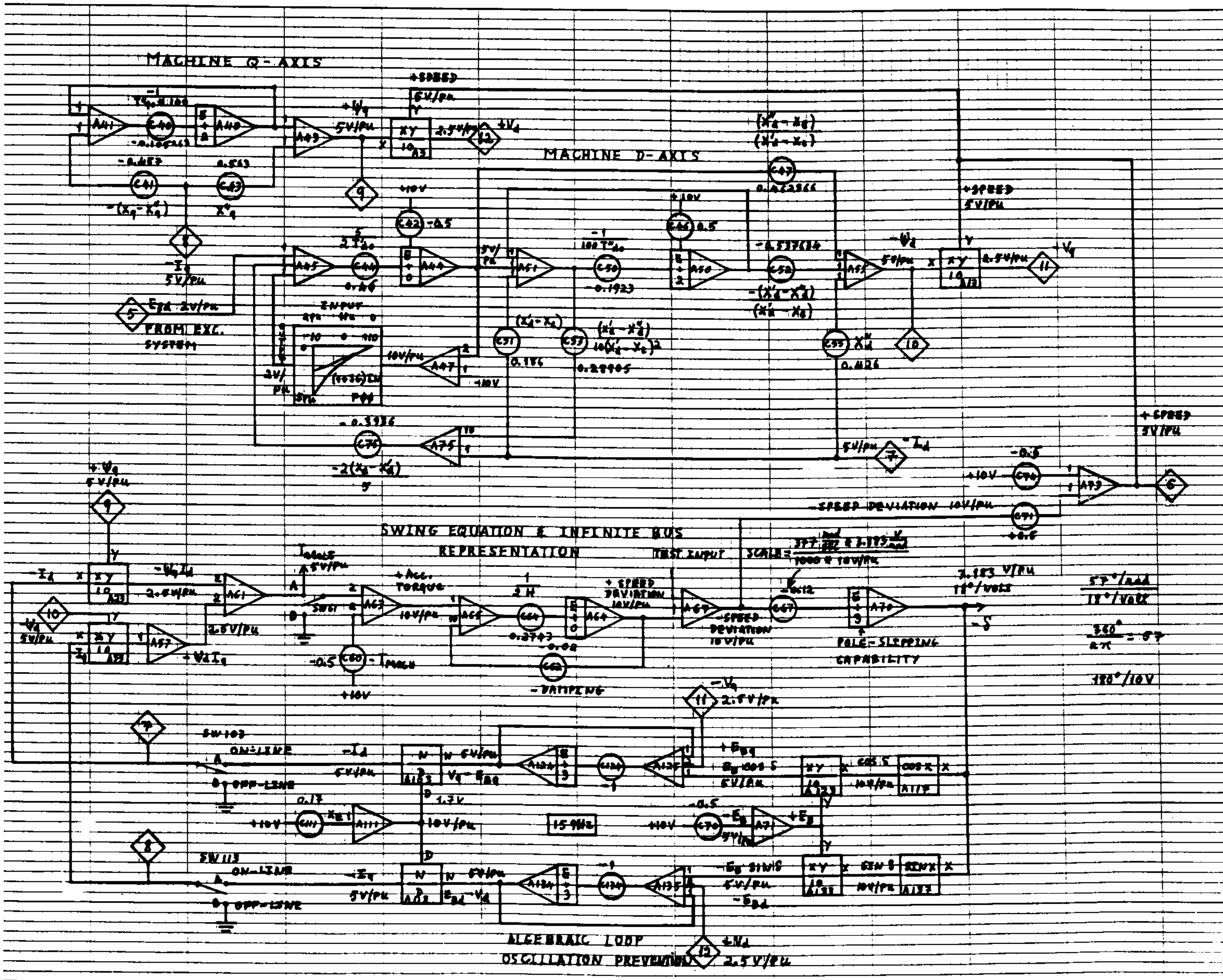


Figure A-1. - Excitation system model.



F 00 (SATURATION CURVE)

DSFG 00

01	-1.0000
02	-1.0000
03	-1.0000
04	-1.0000
05	-1.0000
06	-1.0000
07	-1.0000
08	-1.0000
09	-1.0000
10	-1.0000
11	-1.0000
12	-1.0000
13	-1.0000
14	1.0000
15	-0.7600
16	-0.5600
17	-0.4300
18	-0.3540
19	-0.3080
20	-0.2740
21	-0.2460
22	-0.2250
23	-0.2060
24	+0.1900
25	-0.1760
26	-0.1630
27	-0.1520
28	-0.1400
29	-0.1280
30	-0.1160
31	-0.1050
32	-0.0940
33	-0.0800
34	-0.0700
35	-0.0600
36	-0.0500
37	-0.0400
38	-0.0300
39	-0.0200
40	-0.0100
41	+0.0000

Figure A-2. - Machine D&Q, swing equation, and infinite bus models.

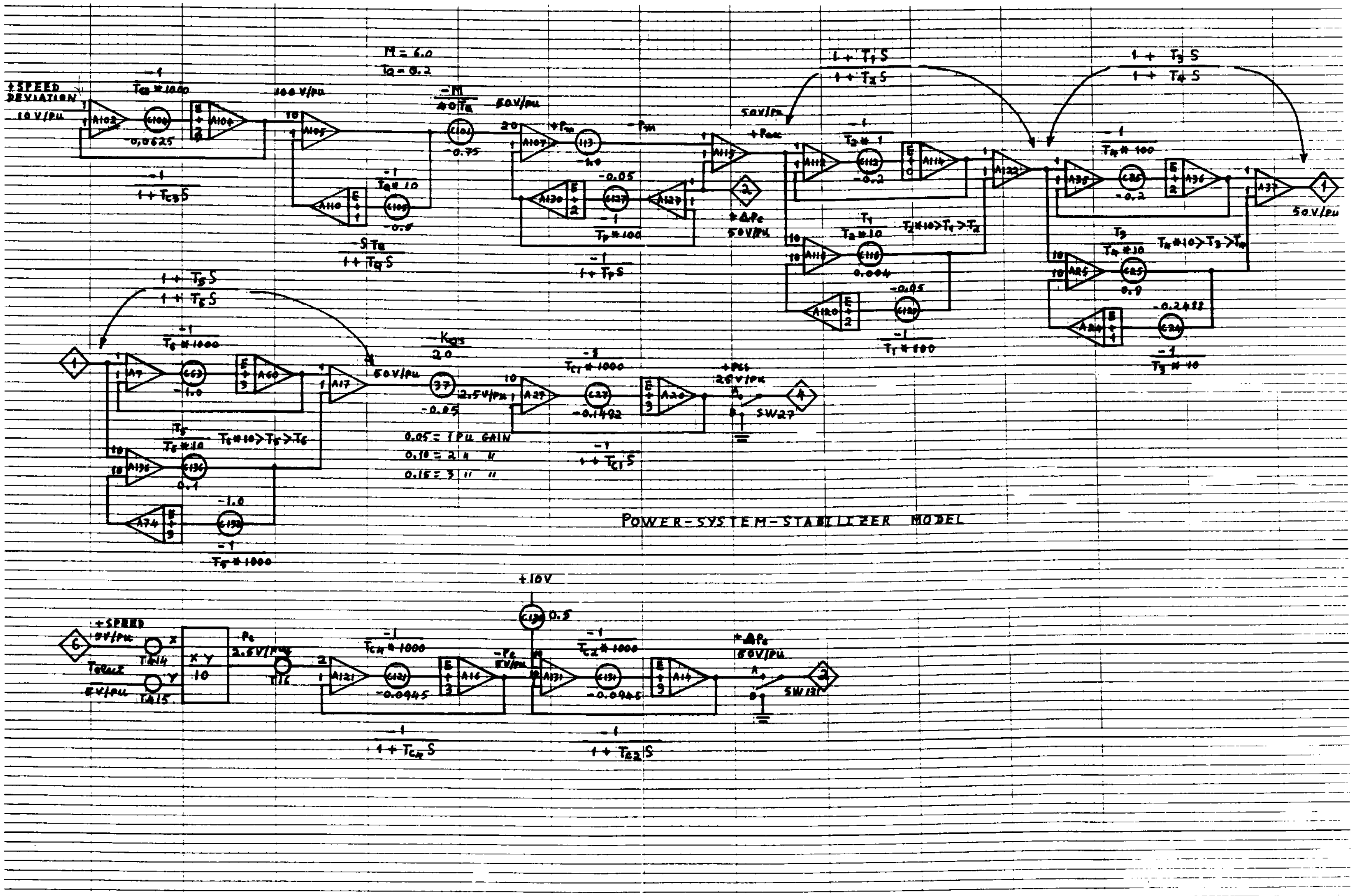


Figure A-3. – Power system stabilizer model.

☆ U.S. GOVERNMENT PRINTING OFFICE 1992: 673-185/60,013 REGION NO. 8