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WECC Guideline:

Criteria to Determine Excitation System Suitability for PSS in WECC System

Date: 1/20/1993

Introduction

This guideline provides instructions regarding how to determine if an excitation system is suitable for a power system stabilizer.

Approved By:

Approving Committee, Entity or Person	Date
WECC Technical Studies Subcommittee	January 20, 1993

CRITERIA TO DETERMINE EXCITATION SYSTEM SUITABILITY FOR PSS IN WSCC SYSTEM

REPORT PREPARED BY

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December 17, 1992

(This report was approved by Technical Studies Subcommittee at Meeting #100 in San Diego, California on January 20, 1993)

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1.0 PURPOSE

In evaluating the list of machines 75 MVA and above that are not equipped with Power System Stabilizers (PSS), WSCC System Review Work Group (SRWG) encountered some WSCC members who reported that their exciters were "not fast enough" to warrant installation of PSS. The "not fast enough" terminology raised questions regarding the need for a definitive criterion to address whether or not an excitation system is fast enough to be suitable for PSS. The Modelling Working Group (MWG) was given the assignment to develop a criterion to assess whether an excitation system is fast enough for PSS installation. This report presents the results of the investigation.

2.0 CONCLUSIONS AND RECOMMENDATIONS

2.1 Conclusions

The combination of the generator, the excitation system, and the power system (GEP) to which the generator is connected is considered to be too slow to justify PSS installation if the closed loop GEP phase lag between machine terminal voltage and voltage regulator reference input ($\partial E_t/\partial E_{ref}$) exceeds that of the following third order benchmark system in the frequency range of interest (0.1 to 1.0 Hz).

$$T(S) = \frac{(6.28)^3}{(S+.628)(S+6.28)(S+62.8)} \qquad (1)$$

The magnitude and phase of the benchmark system are shown in Figure 1. The benchmark system has a phase lag of 135° at 1.0 Hz.

Conversely, if the phase lag of GEP is less than that of the benchmark system in the frequency range of interest, the generator should be considered suitable for PSS that is, if GEP phase lag curve falls above T(s) phase lag curve in Figure 1, then the generator is considered suitable for PSS.

It should be noted that PSS suitability of the generator based upon the above criteria does not necessarily justify PSS installation irrespective of the cost. There are several other factors such as size of the unit, capacity factors and cost of retrofitting which should be given due consideration.

2.2 Recommendations

The modelling work group recommendations are as follows:

1. All existing generators of 75 MVA or larger should be considered for PSS.
2. All new machines with continuously acting voltage regulators should be considered for PSS.
3. If the phase lag of $\partial E_t/\partial E_{ref}$ (closed loop) is larger than the phase lag of the benchmark system defined by equation (1), then the combined system (GEP) is considered to be too slow for PSS installation. Conversely, if the combined system phase lag is less than that of the benchmark, the combined system is judged suitable for PSS considerations.
4. The frequency range of interest for PSS suitability considerations is from 0.1 Hz to 1.0 Hz.
5. The phase lag of the GEP should be either directly measured or should be calculated from programs such as EPRI's Small Signal Stability Program (SSSP). The measured data is preferable whenever possible.

3.0 BACKGROUND

- PSS is needed to neutralize the negative damping action of voltage regulators.

- High gain, fast acting voltage regulators create negative damping, but the same voltage regulators are also most suitable for PSS.

- High gain and fast acting are relative terms. There is no precise definition. IEEE Standards 421.2-1990 defines the high initial response system.

- High initial response systems are defined as those with voltage response time of 0.1 or less.

- Ignoring the precise definition, a high initial response or a fast acting excitation system is that where generator main field can reach its maximum value within 0.1 seconds of demand.

- The 0.1 seconds is not a hard limit and many exciters with larger response time are generally fast enough for PSS purposes.

- Examples of <u>very fast</u> acting excitation systems are:
  Static excitation systems
  ALTHYREX excitation systems

In these systems, the voltage regulator is used to control the firing angle of thyristors. There is negligible delay in reaching the desired field voltage.

- Examples of <u>fast</u> acting excitation systems are:
  Westinghouse brushless excitation systems
  General Electric SCPT excitation systems.
  In these regulators, an additional time constant of alternator is involved. The voltage regulator controls excitation of the alternator which, in turn, controls the main generator field.

- Examples of relatively <u>slow</u> excitation systems are:
  Amplidyne regulator excitation systems
  MAG-A-STAT regulator excitation systems
  These systems are comprised of at least two additional time constants other than the generator main field time constant. The frequency response is characterized by steep phase and gain decay past 1 to 2 Hz range. Generally, these systems do not create any significant undamping due to voltage regulator action.

4.0 STUDY RESULTS

Industry experts were contacted and a limited literature review was conducted to find if there exists any such criteria which can define an excitation system's suitability for PSS. No such criteria was found.

- WSCC's interest in PSS is primarily for the damping of low frequency intertie mode in the frequency range of 0.1 Hz to 1.0 Hz. PSS on almost any excitation system (slow or fast) can contribute some positive damping at these low frequency modes when PSS is tuned properly.

- Effective damping contribution of PSS depends upon many factors in addition to the type of excitation system. Some of these are:
  - Unit size (MVA)
  - Unit inertia (H)
  - Type of PSS signal (speed, frequency, accelerating power)
  - Frequency of oscillations
  - Location of the unit in the interconnected system

- A more appropriate question would be how effective a PSS is effective enough to justify the cost. In other words, how much positive damping should it contribute for it to be cost effective.

- An individual unit contributes very little to the overall damping of intertie mode. It is practically impossible to determine the incremental damping using time simulation stability studies.

- A more appropriate tool to determine the incremental contribution to the damping is an eigenvalue study. Even then, the incremental damping due to PSS on a unit is generally a very small number due to large interconnected system and depends heavily on the system and loads represented.

4.1 Absolute Damping

To establish uniformity of criteria, the damping calculations are made on two benchmark systems shown in Figure 2. Most eigenvalue studies were conducted using the benchmark system #1 of Figure 2 with the parameters listed below.

- Unit MVA varied from 50 to 1000
- Unit Inertia Constant (H) varied from 1 to 3
- Type of PSS input signal (speed, frequency)
- Type of exciter (AC4, DC1)
- System Inertia

These study results are tabulated in Table 1.

The absolute damping from Table 1 have been plotted in Figures 3a to 3d as a function of unit inertia and unit MVA. It is seen that PSS contribution to damping varies greatly as a function of many of the factors listed above.

4.2 Relative Damping

In an effort to reduce the variation of PSS damping contribution, a new method called Relative Damping Contribution (RDC), was used to study PSS suitability. Relative damping contribution is relatively independent of the size and inertia of the interconnected system and is a measure of the relative contribution of the PSS on the study unit. RDC is defined as follows:

$$RDC = \Delta\sigma_{abs} \times \frac{E_{sys} + E_{unit}}{E_{unit}}$$

Where $\Delta\sigma_{abs}$ = Change in damping of the intertie mode due to PSS (rad/s)
E_{sys} = Stored energy (MWS) of the system not including the study unit.
E_{unit} = Stored energy (MWS) of the study unit.

- Figure 4a shows impact of unit MVA with inertia constant "H" fixed at 3 pu. Three curves are shown for different input signals and different type of exciters. RDC for some is seen to decrease, for others, seen to increase and for yet others stay relatively constant with unit size. The RDC varies from a high of .07 rad/s to a low of .03 rad/s.

- Figure 4b shows the impact of unit inertia constant "H" on RDC for various parameters. In each case, the inertia is seen to have a significant impact on RDC. The smaller the inertia, the smaller is RDC. The graph suggests that PSS may not be cost effective on units with relatively small inertia.

- Figure 4c shows the impact of varying study machine inertia with system inertia reduced to 1/4 of the benchmark case value. The oscillation frequency doubles to around 0.85 Hz and the RDC values are much larger than those in Figures 4a and 4b. The increased RDC values are due to increased effective PSS gain at the higher oscillation frequency. The 0.44 Hz frequency case RDC values from Figure 3 are also shown for comparison.

- Selected eigenvalue studies were also conducted using the Benchmark System #2 in Figure 2. Once again, inertia was varied. Surprisingly, for this system, the RDC values are much larger than for the Benchmark System #1 and the RDC values reduce with increased inertia. These results are shown graphically in Figure 4d and are tabulated in Table 1.

Based upon study results summarized above, it is concluded that RDC values vary greatly depending upon the system and its inertia, excitation system and type of PSS input signal.

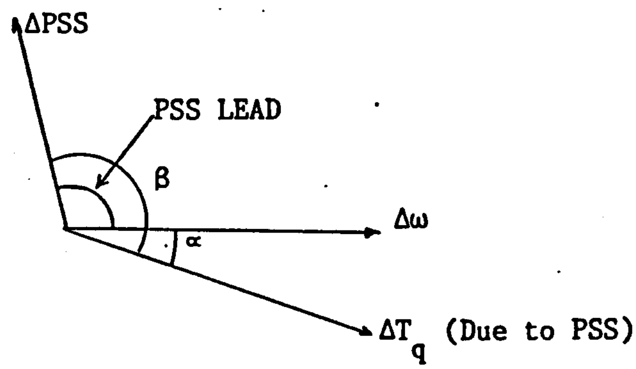
4.3 Phase Lag Criteria

A much simpler approach of determining the PSS suitability based upon phase lag of GEP (generator excitation system and the power system combined) was investigated. The combined system closed loop transfer function which PSS has to work through is denoted as GEP(s) and is discussed in detail in Reference 1. GEP(s) is given by:

$$GEP(s) = \frac{K_2}{K_6}\left(\frac{\partial E_t}{\partial E_{ref}}\right)$$

E_t is the generator terminal voltage and E_{ref} is the voltage regulator reference input. K_2 and K_6 are constants and depend upon the operating point (generator loading and system strength). K_2 and K_6 are constants for a given unit loading and the power system.

For PSS to be effective, it must overcome the phase lag of $\partial E_t/\partial E_{ref}$ in the frequency range of interest (0.1 to 1.0 Hz). A typical second order PSS frequency response is shown in Figure 5. It produces a peak phase compensation of 110° for lead-lag ratio of 10. A more typical value is a lead-lag ratio of 6 with a peak phase compensation of 100° The phasor diagram below shows the relationship between various quantities of interest. For practical purposes, the phase between PSS input signal (ΔPSS) and torque due to PSS (ΔT_q) is the same as that between ΔE_{Ref} and ΔE_t (Ref. 1). For typical speed or frequency input PSS, the PSS signal would usually provide 90° to 100° lead represented by the phasor ΔPSS as shown in the phasor diagram below.



The angle β represents lag of $\partial E_t/\partial E_{ref}$ and positions the torque component due to PSS input. For most effective PSS, ΔT_q should be in phase with $\Delta\omega$. However, reasonable effective damping may still occur as long as the angle α is less than 45°. For α greater than 45° PSS effectiveness starts to reduce fast. It would thus be reasonable to say that for PSS to be effective, the phase lag between ΔT_q and ΔPSS which is the same as the phase of $\partial E_t/\partial E_{ref}$ should be less than 135°.

One complication to this simple approach is that both PSS(s) and $\partial E_t/\partial E_{ref}$ phase lags are functions of frequency. Thus, specifying phase at one given frequency may be too simplistic. Since our highest frequency of interest for PSS application is 1.0 Hz, it would be reasonable to propose a maximum phase lag of 135° at 1.0 Hz.

A simple third order transfer function with corner frequencies at 0.1, 1.0 and 10.0 Hz is used as a benchmark for determining PSS effectiveness. The transfer function is shown on next page and its frequency response is shown in Figure 1.

$$T(s) = \frac{(6.28)^3}{(S+.628)(S+6.28)(S+62.8)} \quad (1)$$

The proposed criteria is as follows:

> If the phase lag of $\partial E_t/\partial E_{ref}$ (closed loop) is larger than the phase lag of the benchmark system defined by equation (1), then the combined system is considered to be too slow for PSS installation. Conversely, if $\partial E_t/\partial E_{ref}$ phase lag is less than that of the benchmark, the combined system is judged suitable for PSS considerations.

The main advantage of such a criteria is that it is very simple to understand and apply. $\partial E_t/\partial E_{ref}$ can be easily measured or can be calculated using program such as EPRI's Small Signal Stability program (SSSP). The main disadvantage of this approach is that unlike previously discussed methods, it does not give any quantitative answer to PSS effectiveness.

4.4 Application of Phase Lag Criteria

An example of how the criteria can be applied follows. A measured $\partial E_t/\partial E_{ref}$ for a 250 MVA unit with Westinghouse brushless exciter system in a strong system environment is compared with the proposed T(s) in Figure 6a. It is clearly seen that $\partial E_t/\partial E_{ref}$ phase lag is less than T(s) phase lag in the frequency range of interest (0.1 to 1 Hz). Thus, this system would be considered suitable for PSS. Notice that phase has a large dip near 1.6 Hz due to local mode. This is very typical for a heavily loaded unit and $\partial E_t/\partial E_{ref}$ phase lag at the local mode should not be used as a criteria for PSS.

Figure 6b compares $\partial E_t/\partial E_{ref}$ phase to T(s) phase for a relatively slow excitation system. Comparison indicates that this system is inferior to the benchmark because $\partial E_t/\partial E_{ref}$ phase lag exceeds T(s) phase lag in the frequency range of interest and, hence, the system will not be suitable for PSS.

The proposed criteria should not be considered as absolute. Actual frequencies of interest, PSS settings, and type of input signal have significant impact on how much damping will be contributed by PSS on a particular unit in a particular environment. Figs. 7a, 7b, and 7c show the combined open loop frequency response of the proposed benchmark system with three different PSS settings. It is seen that the phase lags vary widely. Figure 7a shows relatively flat phase in 0.1 to 1.0 Hz range. Figure 7b shows a response which is less flat but has a wide bandwidth and 7c shows significant phase lag for frequency higher than 0.5 Hz but stays flat between 0.5 to 2.0 Hz.

There is another factor which is not directly covered by this criteria. That is the gain of $\partial E_t/\partial E_{ref}$. Usually systems which have large phase lag in the frequency range of interest also show a large attenuation and, thus, PSS effectiveness for systems with large phase lags would be even lower due to gain considerations. Thus, the proposed criteria does indirectly account for the gain of the combined system.

5.0 STUDY DETAILS

All studies were conducted using an eigenvalue program from Power Math Associates called SSR/EIGEN.

5.1 System Representation

Two benchmark systems have been studied. Benchmark System #1 representation is shown in Figure 2a. The study machine data is taken from a typical 900 MVA unit in WSCC system. The impedances and X/R ratio are for typical 500 kV lines. The Benchmark System #2 representation is shown in Figure 2b.

5.2 Excitation System Representation

The types of excitation systems have been studies. Figure 8a shows a typical AC4 type excitation system. Figure 8b shows a typical DC1 type excitation system.

5.3 PSS Representation

Power system stabilizer was represented by a two-stage lead/lag circuit with a washout stage as shown in Figure 8. The lead/lag time constants were fixed at 0.2 and 0.02 seconds throughout the study.

5.4 Input Signals

Two kinds of PSS input signals were used, speed and frequency. These are the most commonly used PSS input signals. Another commonly used signal is accelerating power which was not used in these studies.

5.5 Study Method

There are a large number of variables and studying all of them would have been out of scope of this study. Therefore, a selected number of variables were chosen to investigate the application of the method. PSS optimization consisted of optimizing PSS gain only. The gain optimization consisted of first finding the PSS instability gain. This was done by increasing the PSS gain until the PSS eigenvalue became unstable. The optimum PSS gain was taken as one-third of the instability gain.

PSS's contribution to damping was calculated by running a case with zero PSS gain and comparing the real parts of intertie mode from the one-third of instability gain case to the zero PSS gain case.

5.6 Sample Run

A sample eigenvalue case is attached as Exhibit 1.

6.0 REFERENCES

1. E. V. Larsen, D. A. Swann, "Applying Power System Stabilizer: Part I General Concepts", IEEE Trans. on PAS Vol. 100, No. 6, June 1981, pp. 3017-3024.

2. "Criteria and Definitions for Excitation Systems for Synchronous Machines". IEEE Standards 421-72, December, 1972.

3. "IEEE Guide for Identification, Testing, and Evaluation of the Dynamic Performance of Excitation Control System," IEEE Standards 421.2 - 1990.

4. C. Concordia, F. P. DeMello, "Concepts of Synchronous Machine Stability As Affected by Excitation Control", IEEE Trans PAS Vol. 88, Apr. 1969, pp 316-329.

TABLE – 1

(Benchmark System 1)

SPEED DEV INPUT PSS EXCITER TYPE AC-4

CASE #	Esys MWS	Study M/C MVA	H	Sigma For Case NO PSS	WITH PSS	DeltaSigma Absolute	RDC	Freq (Hz)
1	35000	1000	3	-0.000405	-0.005466	0.005061	0.064106	0.44
2	35000	500	3	-0.000071	-0.002150	0.002080	0.050601	0.44
3	35000	250	3	0.000191	-0.000742	0.000933	0.044473	0.44
4	35000	100	3	0.000375	0.000034	0.000341	0.040124	0.44
5	35000	50	3	0.000440	0.000274	0.000167	0.039080	0.44
1	35000	1000	3	-0.000405	-0.005466	0.005061	0.064107	0.44
7	35000	1000	2	0.000135	-0.001826	0.001961	0.036284	0.44
8	35000	1000	1	0.000441	0.000170	0.000271	0.009760	0.44

FREQUENCY INPUT PSS EXCITER TYPE AC-4

CASE #	Esys MWS	Study M/C MVA	H	Sigma For Case NO PSS	WITH PSS	DeltaSigma Absolute	RDC	Freq (Hz)
9	35000	1000	3	-0.000405	-0.003217	0.002812	0.035619	0.44
10	35000	500	3	-0.000071	-0.001512	0.001442	0.035077	0.44
11	35000	250	3	0.000191	-0.000552	0.000743	0.035421	0.44
12	35000	100	3	0.000375	0.000074	0.000301	0.035372	0.44
13	35000	50	3	0.000440	0.000288	0.000153	0.035806	0.44
9	35000	1000	3	-0.000405	-0.003217	0.002812	0.035620	0.44
14	35000	1000	2	0.000135	-0.001299	0.001434	0.026535	0.44
15	35000	1000	1	0.000441	0.000152	0.000289	0.010418	0.44

FREQUENCY INPUT PSS EXCITER TYPE DC-1

CASE #	Esys MWS	Study M/C MVA	H	Sigma For Case NO PSS	WITH PSS	DeltaSigma Absolute	RDC	Freq (Hz)
16	35000	1000	3	-0.000161	-0.003082	0.002922	0.037006	0.44
17	35000	500	3	0.000007	-0.001722	0.001729	0.042072	0.44
18	35000	250	3	0.000216	-0.000732	0.000948	0.045197	0.44
19	35000	100	3	0.000382	-0.000022	0.000404	0.047490	0.44
20	35000	50	3	0.000443	0.000235	0.000209	0.048919	0.44
16	35000	1000	3	-0.000161	-0.003082	0.002922	0.037006	0.44
21	35000	1000	2	0.000268	-0.001385	0.001653	0.030579	0.44
22	35000	1000	1	0.000489	-0.000015	0.000504	0.018154	0.44
19	35000	100	3	0.000382	-0.000022	0.000404	0.047490	0.44
23	35000	100	2	0.000456	0.000232	0.000224	0.039406	0.44
24	35000	100	1	0.000496	0.000430	0.000066	0.023226	0.44

Table- 1 Continued)

(Benchmark System # 1 Results Continued)

FREQUENCY INPUT PSS EXCITER TYPE DC-1

CASE #	Esys MWS	Study M/C MVA	H	Sigma For Case NO PSS	WITH PSS	DeltaSigma Absolute	RDC	Freq (Hz)
25	8750	100	3	-0.000823	-0.006814	0.005991	0.180729	0.85
26	8750	100	2	0.0008619	-0.002209	0.003071	0.137423	0.85
27	8750	100	1	0.001734	0.0008777	0.000856	0.075783	0.85
28	35000	100	3	-0.00044	-0.00191	0.001470	0.172970	0.85

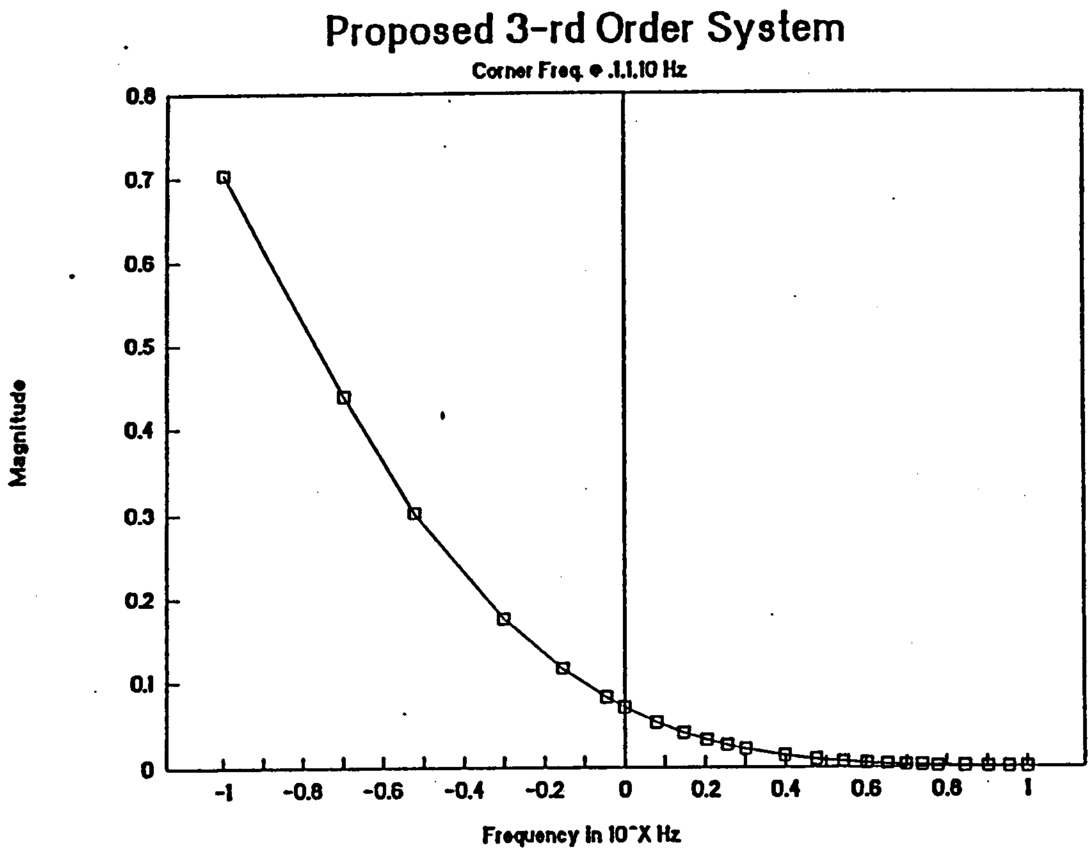
Benchmark System 2

FREQUENCY INPUT PSS EXCITER TYPE DC-1

CASE #	Esys MWS	Study M/C MVA	H	Sigma For Case NO PSS	WITH PSS	DeltaSigma Absolute	RDC	Freq (Hz)
31	140000	100	3	-0.058750	-0.060021	0.001271	0.594404	0.43
32	140000	100	2	-0.058780	-0.059780	0.001000	0.701000	0.43
33	140000	100	1	-0.058800	-0.059360	0.000560	0.784560	0.43
34	35000	100	3	-0.234900	-0.243000	0.008100	0.953100	0.85

NOTES:

1. RDC=Absolute DelSig*((Esys+Eunit)/Eunit)
2. For Cases 25,26,27 Tie Bus M/C MVA=2500
3. For Case 28 Tie Line Imped Reduced by 4
4. For Cases31,32,33 Tie Bus MVA=40000
5. For Case 34 Tie Bus MVA Reduced To 10000


Proposed 3-rd Order System
Corner Freq. @ .1,1,10 Hz
Magnitude
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1
Frequency in 10^X Hz

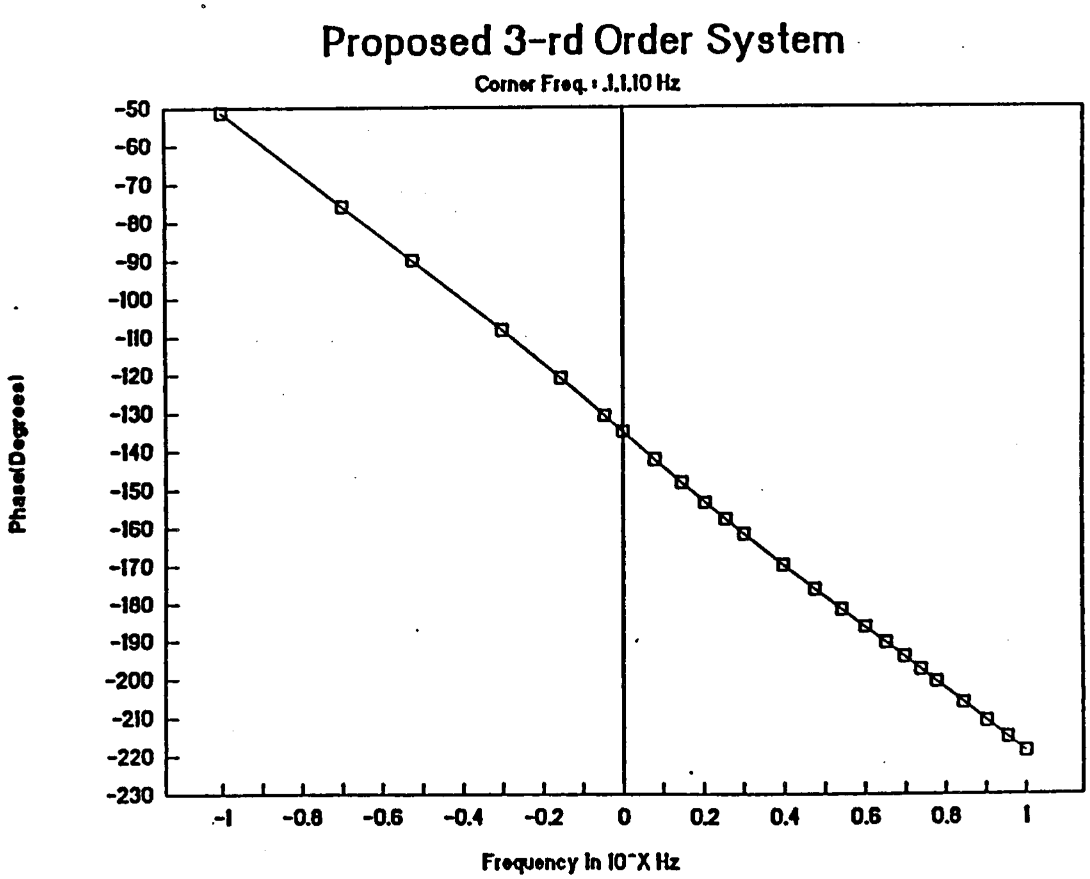
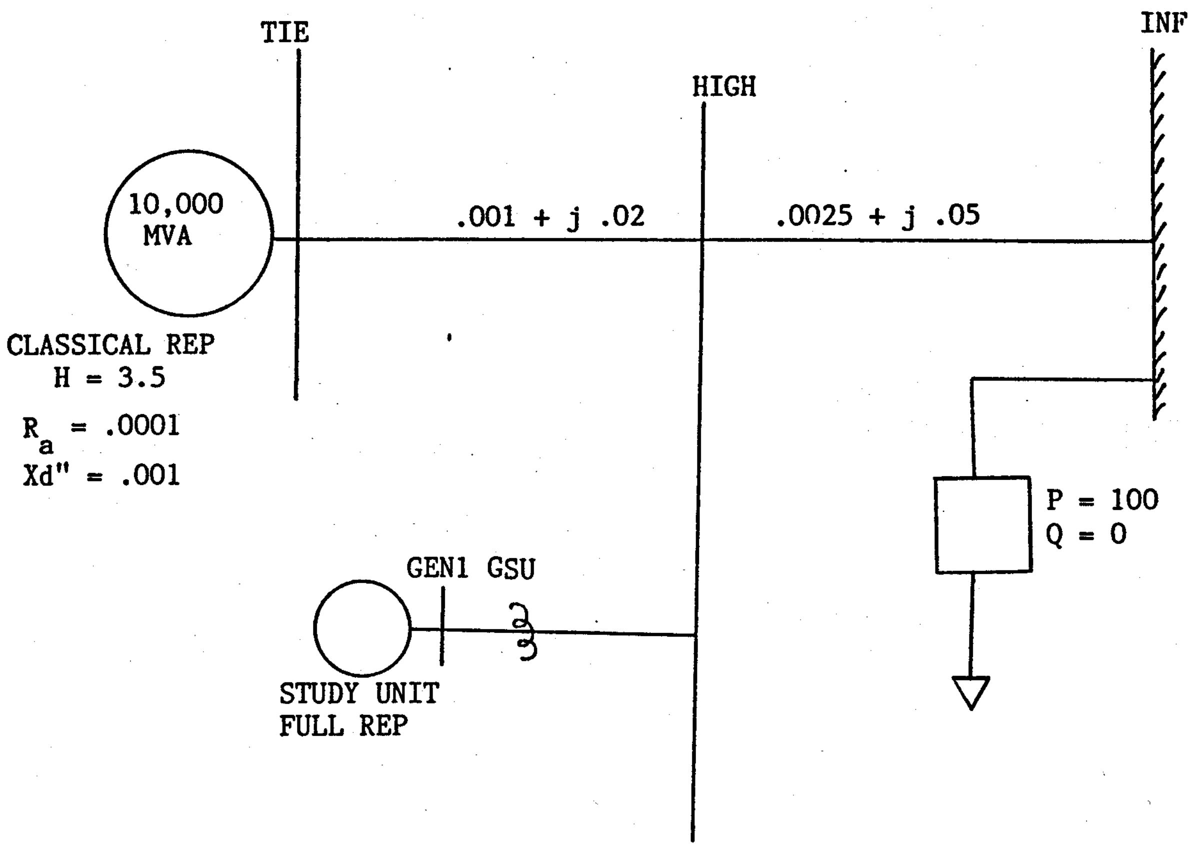
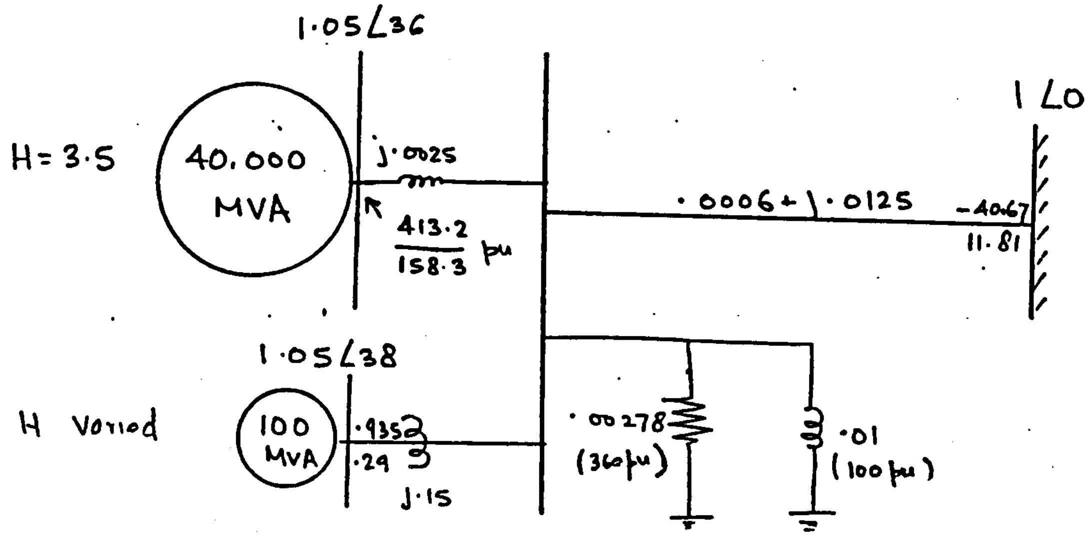

Proposed 3-rd Order System
Corner Freq. : .1,1,10 Hz
Phase(Degrees)
-50
-60
-70
-80
-90
-100
-110
-120
-130
-140
-150
-160
-170
-180
-190
-200
-210
-220
-230
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1
Frequency in 10^X Hz

Fig. 1



All impedance data are in pu on 100 MVA base
GSU = 15% on study unit MVA base

Fig. 2a



BENCH MARK SYSTEM 2

All values on 100 MVA Base Including Power Flows

Fig. 2b

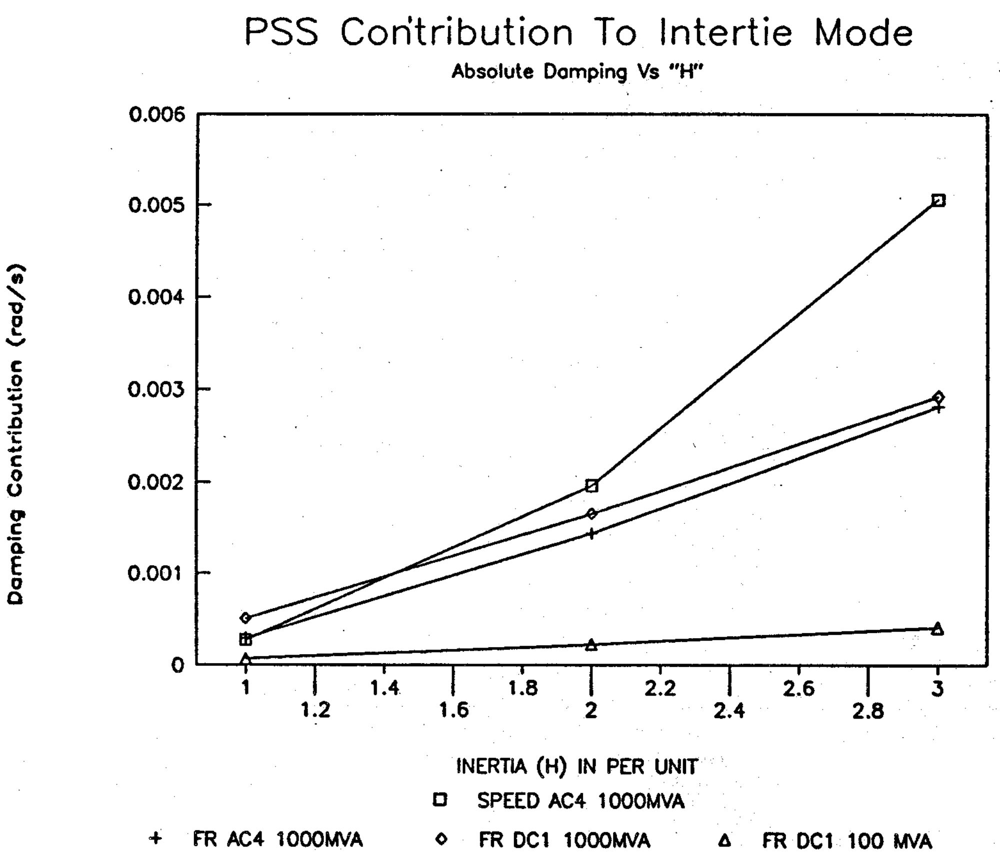
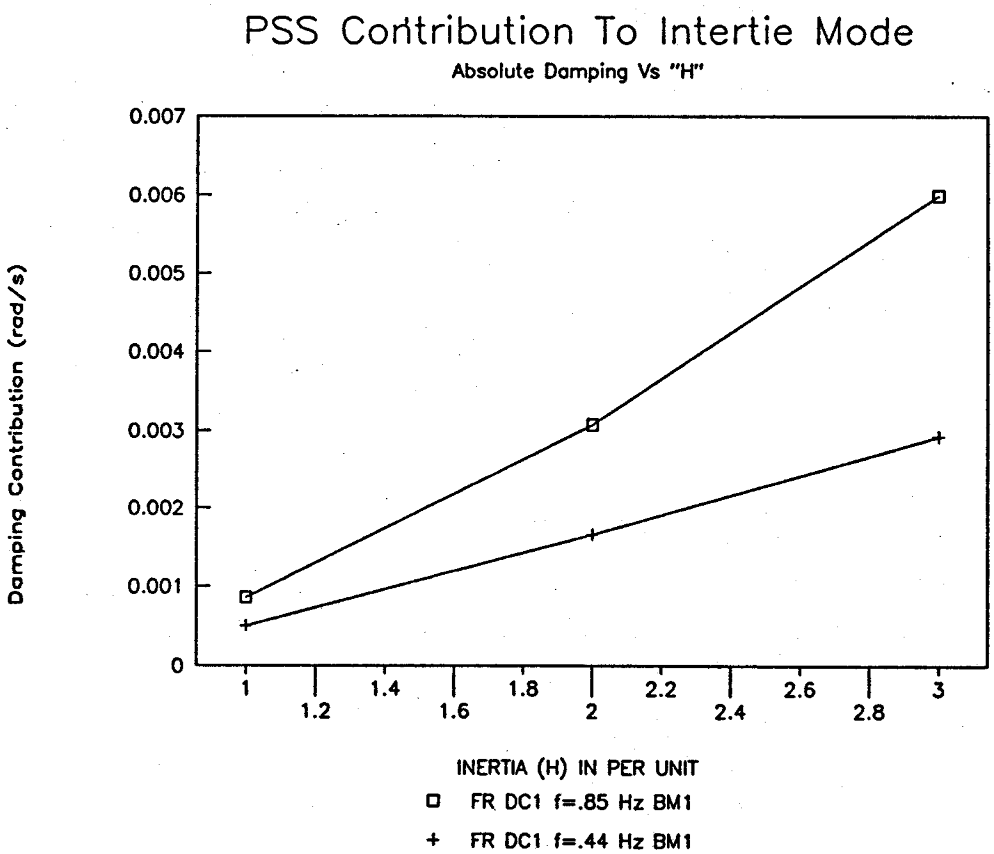

PSS Contribution To Intertie Mode
Absolute Damping Vs "H"
Damping Contribution (rad/s)
0.006
0.005
0.004
0.003
0.002
0.001
0
1
1.2
1.4
1.6
1.8
2
2.2
2.4
2.6
2.8
3
INERTIA (H) IN PER UNIT
SPEED AC4 1000MVA
FR AC4 1000MVA
FR DC1 1000MVA
FR DC1 100 MVA

Fig. 3b



PSS Contribution To Intertie Mode
Absolute Damping Vs "H"
Damping Contribution (rad/s)
0.007
0.006
0.005
0.004
0.003
0.002
0.001
0
1
1.2
1.4
1.6
1.8
2
2.2
2.4
2.6
2.8
3
INERTIA (H) IN PER UNIT
FR DC1 f=.85 Hz BM1
FR DC1 f=.44 Hz BM1

Fig. 3c

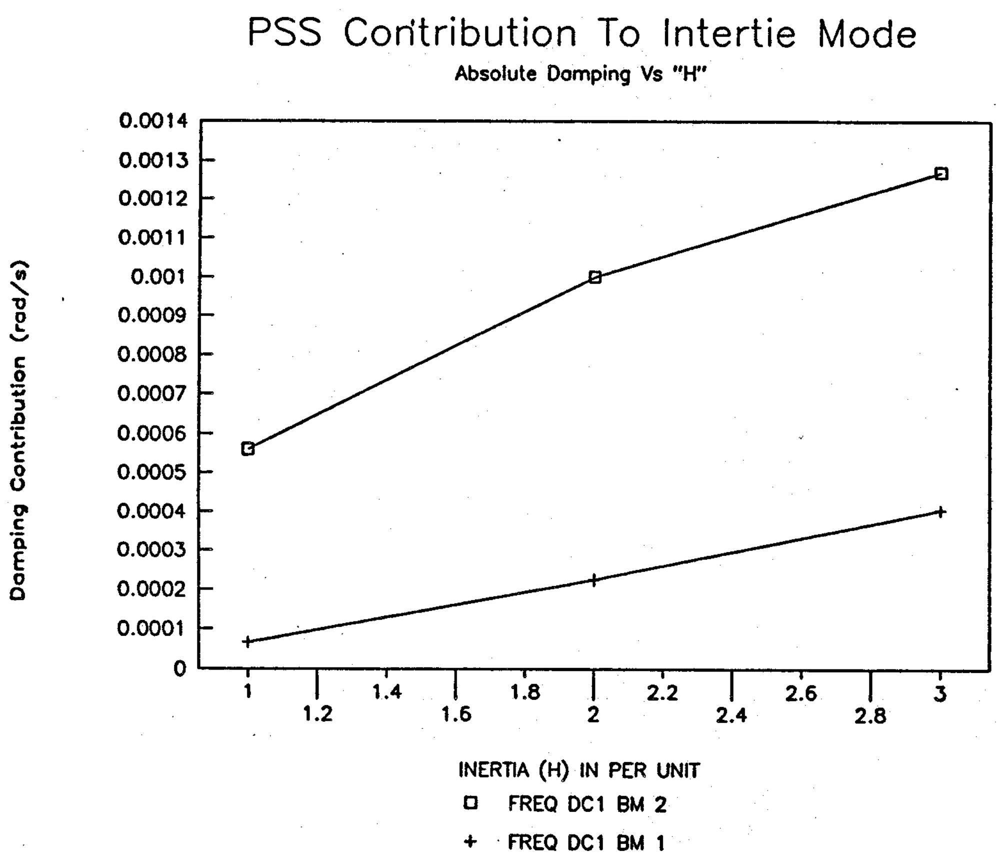

PSS Contribution To Intertie Mode
Absolute Damping Vs "H"
Damping Contribution (rad/s)
0.0014
0.0013
0.0012
0.0011
0.001
0.0009
0.0008
0.0007
0.0006
0.0005
0.0004
0.0003
0.0002
0.0001
0
1
1.2
1.4
1.6
1.8
2
2.2
2.4
2.6
2.8
3
INERTIA (H) IN PER UNIT
FREQ DC1 BM 2
FREQ DC1 BM 1

Fig. 3d

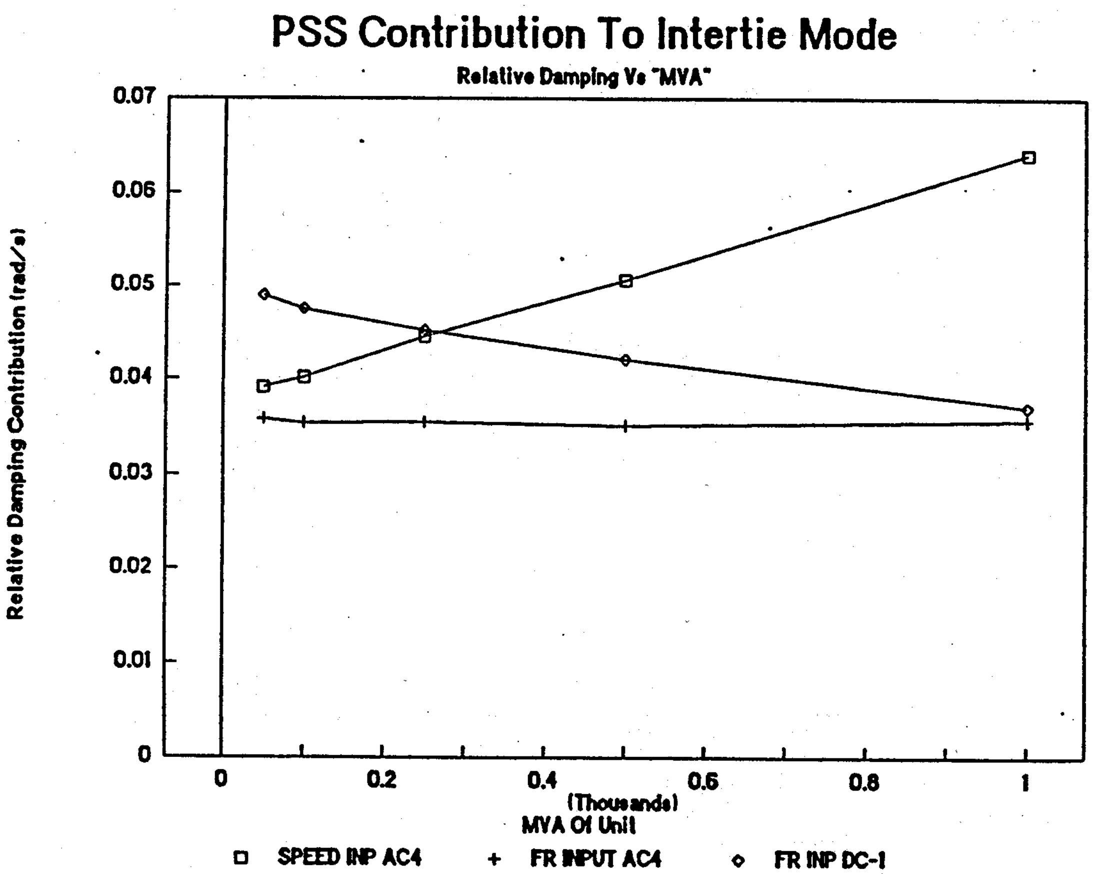

PSS Contribution To Intertie Mode
Relative Damping Vs "MVA"
Relative Damping Contribution (rad/s)
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
0
0.2
0.4
0.6
0.8
1
(Thousands)
MVA Of Unit
SPEED INP AC4
FR INPUT AC4
FR INP DC-1

FIG. 4a

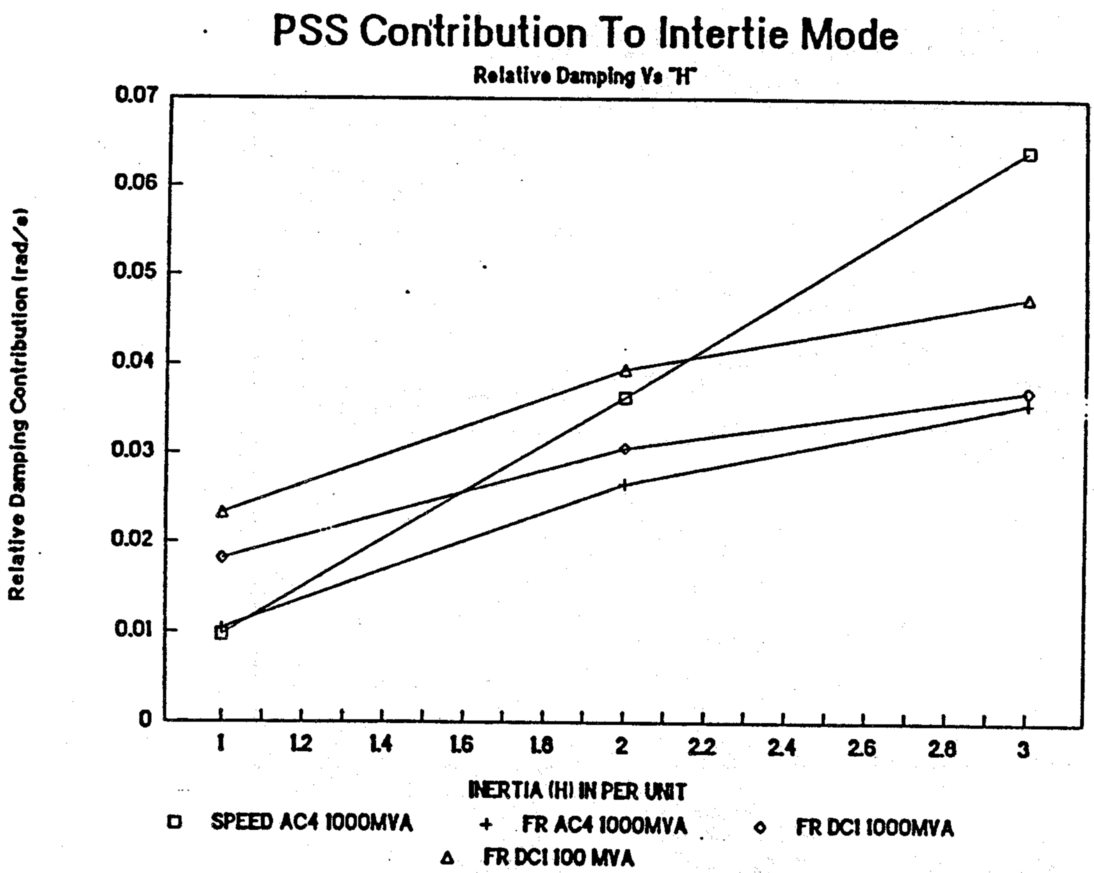

PSS Contribution To Intertie Mode
Relative Damping Vs "H"
Relative Damping Contribution (rad/s)
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
1
1.2
1.4
1.6
1.8
2
2.2
2.4
2.6
2.8
3
INERTIA (H) IN PER UNIT
SPEED AC4 1000MVA
FR AC4 1000MVA
FR DC1 1000MVA
FR DC1 100 MVA

FIG. 4b

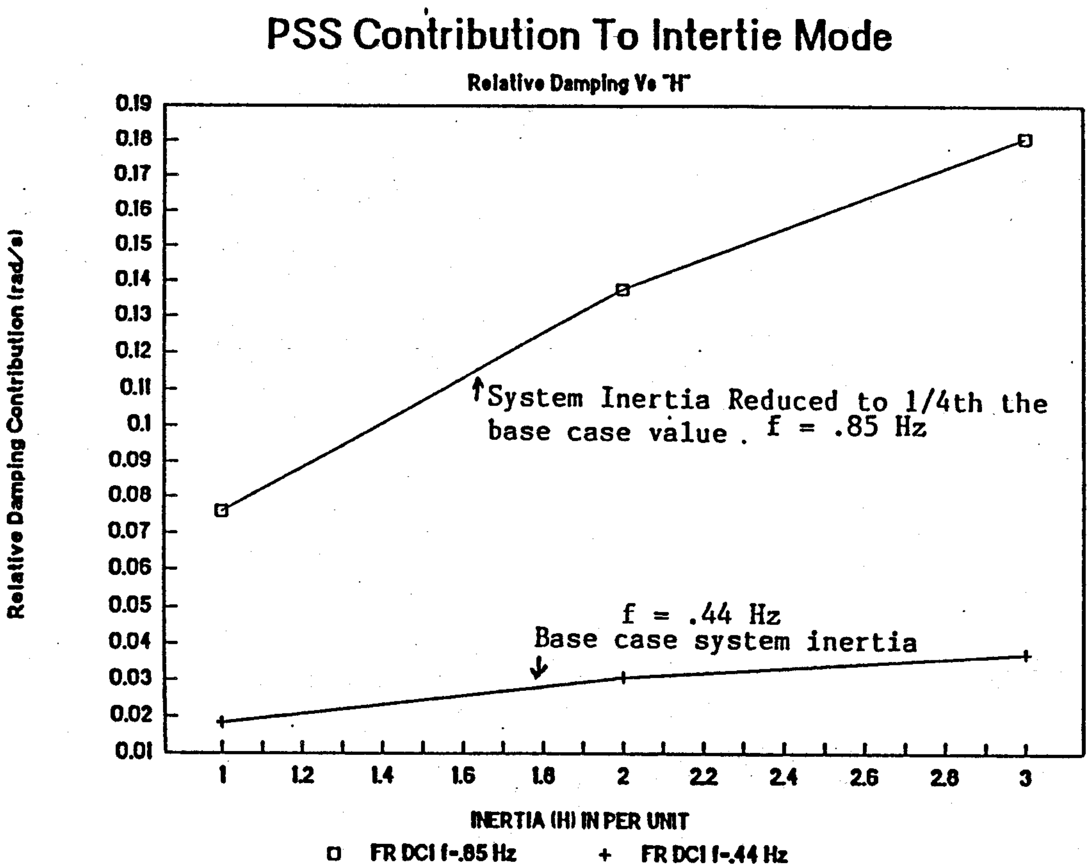
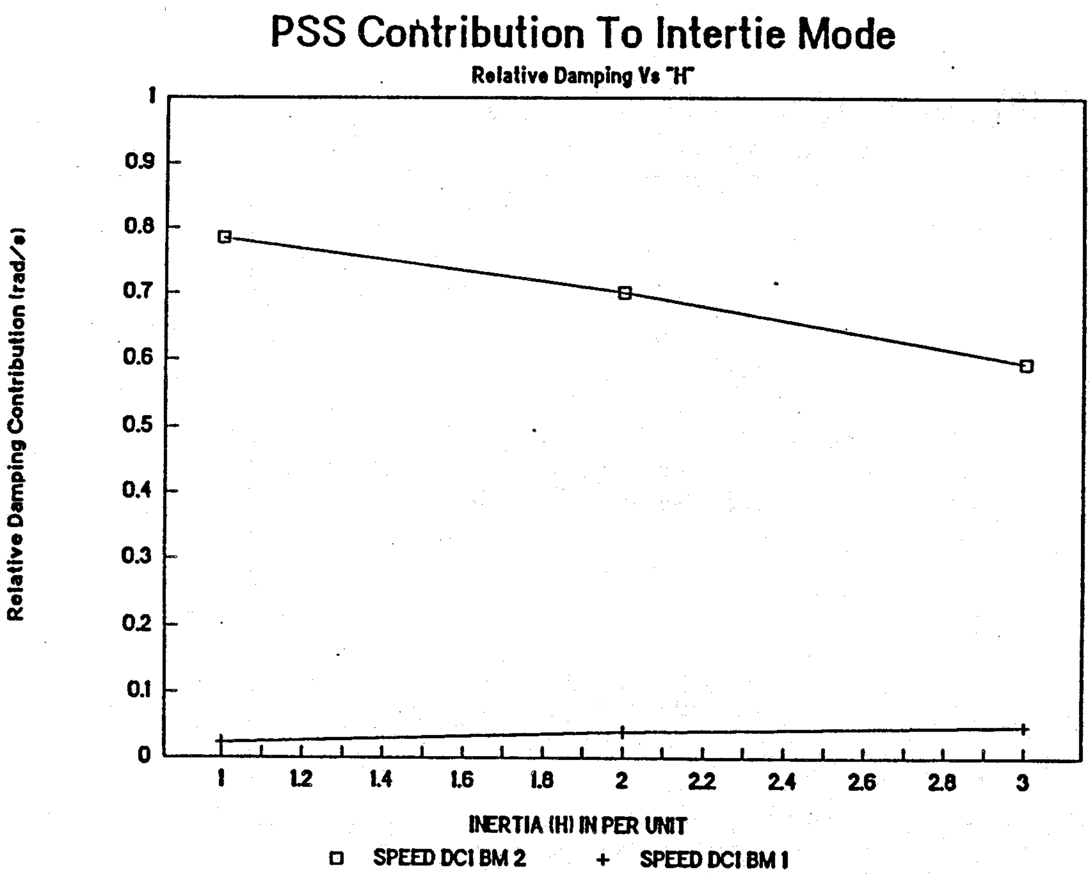
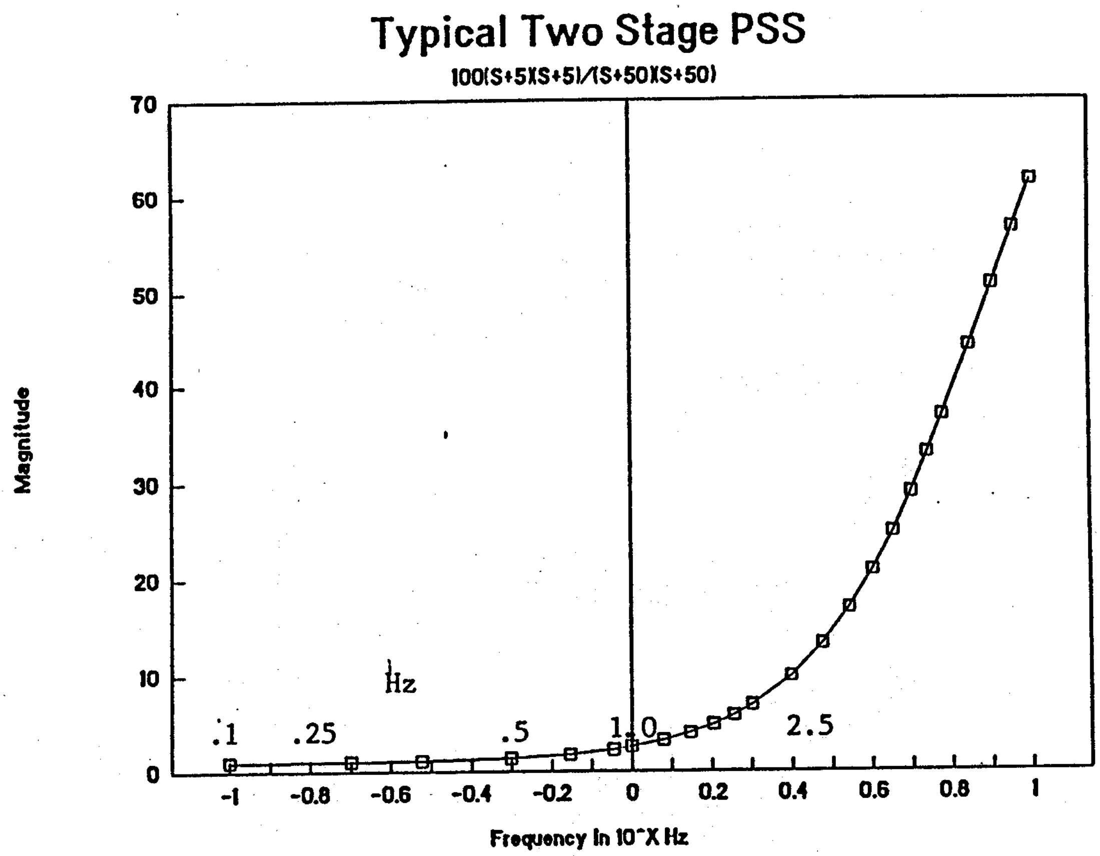

PSS Contribution To Intertie Mode
Relative Damping Vs "H"
Relative Damping Contribution (rad/s)
0.19
0.18
0.17
0.16
0.15
0.14
0.13
0.12
0.11
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
1
1.2
1.4
1.6
1.8
2
2.2
2.4
2.6
2.8
3
System Inertia Reduced to 1/4th the base case value. f = .85 Hz
f = .44 Hz
Base case system inertia
INERTIA (H) IN PER UNIT
FR DC1 f-.85 Hz
FR DC1 f-.44 Hz

FIG. 4c



PSS Contribution To Intertie Mode
Relative Damping Vs "H"
Relative Damping Contribution (rad/s)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
1
1.2
1.4
1.6
1.8
2
2.2
2.4
2.6
2.8
3
INERTIA (H) IN PER UNIT
□ SPEED DC1 BM 2
+ SPEED DC1 BM 1

FIG. 4d


Typical Two Stage PSS
100(S+5)(S+5)/(S+50)(S+50)
Magnitude
70
60
50
40
30
20
10
0
Hz
.1
.25
.5
1.0
2.5
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1
Frequency In 10^X Hz

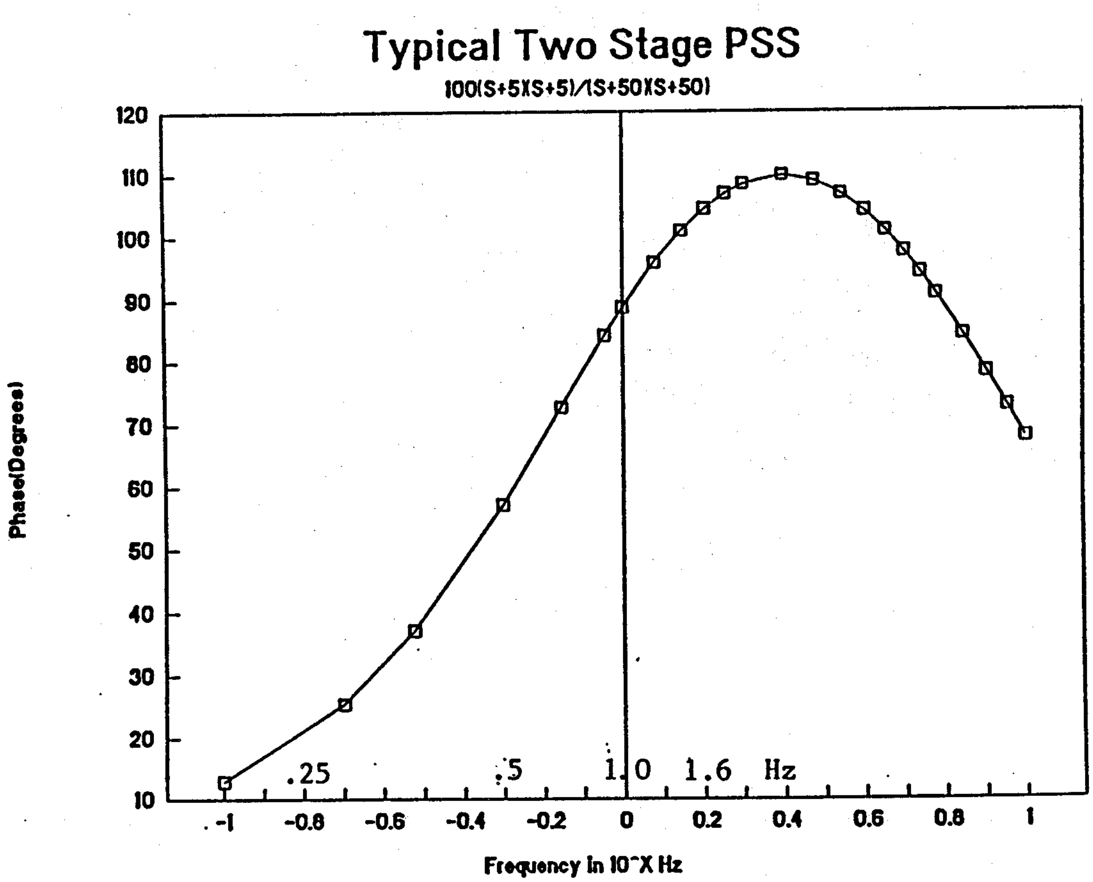
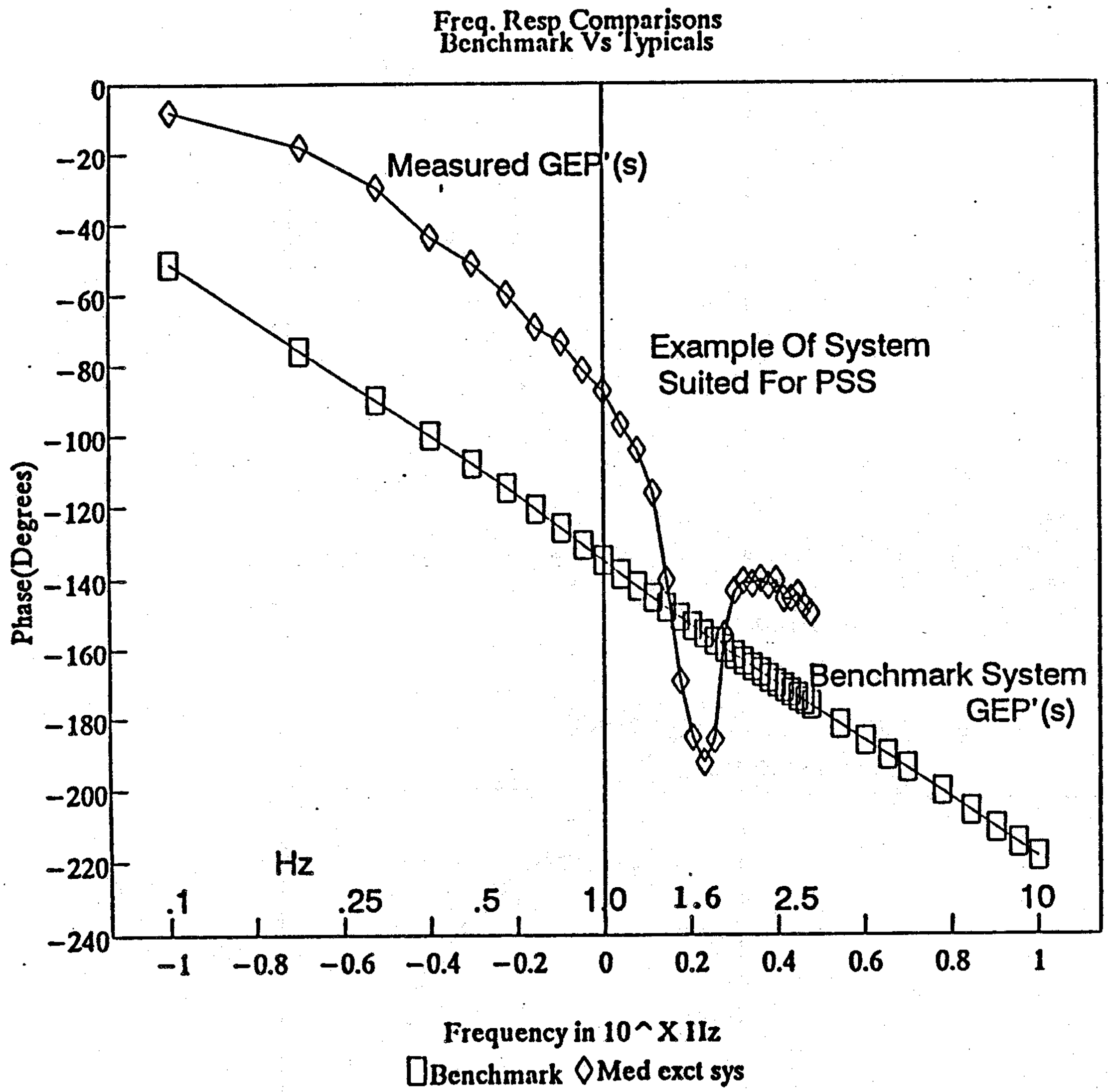

Typical Two Stage PSS
100(S+5)(S+5)/(S+50)(S+50)
Phase(Degrees)
120
110
100
90
80
70
60
50
40
30
20
10
.25
.5
1.0
1.6
Hz
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1
Frequency In 10^X Hz

FIG. 5



Freq. Resp Comparisons
Benchmark Vs Typicals
Measured GEP'(s)
Example Of System
Suited For PSS
Benchmark System
GEP'(s)
Phase(Degrees)
0
-20
-40
-60
-80
-100
-120
-140
-160
-180
-200
-220
-240
Hz
.1
.25
.5
1.0
1.6
2.5
10
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1
Frequency in 10^X Hz
Benchmark
Med exct sys

FIG. 6a

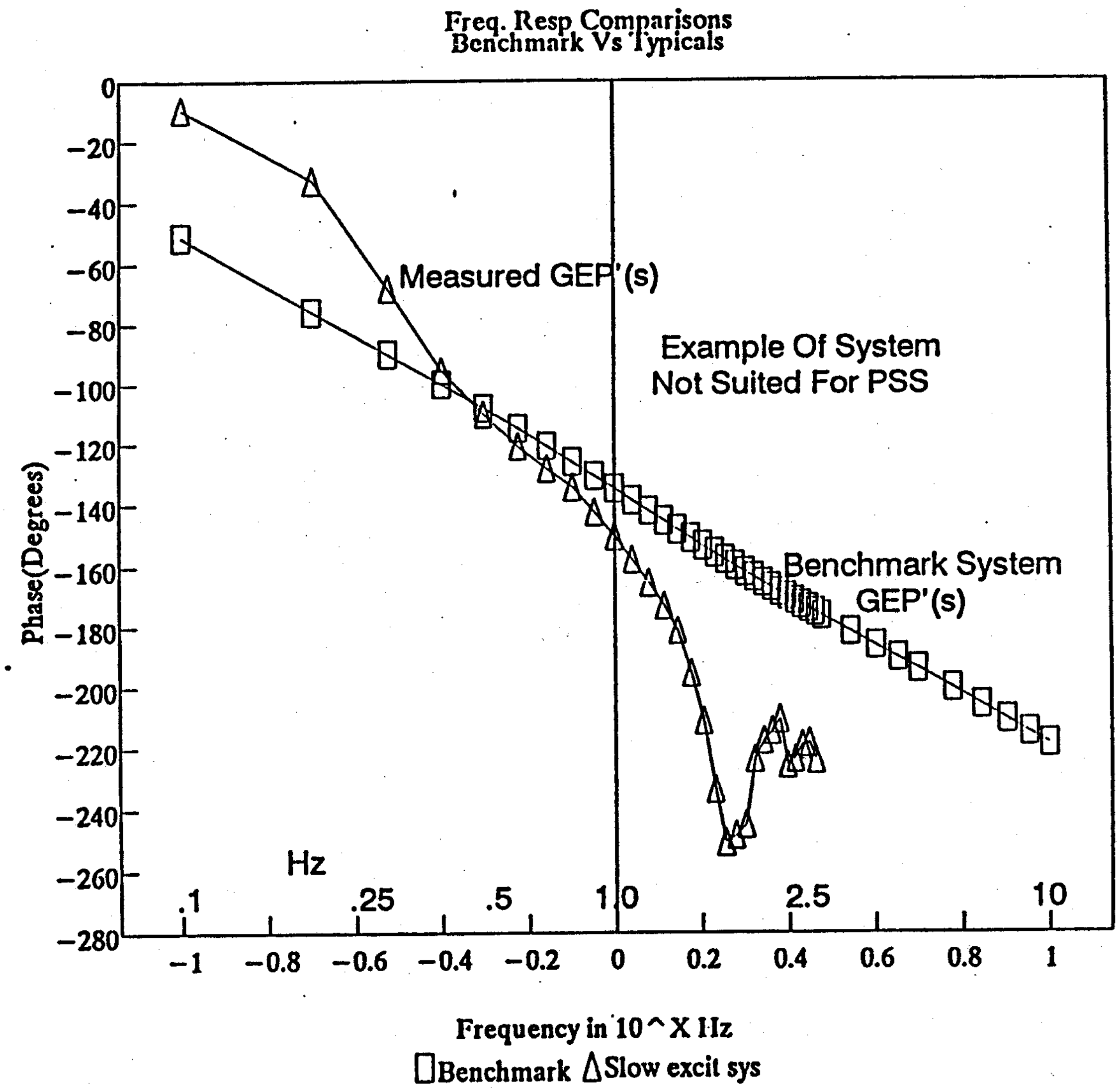

Freq. Resp Comparisons
Benchmark Vs Typicals
Measured GEP'(s)
Example Of System
Not Suited For PSS
Benchmark System
GEP'(s)
Hz
.1
.25
.5
1.0
2.5
10
Phase(Degrees)
0
−20
−40
−60
−80
−100
−120
−140
−160
−180
−200
−220
−240
−260
−280
−1
−0.8
−0.6
−0.4
−0.2
0
0.2
0.4
0.6
0.8
1
Frequency in 10^X Hz
Benchmark
Slow excit sys

FIG. 6b

PSS(s)=(1+.5s)(1+.5s)/(1+.05s)(1+.05s)

GEP'(s) has corner freq. @ .1,1,10 Hz (BENCHMARK SYSTEM)

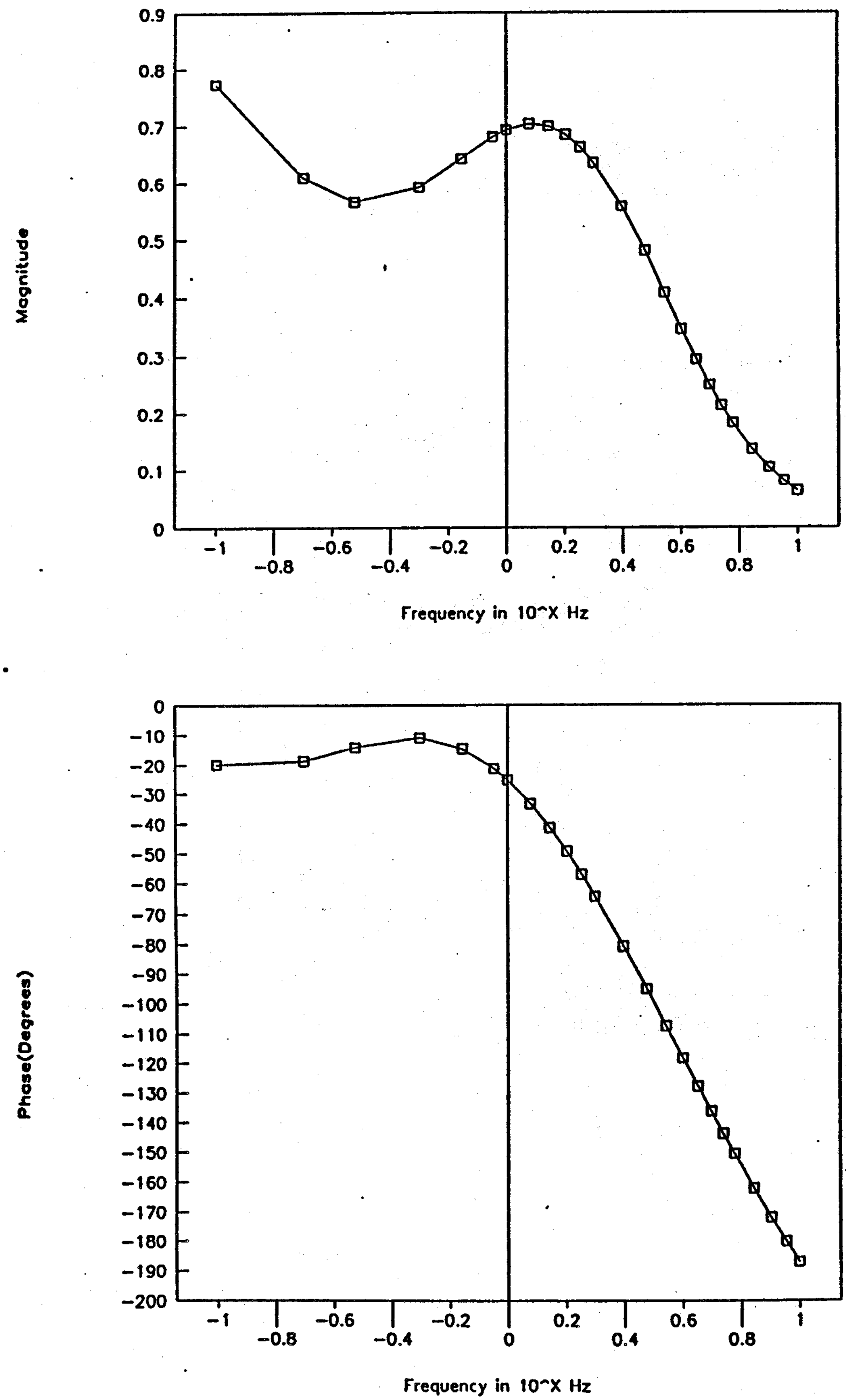


FIG. 7a

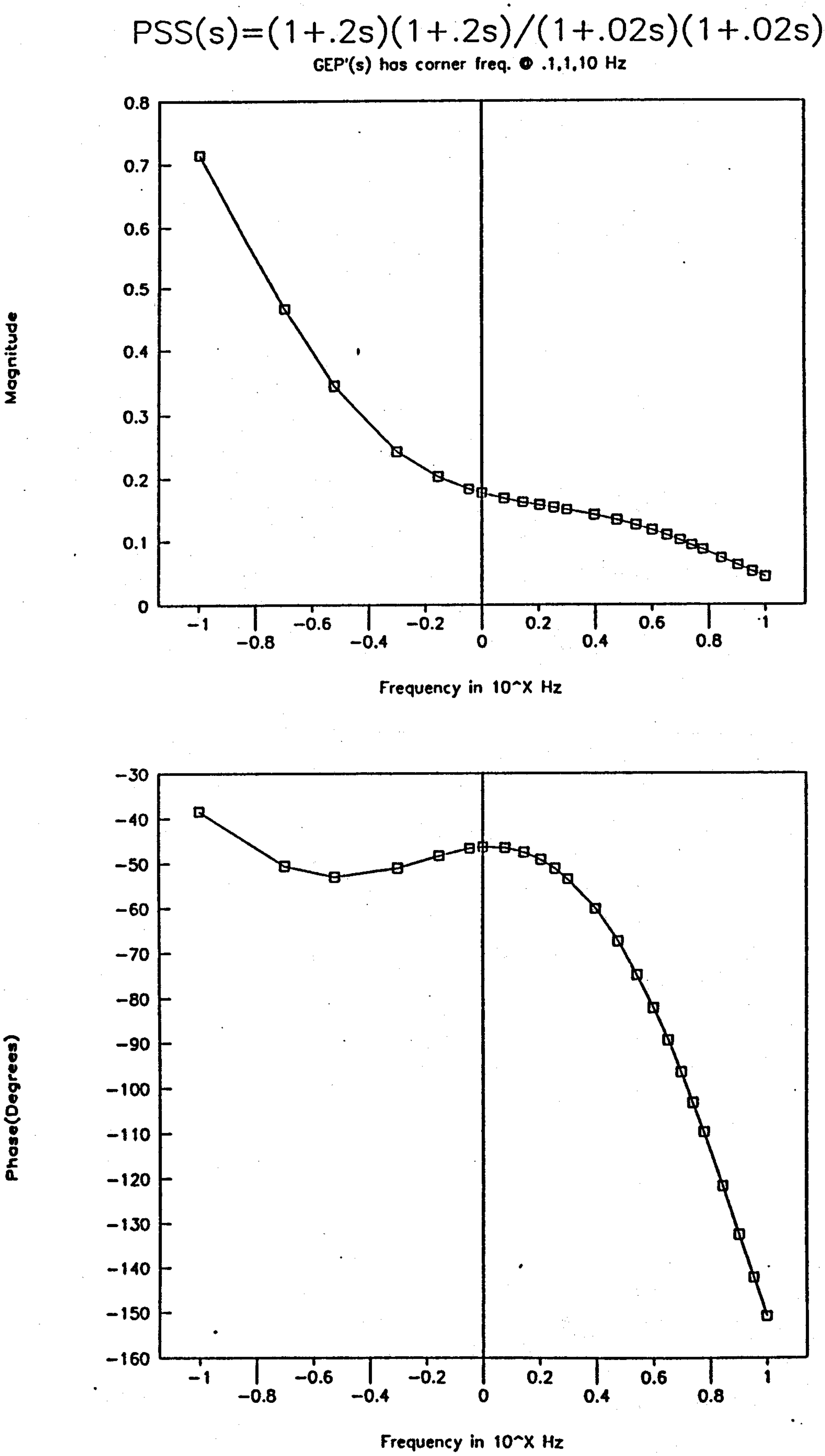

PSS(s)=(1+.2s)(1+.2s)/(1+.02s)(1+.02s)
GEP'(s) has corner freq. @ .1,1,10 Hz
Magnitude
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1
Frequency in 10^X Hz
Phase(Degrees)
-30
-40
-50
-60
-70
-80
-90
-100
-110
-120
-130
-140
-150
-160
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1
Frequency in 10^X Hz

FIG. 7b

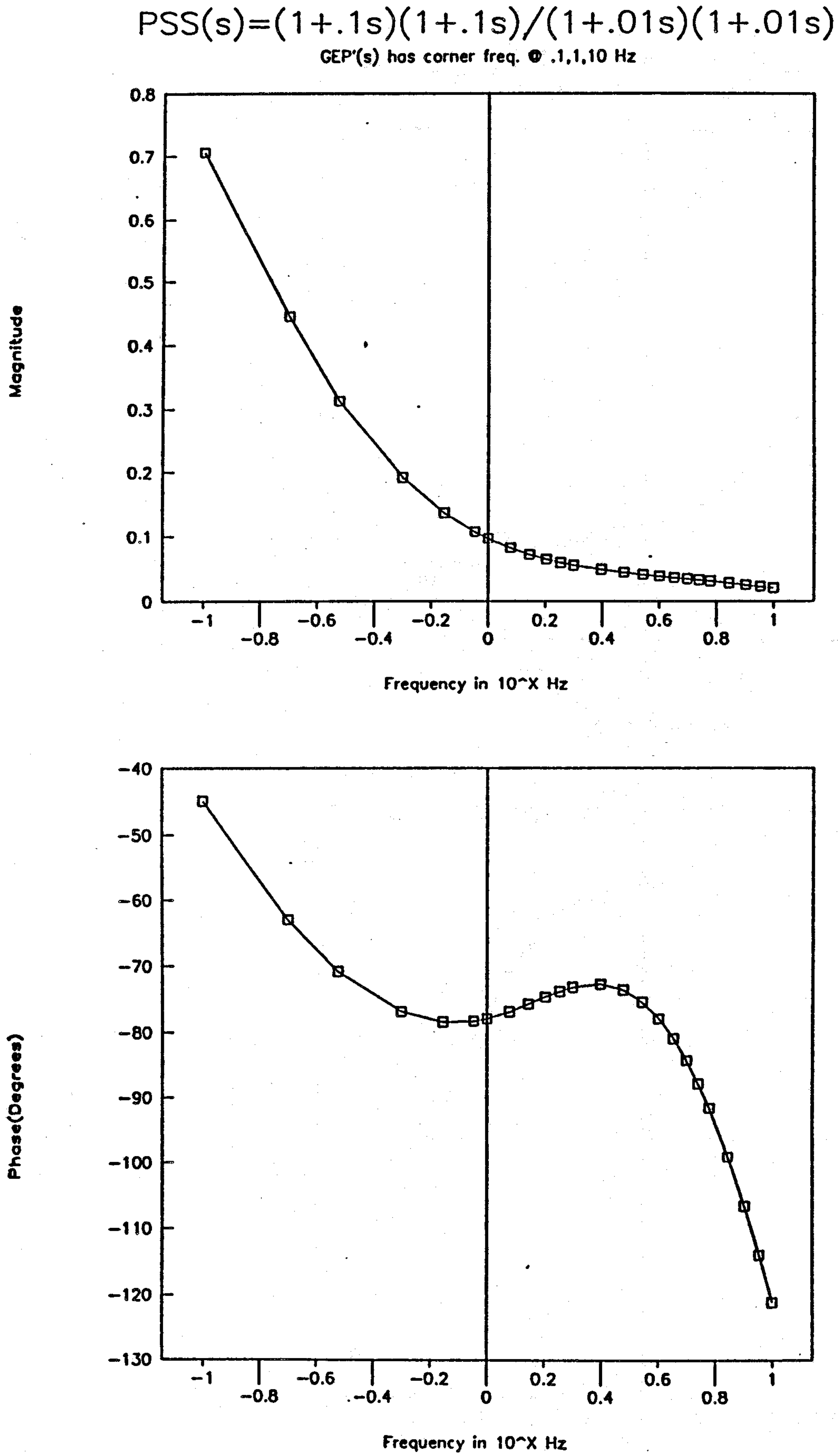

PSS(s)=(1+.1s)(1+.1s)/(1+.01s)(1+.01s)
GEP'(s) has corner freq. @ .1,1,10 Hz
Magnitude
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1
Frequency in 10^X Hz
Phase(Degrees)
-40
-50
-60
-70
-80
-90
-100
-110
-120
-130
Frequency in 10^X Hz

FIG.. 7c

CASES WITH TYPE "AC4" EXCITER

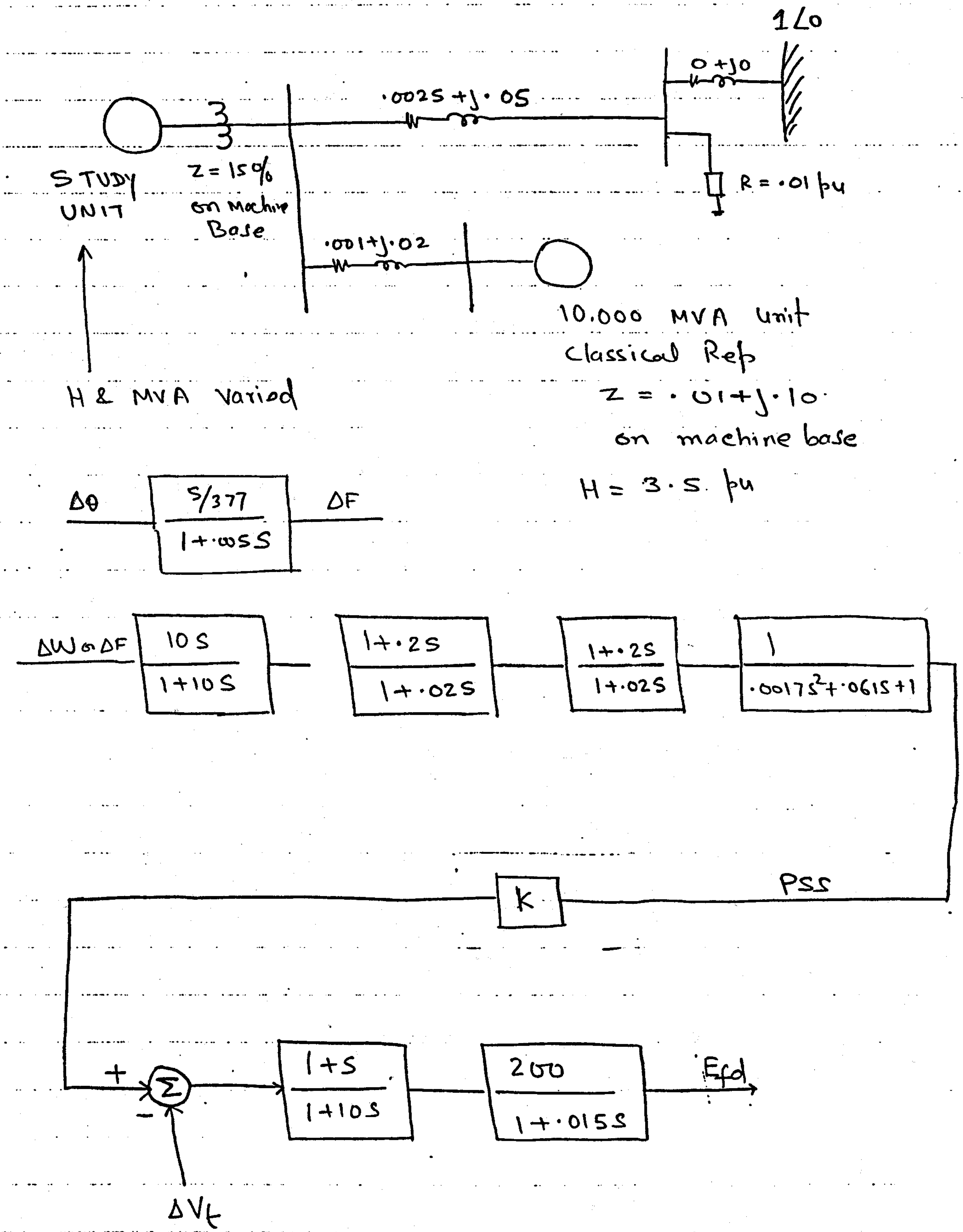
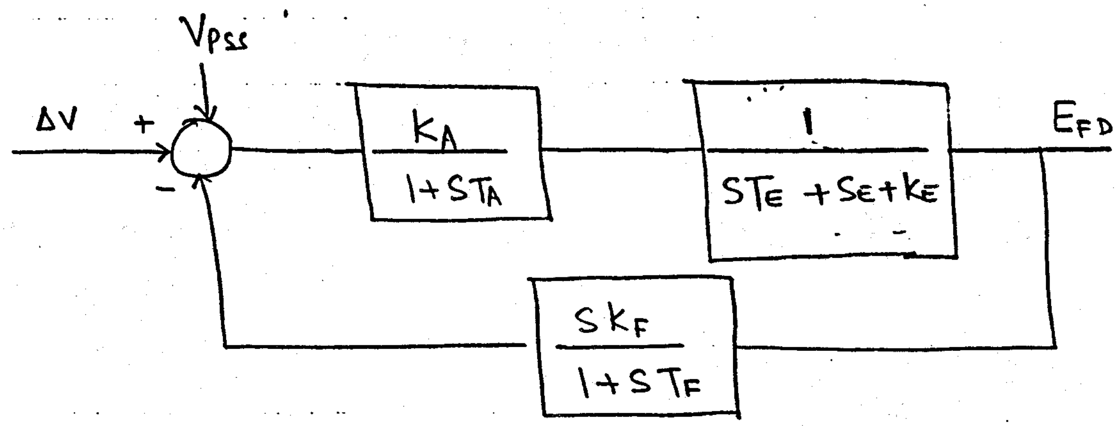


Fig. 8a

CASES WITH TYPE "DC1" EXCITER

WSCC TYPE A (IEEE DC1) EXC. SYS.

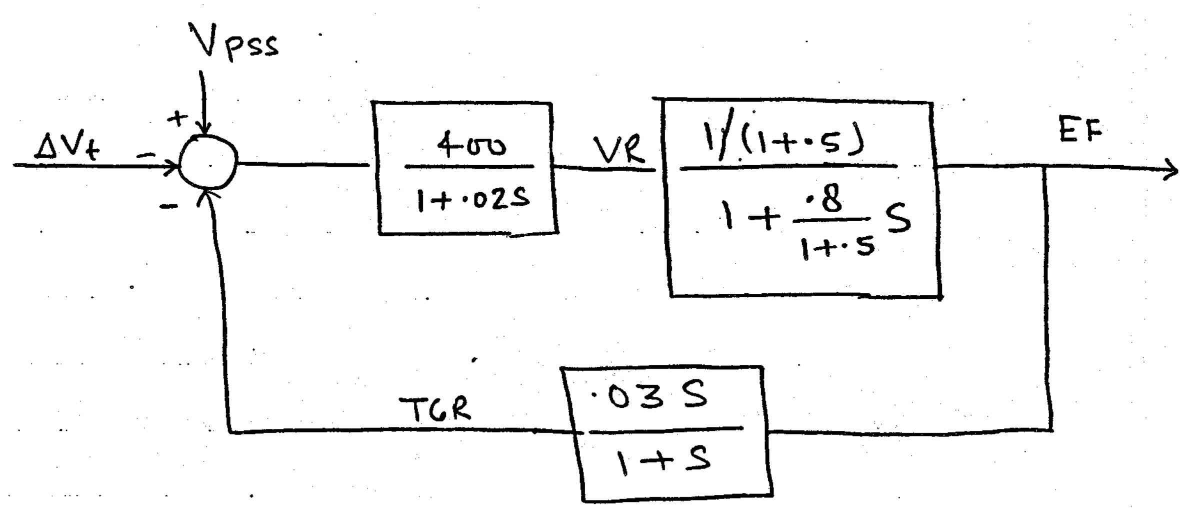
Use Typical values from Committee Paper (PAS - Feb 81)



$K_A = 400 \quad T_A = .02 \quad K_E = 1 \quad T_E = .8 \quad S_E(.75) = .5$

$K_F = .03 \quad T_F = 1.0$

SSR/EIGEN PROGRAM MODEL



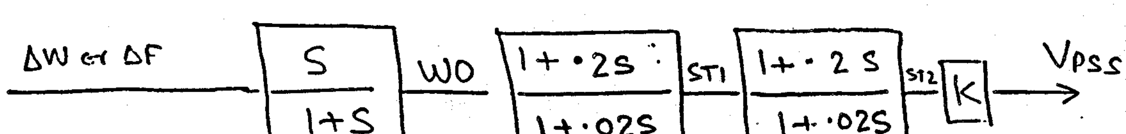


Fig. 8b

3-13-92

PSS Effectiveness Study For Modeling Work Group

EXHIBIT 1

MVA=100 ' H=1

SYSTEM BASE MVA 100.0 HFAC 1. XC INCREMENTED THROUGH 0 STEPS

GENERATOR 1 HAS A TWO AXIS MODEL, IS NAMED GEN1 AND CONNECTED TO BUS GEN1
MVA 100.0 XL 0.1300 RA 0.0019 VT 1.0000 DEL 8.5000
VOLTAGE REGULATOR OUTPUT NAMED VFU1
XD 1.760 XDP 0.220 XDPP 0.175 TDOP 4.200 TDOPP 0.032
XQ 1.680 XQP 0.400 XQPP 0.175 TQOP 0.600 TQOPP 0.066

MECHANICAL SYSTEM IS 1 MASS CLASSICAL, GENERATOR IS 1, EXCITER IS 1
MASS 1 J 2.0000 D 0.00000E+00

GENERATOR 2 HAS A SIMPLE MODEL, IS NAMED INFBUS AND CONNECTED TO BUS INFBUS
MVA 100.0 XL 0.0000 RA 0.0000 VT 1.0000 DEL 0.0000

GENERATOR 3 HAS A SIMPLE MODEL, IS NAMED TIEBUS AND CONNECTED TO BUS TIEBUS
MVA 9999.0 XL 0.1000 RA 0.0100 VT 1.0000 DEL 0.0000

MECHANICAL SYSTEM IS 1 MASS CLASSICAL, GENERATOR IS 1, EXCITER IS 1
MASS 1 J 7.0000 D 0.00000E+00

BRANCH DATA

I	FROM BUS	TO BUS	XL	R	XC	INCR XC
1	GEN1	HIGH500	0.15000	0.00000	0.00000	0.00000
2	HIGH500	INFBUS	0.05000	0.00250	0.00000	0.00000
3	HIGH500	TIEBUS	0.02000	0.00100	0.00000	0.00000
4	INFBUS		0.00000	0.01000	0.00000	0.00000

RESULTS FROM YMAT: NODE, COMPLEX VOLTAGE, CURRENT, AND POWER

GEN1	1.713	0.2560	1.558	0.1226	0.9000	0.6295E-01
INFBUS	1.732	0.0000E+00	172.8	-0.3502E-01	99.74	0.2022E-01
TIEBUS	1.732	0.0000E+00	-1.113	-0.8755E-01	-0.6424	0.5055E-01

COMPUTED MACHINE PARAMETERS ON THE SYSTEM BASE:

FOR MACHINE GEN1 , STEADY STATE FIELD CURRENT IS , 2.0563
Ld 1.760000 LF 1.725260 LD 1.720000 LAD 1.630000
Lq 1.680000 LG 1.876953 LQ 1.604000 LAG 1.550000
rd 0.190000E-02 rF 0.108962E-02 rD 0.149208E-01
rq 0.190000E-02 rG 0.829795E-02 rQ 0.130218E-01

EIGEN/SSR (OS/2 Version) : MWG PSS STUDY
Files: MWGC1.dat & MWG2.aux

MVA=100 H=1 EXCITATION Type= WSCC-A (DC1)

EXHIBIT 1 (Con)

PSS Input=Frequency PSS Gain=1.71 (1/3-rd Inst Gain)

****** PAL100.BAT ******** RUN ON 3-13-1992 AT 11:26

N EQUALS 19

ROOTR	ROOTI	ROOTR	ROOTI
0.00043082	2.74720948	0.00043082	-2.74720948
-0.78729832	0.73452675	-0.78729832	-0.73452675
-1.00000000			
-2.31568320	24.14473273	-2.31568320	-24.14473273
-2.95828698	376.93396058	-2.95828698	-376.93396058
-5.49357252			
-16.16845157	18.86731404	-16.16845157	-18.86731404
-18.97577702			
-19.11602928	376.99116136	-19.11602928	-376.99116136
-28.97073243			
-69.97648295	2.95416821	-69.97648295	-2.95416821
-192.47686559			

TIME FOR THIS DATA SET WAS 0.07 MINUTES

1	VFU1	1.15800E-3			EFDU1			
3	VRU1	400.	0.02		-TGRU1	-VTU1	PSSU1	
3	EFDU1	.6667	.5333		VRU1			
4	TGRU1	.03	1.0		EFDU1			
1	VTU1	.577			GEN1VT			
5	PSSU1	1.71	.02	.2	LLGU1			
5	LLGU1	1.00	.02	.2	WSOU1			
4	WSOU1	1.00	1.00		GEN1FR			
4	GEN1FR	.00265	.005		GEN1TH			

EIGEN/SSR (OS/2 Version) : MWG PSS STUDY
Files: MWGC1.dat & MWG2.aux

EXHIBIT 1 (con)

MVA=100 H=1 EXCITATION Type= WSCC-A (DC1)

PSS Input=Frequency PSS Gain=0.0 (NO PSS CASE)

****** PAL100.BAT ******** RUN ON 3-13-1992 AT 11:21

N EQUALS 19

ROOTR	ROOTI	ROOTR	ROOTI
0.00049617	2.74719061	0.00049617	-2.74719061
-0.78766041	0.73428038	-0.78766041	-0.73428038
-1.00000000			
-1.50595726	22.06111436	-1.50595726	-22.06111436
-2.95825088	376.93397776	-2.95825088	-376.93397776
-5.49366107			
-19.11602928	376.99116134	-19.11602928	-376.99116134
-25.93509745	10.58805510	-25.93509745	-10.58805510
-31.23094562	2.67823436	-31.23094562	-2.67823436
-50.00000000			
-50.00000000			
-200.00000000			

TIME FOR THIS DATA SET WAS 0.07 MINUTES

1	VFU1	1.15800E-3			EFDU1		
3	VRU1	400.	0.02		-TGRU1	-VTU1	PSSU1
3	EFDU1	.6667	.5333		VRU1		
4	TGRU1	.03	1.0		EFDU1		
1	VTU1	.577			GEN1VT		
5	PSSU1	0.00	.02	.2	LLGU1		
5	LLGU1	1.00	.02	.2	WSOU1		
4	WSOU1	1.00	1.00		GEN1FR		
4	GEN1FR	.00265	.005		GEN1TH		

EIGEN/SSR (OS/2 Version) : MWG PSS STUDY
Files: MWGC1.dat & MWG2.aux

MVA=100 H=1 EXCITATION Type= WSCC-A (DC1)

PSS Input=Frequency PSS Gain=5.13 (INST GAIN)

EXHIBIT 1 (Con)

****** PAL100.BAT ******** RUN ON 3-13-1992 AT 11:24

N EQUALS 19

ROOTR	ROOTI	ROOTR	ROOTI
0.00030027	2.74724779	0.00030027	-2.74724779
-0.01133703	29.46794079	-0.01133703	-29.46794079
-0.78657350	0.73501835	-0.78657350	-0.73501835
-1.00000000			
-2.95835889	376.93392579	-2.95835889	-376.93392579
-5.49339562			
-10.05562814	15.94679594	-10.05562814	-15.94679594
-16.44960286			
-19.11602928	376.99116141	-19.11602928	-376.99116141
-29.01969293			
-63.46248782			
-119.56301604			
-168.71710211			

TIME FOR THIS DATA SET WAS 0.07 MINUTES

1	VFU1	1.15800E-3			EFDU1			
3	VRU1	400.	0.02		-TGRU1	-VTU1	PSSU1	
3	EFDU1	.6667	.5333		VRU1			
4	TGRU1	.03	1.0		EFDU1			
1	VTU1	.577			GEN1VT			
5	PSSU1	5.13	.02	.2	LLGU1			
5	LLGU1	1.00	.02	.2	WSOU1			
4	WSOU1	1.00	1.00		GEN1FR			
4	GEN1FR	.00265	.005		GEN1TH			