IEEE PES Task Force on Benchmark Systems for Stability Controls

Report on Benchmark #2
The Brazilian 7 Bus (Equivalent Model)

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The results presented in this report correspond to time-domain simulations of different disturbances and eigenvalue calculations for the Benchmark System #2 performed with PSS/E and ANATEM/PacDyn software.

This system, as described in [1], is oscillatory unstable without power system stabilizers. All linear techniques for locating stabilizers (e.g., transfer function residues, participation factors, etc.) indicate that the unstable mode can be stabilized by a PSS at Itaipu (bus #4).

However, the key characteristic of this system is the presence of a zero in the transfer function associated with the PSS at Itaipu (bus #4) that precludes proper damping of the mode with just one PSS at Itaipu [1]. Therefore, stabilizers at the other machines (except the equivalent machine at bus #7) are necessary to eliminate this poorly located transfer function zero and thus achieve sufficient damping for the unstable oscillation mode.

- **Time domain simulations**

The main objective associated with the selection of these disturbances is to assess the system damping and the effectiveness of the proposed stabilizers in providing damping to these oscillations. Both disturbances excite the unstable interarea mode of 0.85 Hz. Results are presented for the system without PSS, with PSS at Itaipu only, and with PSS at all generators except the equivalent (at bus #7).

The first set of simulations comprises the connection of a 500 Mvar reactor at the Ivaiporã 765 kV bus (bus #6) at $t = 1.0$ second. The reactor is disconnected 100 ms later, without any further changes in the system topology.

The second set of simulations corresponds to a 2% step in voltage reference at the Itaipu machine (bus #4), applied at $t = 1.0$ second. The step is removed (i.e., –2% step is applied) at $t = 11.0$ seconds.

- **Eigenanalysis**

The eigenanalysis consists in the calculation of the linear system eigenvalues and participation factors. The results are summarized in tables.

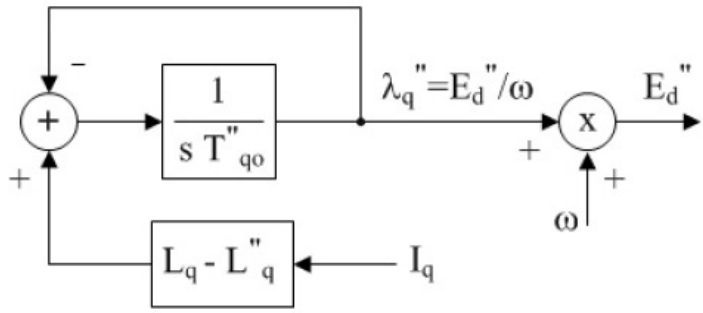
1. System model

1.1 ANATEM/PacDyn Dynamic Simulation Models

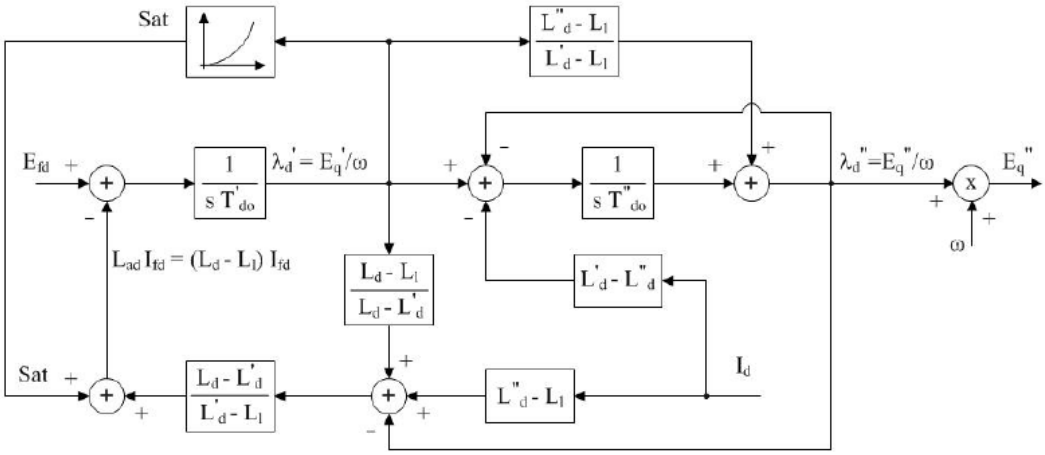
The models and associated parameters for the dynamic simulation models used in the ANATEM/PacDyn setup are described in this section.

1.1.a) Synchronous Machines

The generator model used to represent the salient pole units is the ANATEM library model "Synchronous Machine Model 02", shown in the block diagram in Figure 1, which is a 5th order dynamic model. Saturation effects are neglected in all cases. Details about the implementation of the model are available in the software documentation [2].



a) Quadrature axis



b) Direct axis

Figure 1: Block Diagram for the ANATEM's "synchronous Machine Model 02".

1.1.b) Excitation Systems

The excitation systems of all generators are represented by the ANATEM's library model "Voltage Regulator Model 20" shown in Figure 2, with the parameters in Table 1.

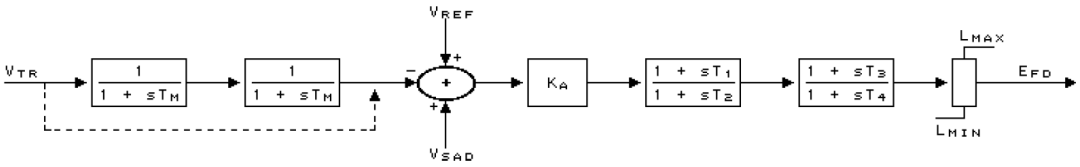


Figure 2: Block Diagram for the Anatem's "Voltage Regulator Model 20".

Table 1: Parameters of the Automatic Voltage Regulators Modeled in ANATEM

Parameter	Value
T_m	0.0 s
K_a	30.00 pu
T_1	0.00 s
T_2	0.05 s
T_3	10.00 s
T_4	10.00 s
L_{min}	-4.00 pu
L_{max}	5.00 pu

1.1.c) Power System Stabilizers

The power system stabilizers are represented in ANATEM by the library model "Stabilizer Model 01" shown in the block diagram in Figure 3, with the parameters in Table 2.

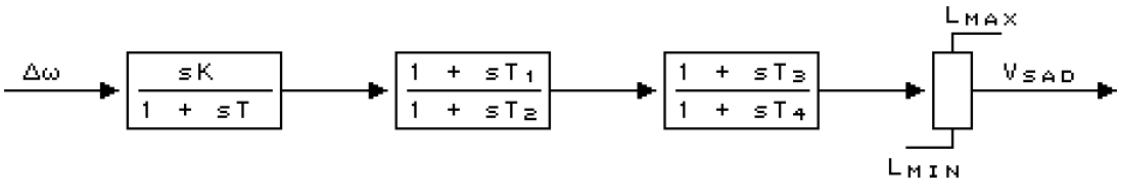


Figure 3: Power System Stabilizer Modeled in ANATEM.

Table 2: Parameters of the Power System Stabilizers Modeled in ANATEM.

Parameter	Value	
	Units 1, 2 and 3	Unit4
K	30 pu	48 pu
T	3.000 s	3.000 s
T_1	0.300 s	0.520 s
T_2	0.075 s	0.065 s
T_3	0.300 s	0.520 s
T_4	0.075 s	0.065 s
L_{min}	-0.100 pu	-0.100 pu
L_{max}	0.100 pu	0.100 pu

1.2 PSS/E Dynamic Simulation Models

The models and associated parameters for the dynamic simulation models used in the PSS/E setup are described in this section.

1.2.a) Synchronous Machines

The generator model used to represent the salient pole units is the PSS®E model GENSAE, shown in the block diagram in Figure 4. This is a 5th order dynamic model with the saturation represented by the geometric (exponential) function $S = S1.0\,E^X$, where X = ln($S1.2$/$S1.0$)/ln($E1.0$) and E is the input. Speed damping D is set to zero for all generators, as should be the case when using sub-transient generator models. Details about the implementation of the model are available in the software documentation [3].

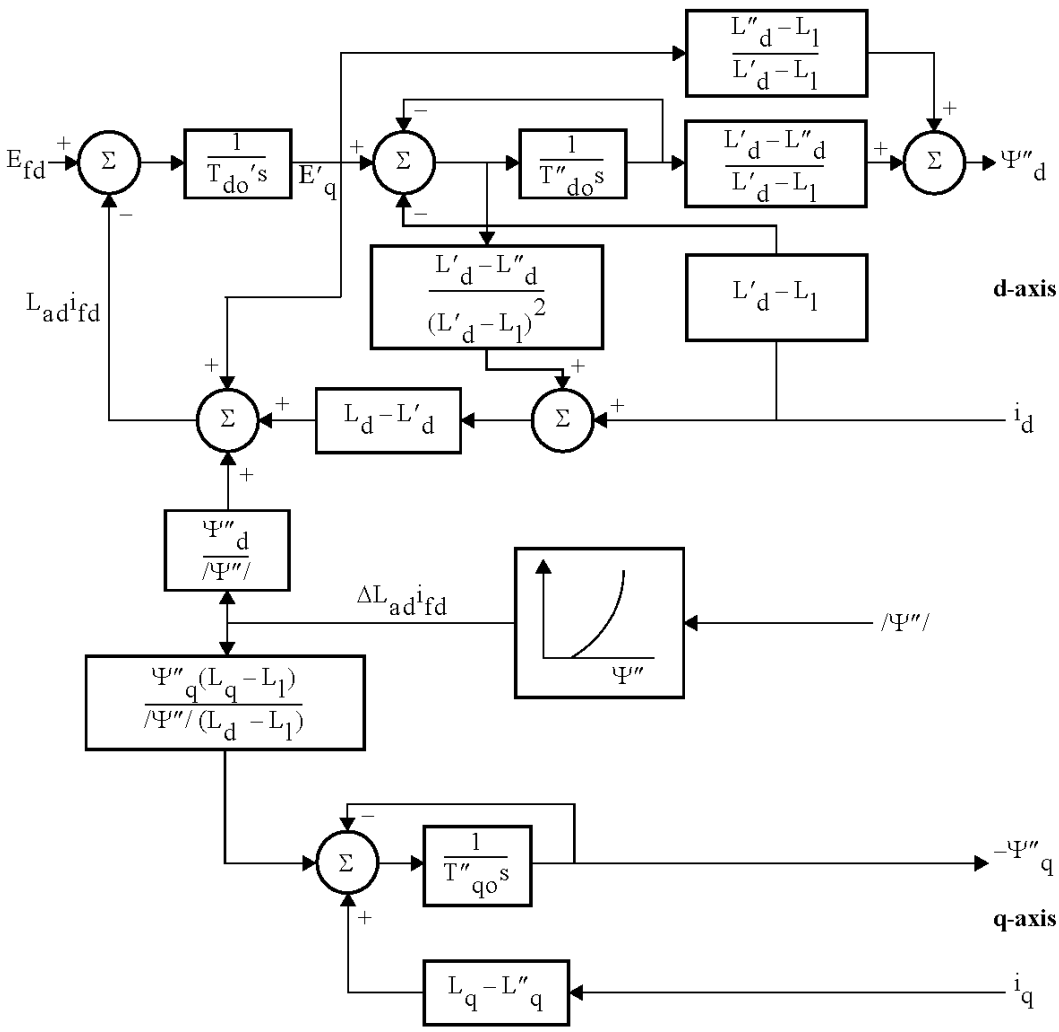


Figure 4: Block Diagram for the PSS/E Model GENSAE.

The details associated with the representation of the saturation of the generators should not dramatically interfere with the results of a small-signal (linearized) analysis of the system performance. On the other hand, the proper representation of saturation is extremely important

for transient stability and the determination of rated and ceiling conditions (minimum and maximum generator field current and generator field voltage) for the excitation system. The assumed saturation factors $S(1.0) = 0.001$ and $S(1.2) = 0.01$ essentially neglect saturation effects.

1.2.b) Excitation Systems

All excitation systems are considered identical and are represented by the same dynamic model and set of parameters. It is used the PSS®E simplified excitation system model SEXS [3], shown in Figure 5, with the parameters presented in Table 3.

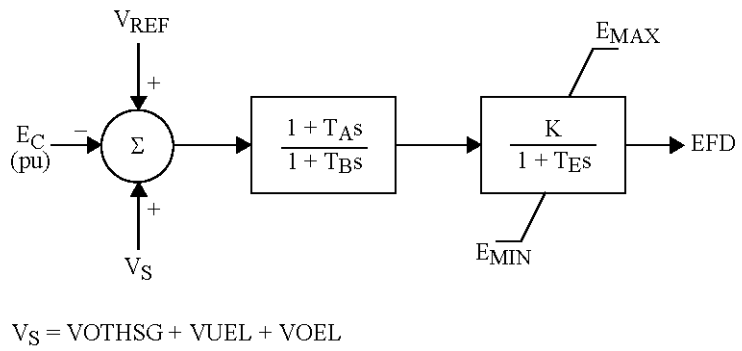


Figure 5: Block Diagram for the PSS/E Model SEXS.

Table 3: Dynamic Model Data for the Excitation Systems (PSS/E Model SEXS)

Parameters			
Description	**Symbol**	**Value**	**Unit**
TGR block 1 transient gain	T_A/T_B	1	–
TGR block 1 denominator time constant	T_B	1	s
Exciter gain	K	30	pu
Exciter time constant	T_E	0.05	s
Max. AVR output	E_{min}	–4	pu
Min. AVR output	E_{max}	5	pu

1.2.c) Power System Stabilizers

This benchmark system considers power system stabilizers (PSS) in all machines except the machine connected to bus #7 (EQUIVALENT). All PSSs are derived from rotor speed deviation and have the same structure, namely two lead-lag blocks, one wash-out block, and a gain.

The IEEE Std. 421.5(2005) model PSS1A [4] are used to represent the power system stabilizers. This model can be represented in PSS®E by the IEEEST model [3]. The block diagram of the IEEEST model is shown in Figure 6 and the used parameters are given in Table 4.

The output limits are set to +/– 10%, while the logic to switch off the PSS for voltages outside a normal operation range is ignored (parameters V_{CU} and V_{CL} set to zero). The input signal is rotor speed deviation.

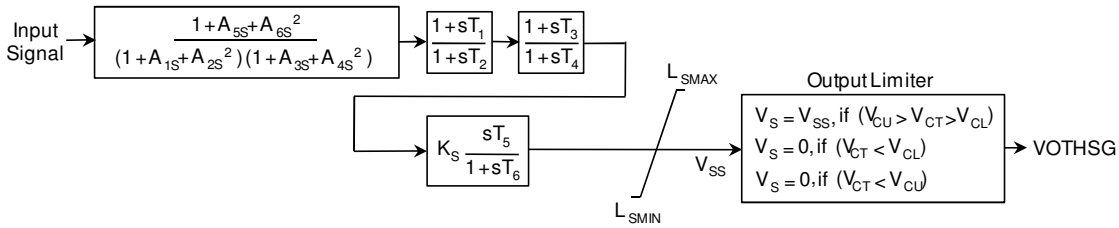


Figure 6: Power System Stabilizer (PSS/E Model IEEEST).

Table 4: Dynamic Model Data for Power System Stabilizers (PSS/E Model IEEEST)

Parameters			**Buses**	
Description	**Symbol**	**Unit**	**1, 2, 3**	**4**
2nd order denominator coefficient	A_1	–	0	0
2nd order denominator coefficient	A_2	–	0	0
2nd order numerator coefficient	A_3	–	0	0
2nd order numerator coefficient	A_4	–	0	0
2nd order denominator coefficient	A_5	–	0	0
2nd order denominator coefficient	A_6	–	0	0
1st lead-lag numerator time constant	T_1	s	0.30	0.52
1st lead-lag denominator time constant	T_2	s	0.075	0.065
2nd lead-lag numerator time constant	T_3	s	0.30	0.52
2nd lead-lag denominator time constant	T_4	s	0.075	0.065
Washout block numerator time constant	T_5	s	3	3
Washout block denominator time constant	T_6	s	3	3
PSS gain	K_S	pu	10	16
PSS max. output	L_{Smax}	pu	0.1	0.1
PSS min. output	L_{Smin}	pu	-0.1	-0.1
Upper voltage limit for PSS operation	V_{CU}	pu	0	0
Lower voltage limit for PSS operation	V_{CL}	pu	0	0

2. Comparison of results ANATEM/PacDyn vs PSS/E

2.1Time-domain simulation results

The time-domain responses for the two perturbations simulated with PSS/E and ANATEM programs are compared in Sections 2.1.a) and 0. An acceptable matching is qualitatively appreciated between the results of both programs, for the cases with and without PSS.

2.1 a) Case A: 500 MVAr Reactor Applied to Bus #6

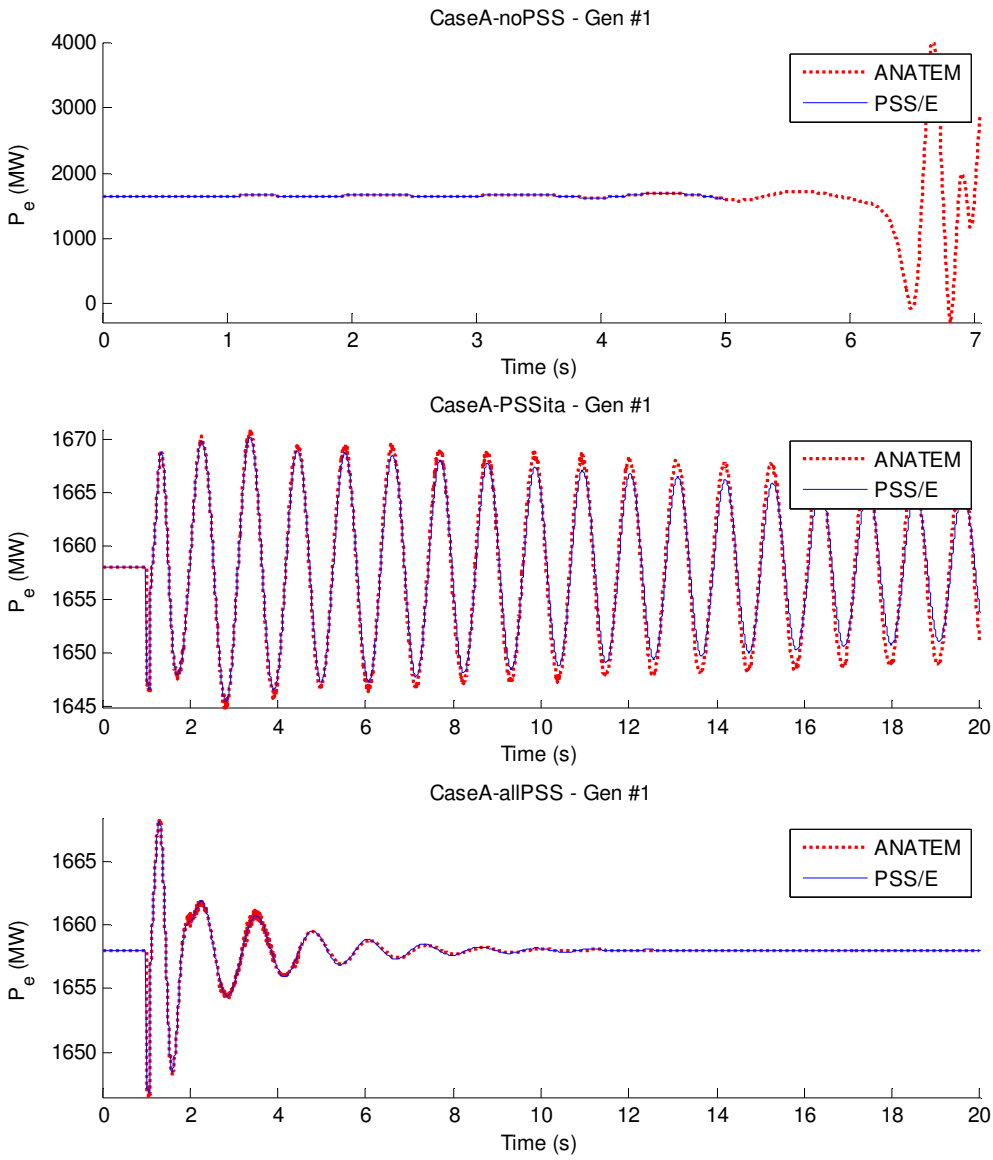


Figure 7: Output power Response of Generator #1 to a 500 MVAr Reactor Applied to Bus #6. Top: no PSS; Center: PSS at Itaipu; Bottom: PSS at all generators.

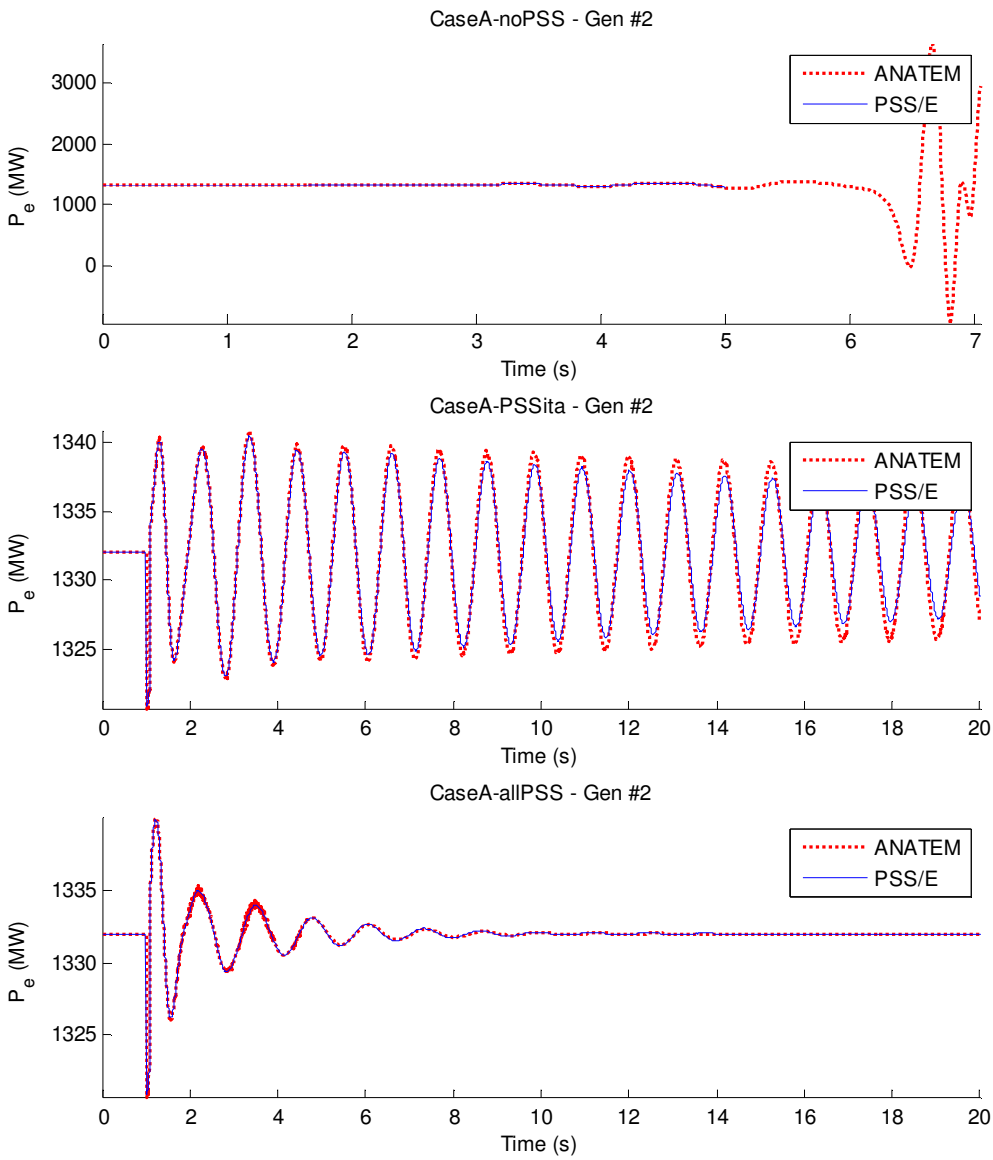


Figure 8: Output power Response of Generator #2 to a 500 MVAr Reactor Applied to Bus #6. Top: no PSS; Center: PSS at Itaipu; Bottom: PSS at all generators.

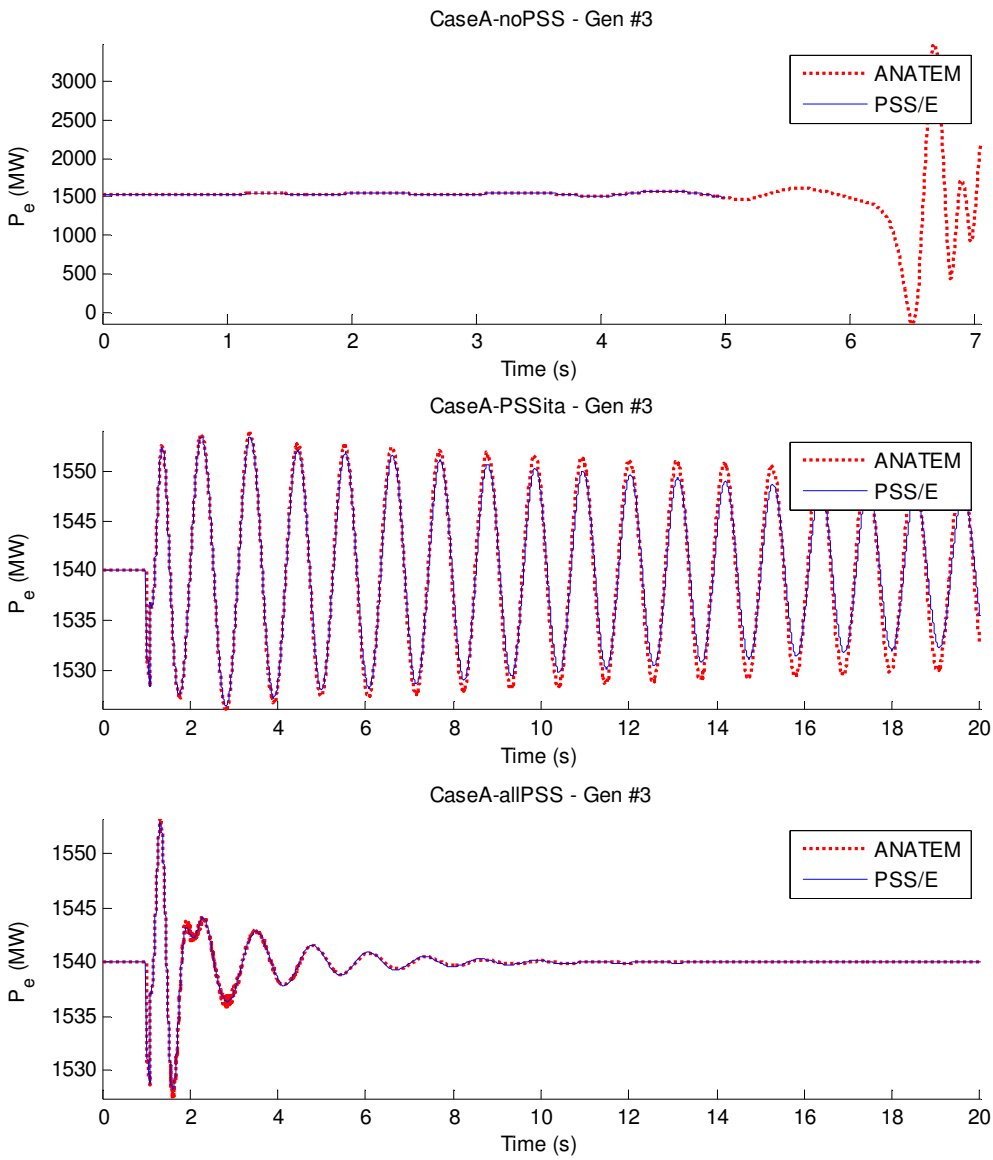


Figure 9: Output power Response of Generator #3 to a 500 MVAr Reactor Applied to Bus #6. Top: no PSS; Center: PSS at Itaipu; Bottom: PSS at all generators.

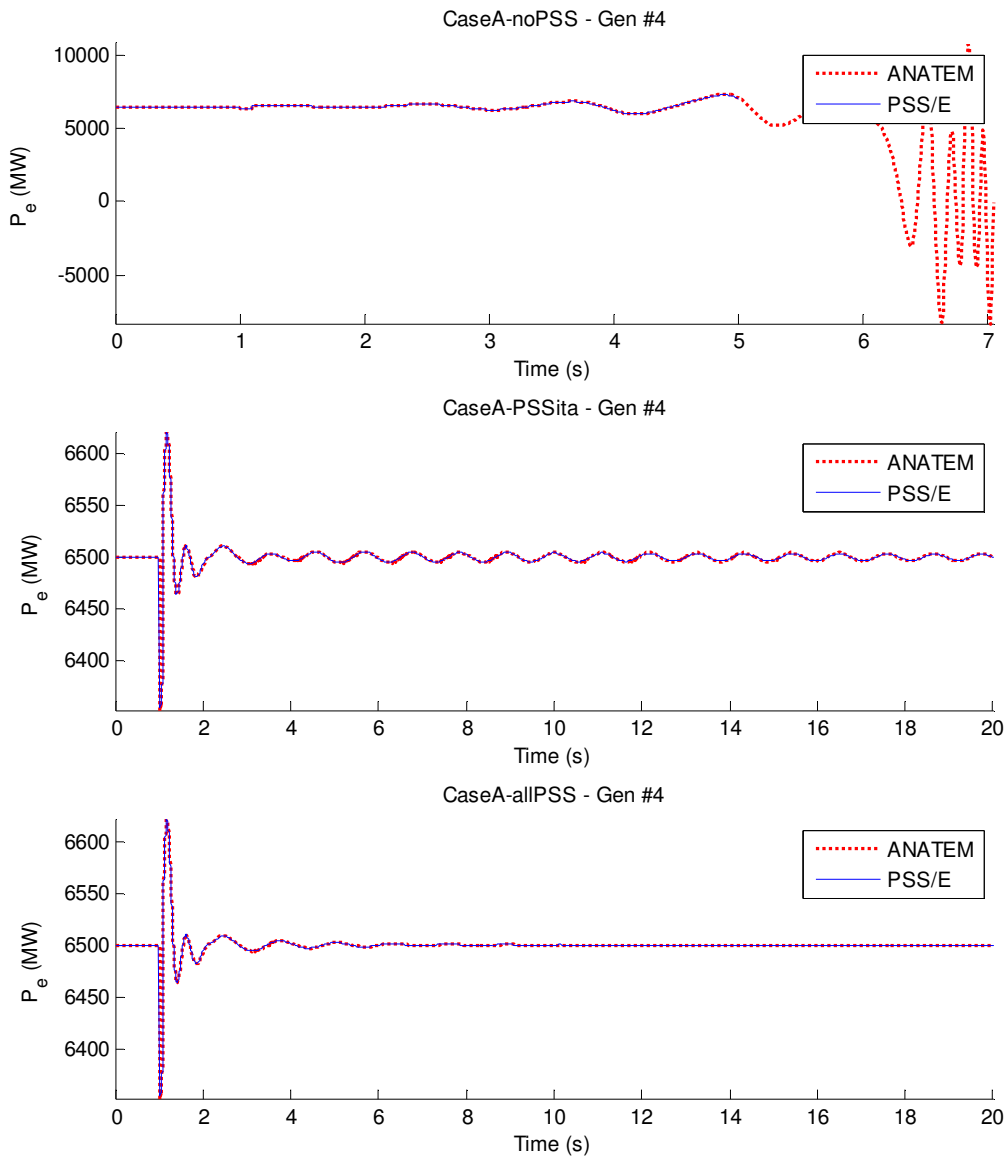


Figure 10: Output power Response of Generator #4 to a 500 MVAr Reactor Applied to Bus #6. Top: no PSS; Center: PSS at Itaipu; Bottom: PSS at all generators.

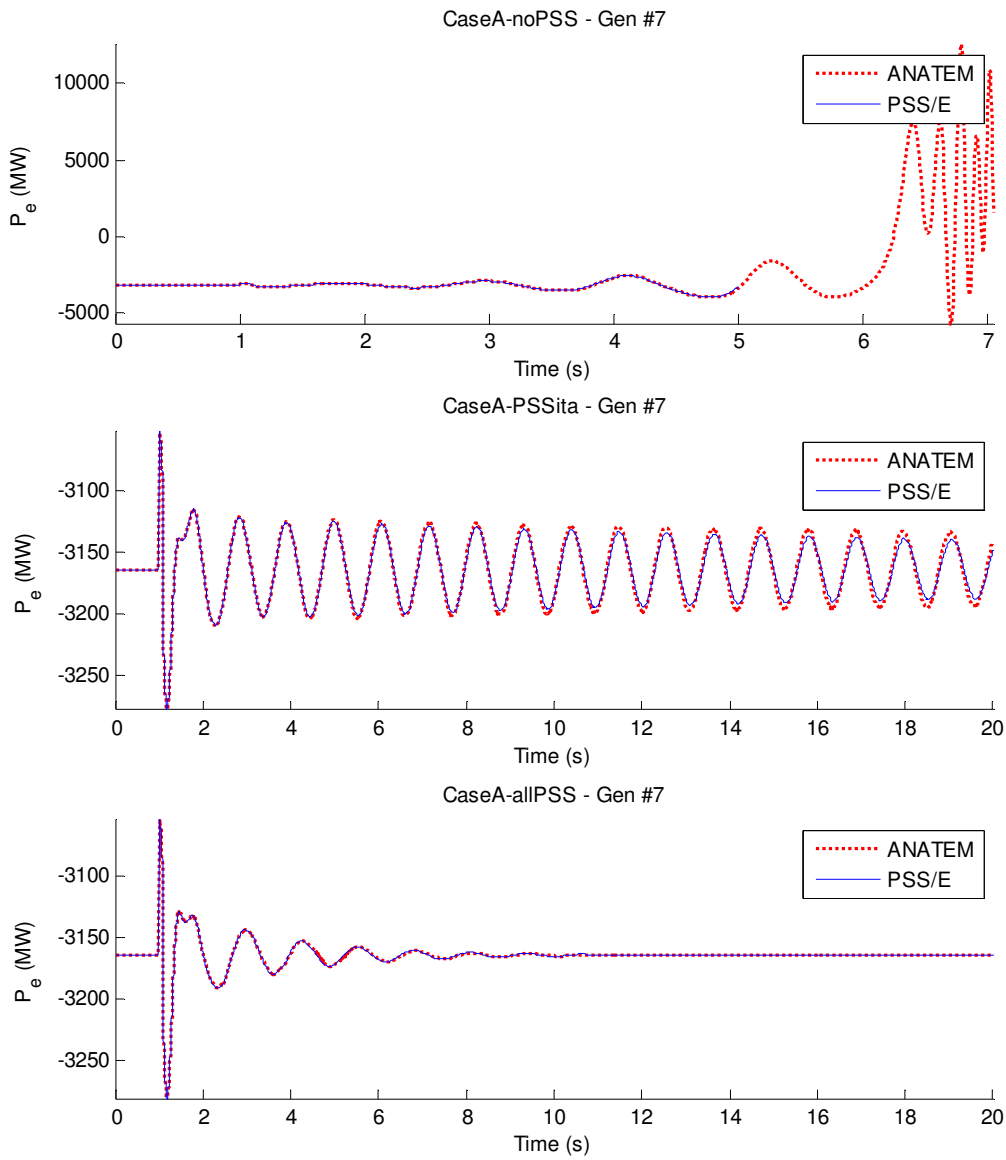


Figure 11: Output power Response of Generator #7 to a 500 MVAr Reactor Applied to Bus #6. Top: no PSS; Center: PSS at Itaipu; Bottom: PSS at all generators.

2.1.b) Case B: Step applied to the AVR reference of Generator #4

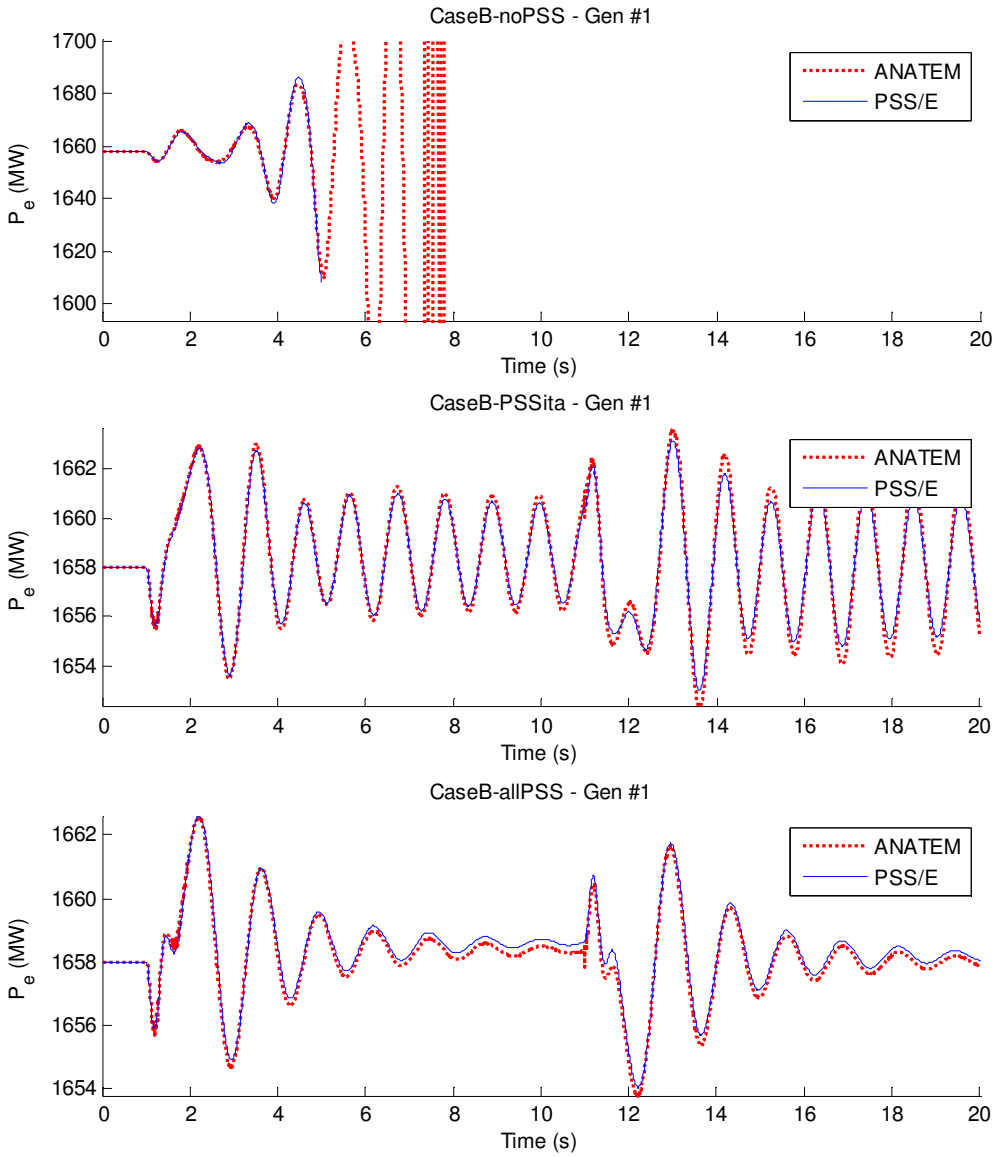


Figure 12: Output power response of Generator #1 to step applied to the AVR reference of Generator #4. Top: no PSS; Center: PSS at Itaipu; Bottom: PSS at all generators.

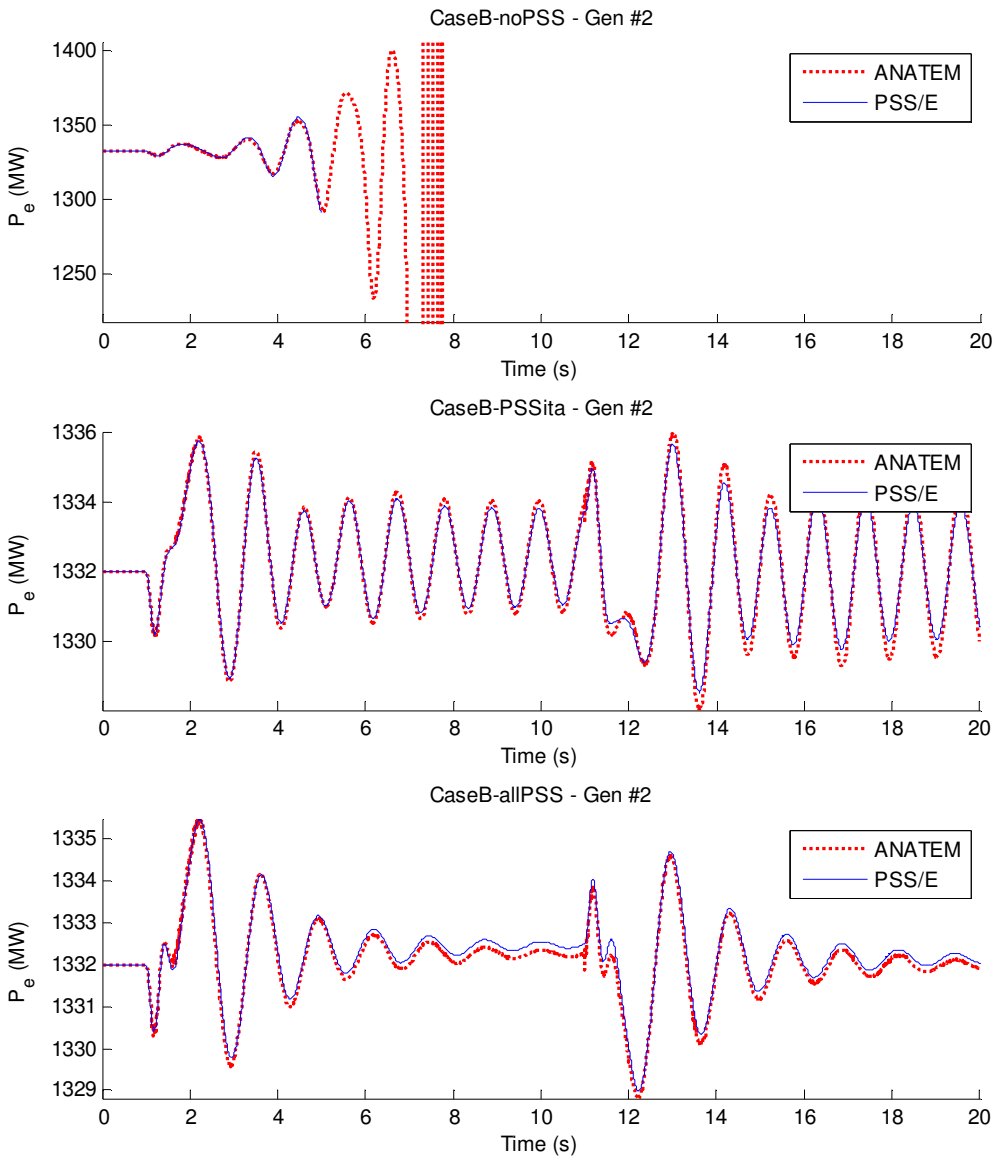


Figure 13: Output power response of Generator #2 to step applied to the AVR reference of Generator #4. Top: no PSS; Center: PSS at Itaipu; Bottom: PSS at all generators.

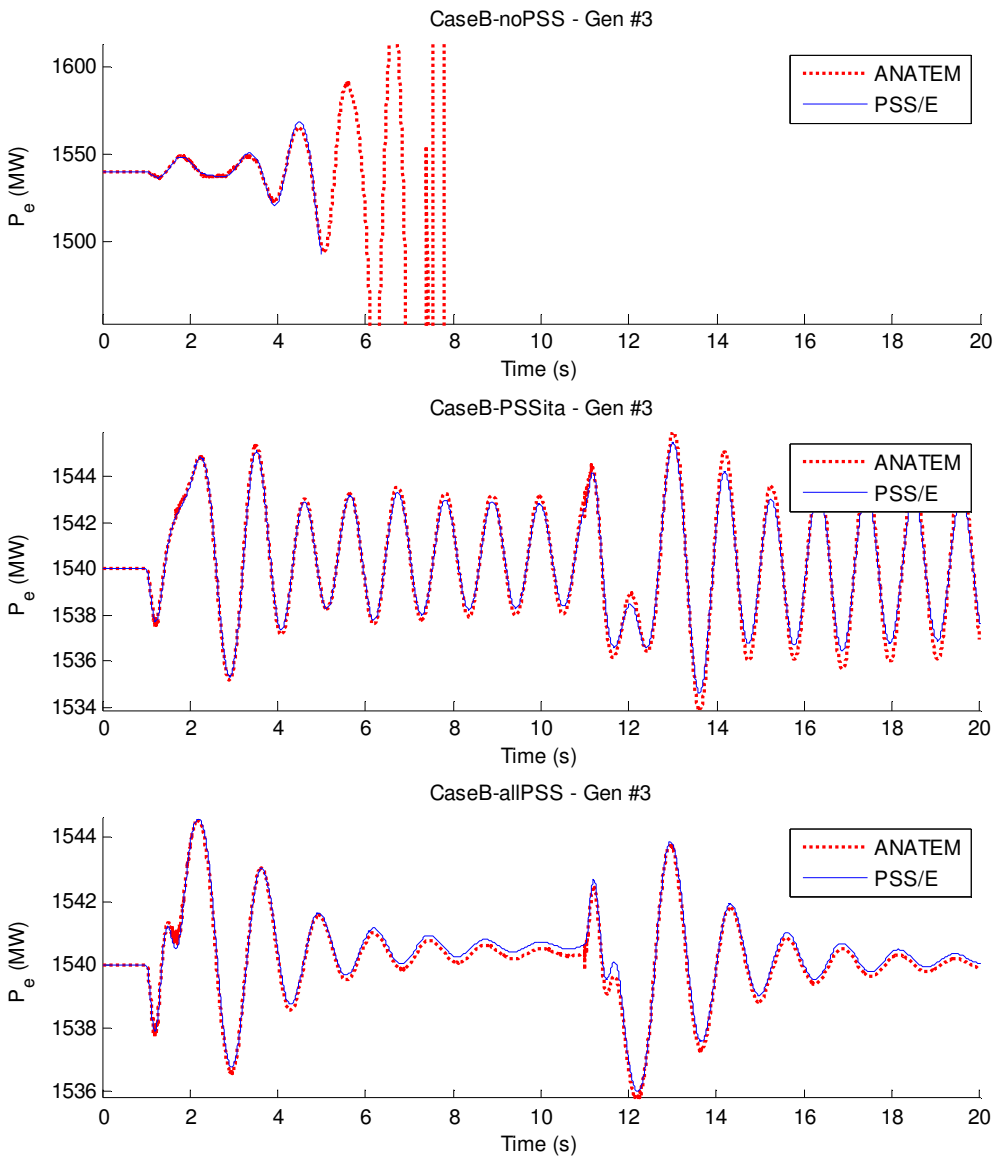


Figure 14: Output power response of Generator #3 to step applied to the AVR reference of Generator #4. Top: no PSS; Center: PSS at Itaipu; Bottom: PSS at all generators.

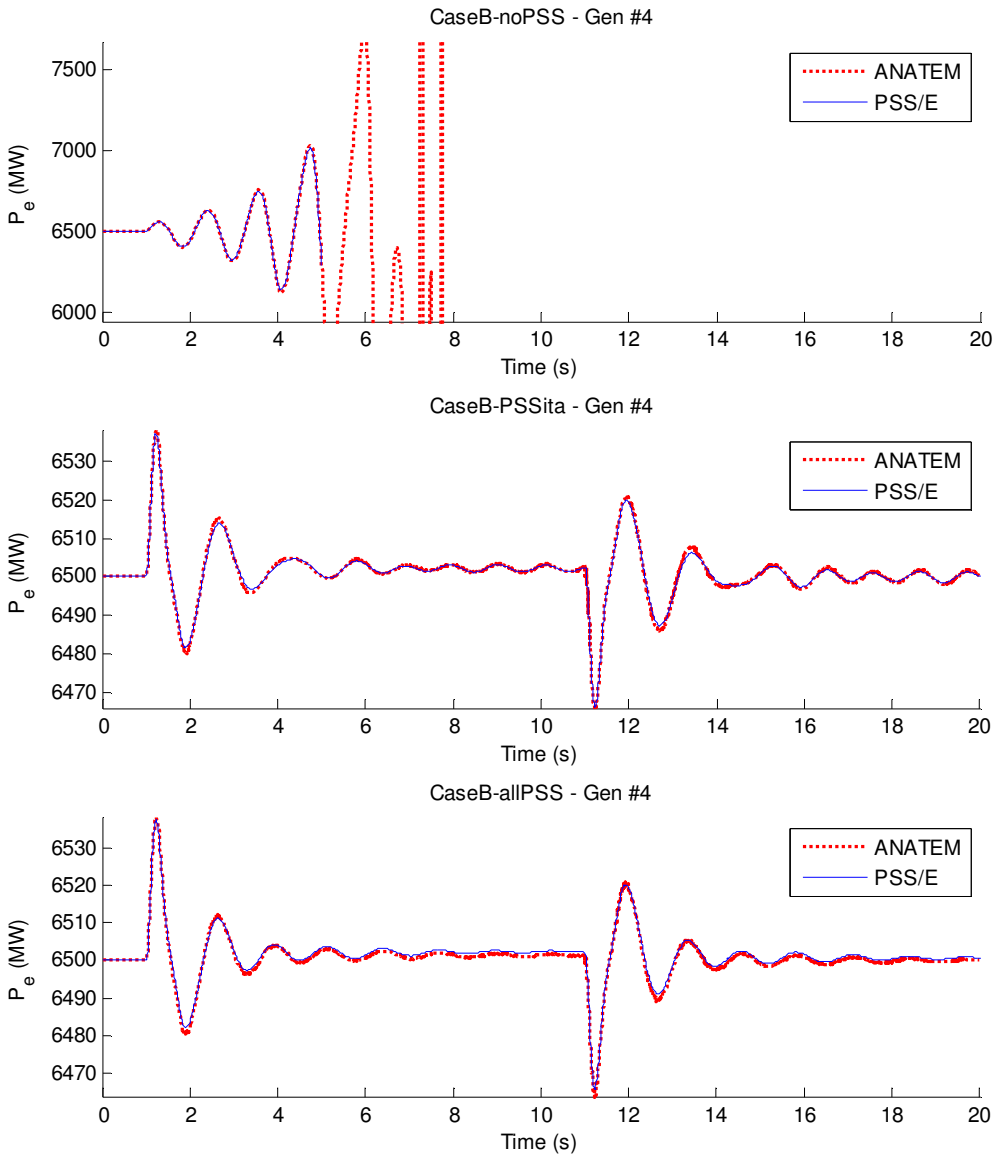


Figure15: Output power response of Generator #4 to step applied to the AVR reference of Generator #4. Top: no PSS; Center: PSS at Itaipu; Bottom: PSS at all generators.

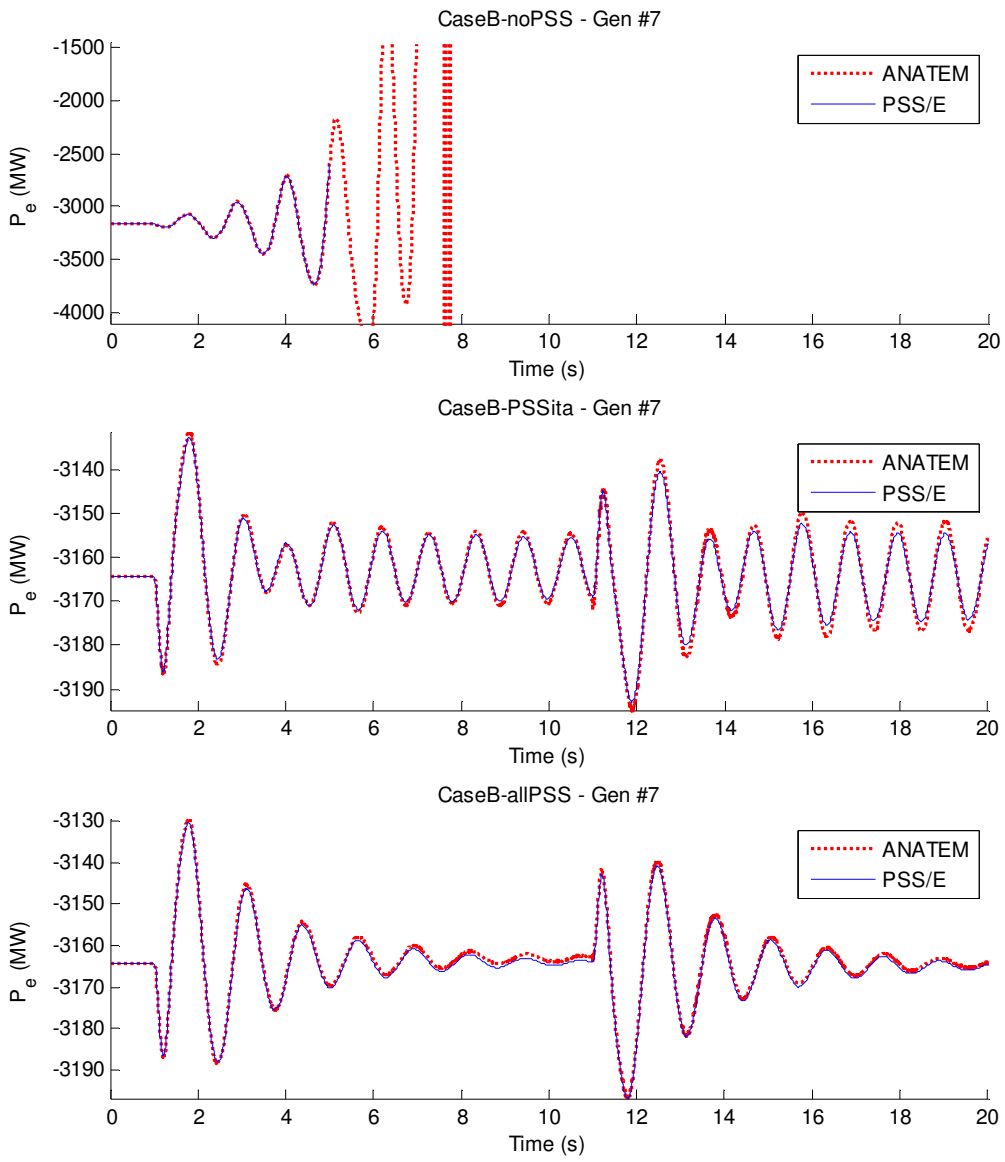


Figure 16: Output power response of Generator #7 to step applied to the AVR reference of Generator #4. Top: no PSS; Center: PSS at Itaipu; Bottom: PSS at all generators.

2.2 Eigenanalysis

2.2.a) PacDyn vs PSS/E PSSPLT Comparison

This section provides the system eigenvalues calculated with both software for the cases with no PSS, with PSS at generator #4 only, and with PSS at all generators. In the first case, good matching is observed for the electromechanical modes. In the last two cases (with PSS), the results obtained with PSSPLT highly depend on the processed signal.

- **System with no PSS**

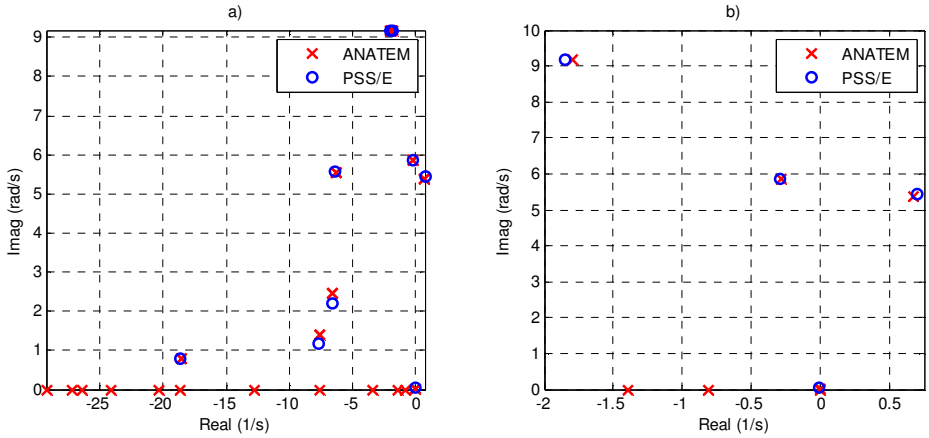


Figure 17: Eigenvalues Calculated with PSS®E Program PSSPLT and PacDyn for the system with no PSS. a) Complete set of eigenvalues; b) Enlarged view in the region of the electromechanical modes.

- **System with PSS at generator #4**

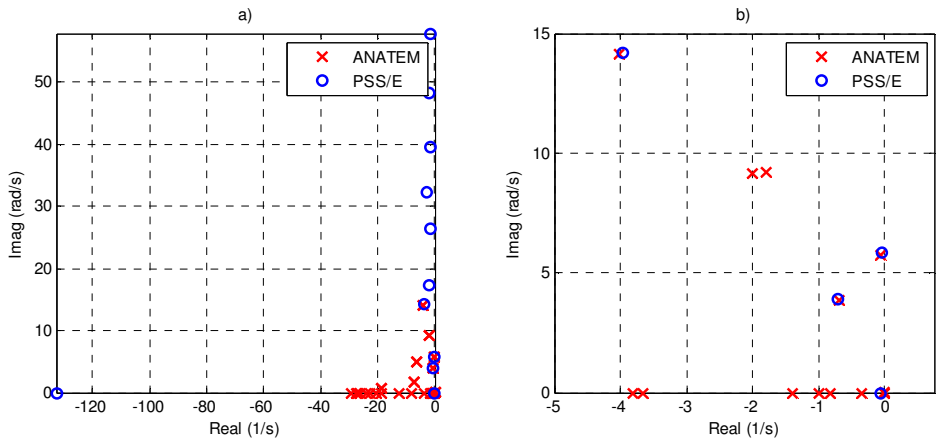


Figure 18: Eigenvalues Calculated with PSS®E Program PSSPLT and PacDyn for the system with PSS at generator #4 (Itaipu). PSS/E results from Table 11 (Itaipu active power). a) Complete set of eigenvalues; b) Enlarged view in the region of the electromechanical modes.

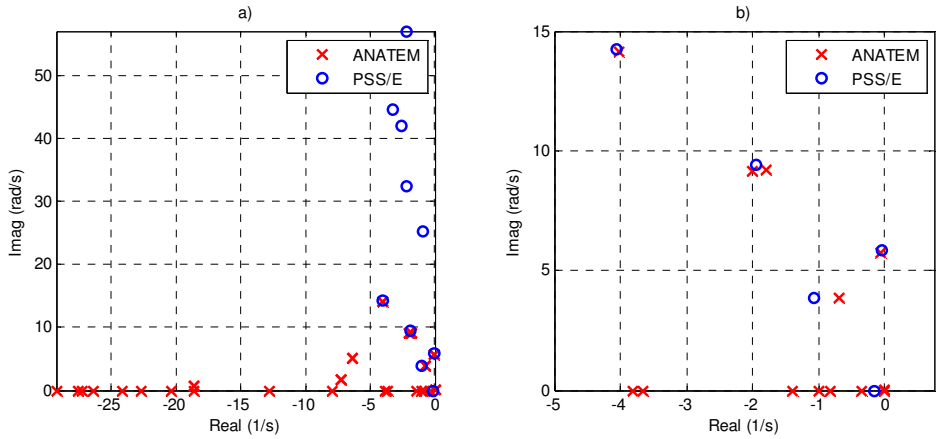


Figure 19: Eigenvalues Calculated with PSS®E Program PSSPLT and PacDyn for the system with PSS at generator #4 (Itaipu). PSS/E results from Table 12 (Santiago active power). a) Complete set of eigenvalues; b) Enlarged view in the region of the electromechanical modes.

- **System with PSS at all generators**

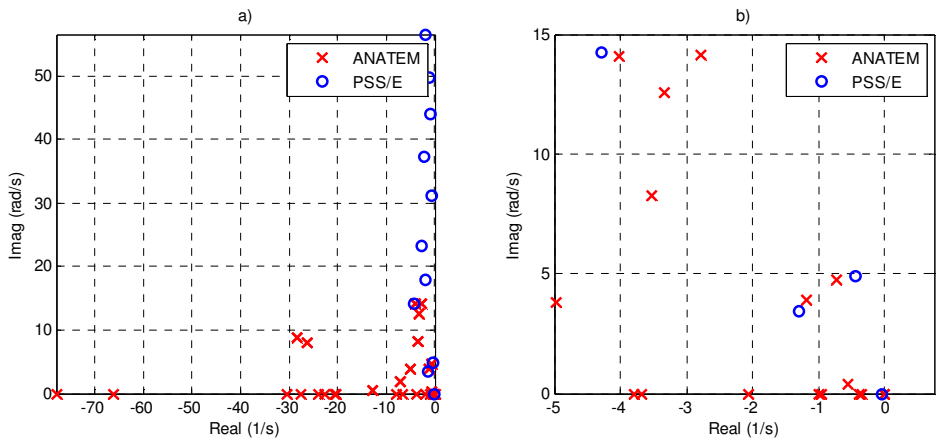


Figure 20: Eigenvalues Calculated with PSS®E Program PSSPLT and PacDyn for the system with PSS at all generators. PSS/E results from Table 13 (Itaipu active power). a) Complete set of eigenvalues; b) Enlarged view in the region of the electromechanical modes.

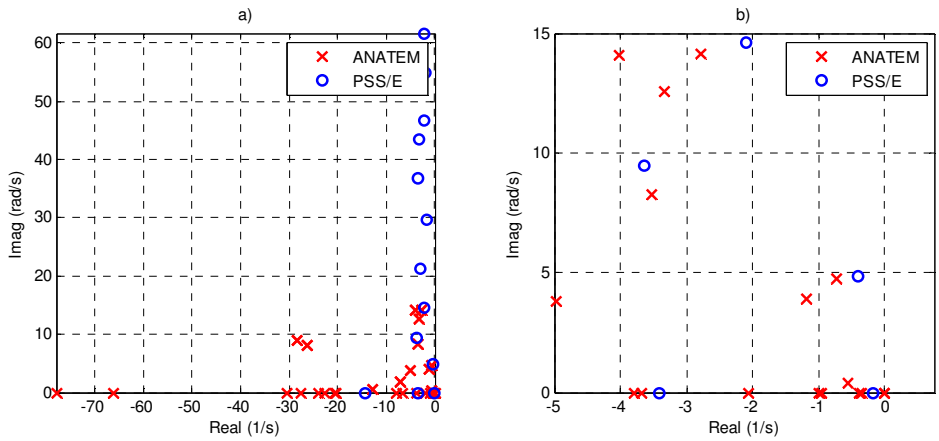


Figure 21: Eigenvalues Calculated with PSS®E Program PSSPLT and PacDyn for the system with PSS at all generators. PSS/E results from

(Santiago active power). a) Complete set of eigenvalues; b) Enlarged view in the region of the electromechanical modes.

2.2.b) PacDyn Results

Table 5: Eigenvalues Calculated with PacDyn for the system without PSS

#	Real	Imaginary	Module	Freq. (Hz)	Damp(%)	Part. Factor			
1	-1.7934	9.1875	9.3609	1.4622	19.158	DELT	S Santiago	#	2
2	-2.0053	9.172	9.3887	1.4598	21.359	DELT	FOZ AREIA	#	1
3	-0.2834	5.8576	5.8645	0.9323	4.8325	WW	S Segredo	#	3
4	-6.3366	5.5294	8.41	0.88	75.347	EQ'	S Segredo	#	3
5	0.6734	5.381	5.423	0.8564	-12.417	WW	EQUIV SE	#	7
6	-6.6097	2.4542	7.0506	0.3906	93.746	EQ'	EQUIV SE	#	7
7	-7.6444	1.3874	7.7693	0.2208	98.393	EQ''	ITAIPU	#	4
8	-18.585	0.7903	18.602	0.1258	99.91	ED''	S Santiago	#	2
9	-9.18E-07	0.00022	0.00022	0.00004	0.4086	DELT	EQUIV SE	#	7
10	-29.222	0	29.222	0	100	ED''	S Segredo	#	3
11	-27.205	0	27.205	0	100	EQ''	S Santiago	#	2
12	-26.348	0	26.348	0	100	EQ''	FOZ AREIA	#	1
13	-24.137	0	24.137	0	100	EQ''	S Segredo	#	3
14	-20.337	0	20.337	0	100	x 0005	AVR-G7	#	7
15	-20.31	0	20.31	0	100	x 0005	AVR-G4	#	4
16	-18.59	0	18.59	0	100	x 0005	AVR-G3	#	3
17	-12.765	0	12.765	0	100	ED''	FOZ AREIA	#	1
18	-7.6223	0	7.6223	0	100	ED''	EQUIV SE	#	7
19	-3.3997	0	3.3997	0	100	EQ'	EQUIV SE	#	7
20	-1.3988	0	1.3988	0	100	EQ'	S Santiago	#	2
21	-0.8114	0	0.8114	0	100	EQ'	S Segredo	#	3
22	-9.18E-07	-0.00022	0.00022	-0.00004	0.4086				
23	-18.585	-0.7903	18.602	-0.1258	99.91				
24	-7.6444	-1.3874	7.7693	-0.2208	98.393				
25	-6.6097	-2.4542	7.0506	-0.3906	93.746				
26	0.6734	-5.381	5.423	-0.8564	-12.417				
27	-6.3366	-5.5294	8.41	-0.88	75.347				
28	-0.2834	-5.8576	5.8645	-0.9323	4.8325				
29	-2.0053	-9.172	9.3887	-1.4598	21.359				
30	-1.7934	-9.1875	9.3609	-1.4622	19.158				

Table 6: Eigenvalues Calculated with PacDyn for the system with PSS at generator #4 (Itaipu)

#	Real	Imaginary	Module	Freq. (Hz)	Damp(%)	Part. Factor			
1	-4.0106	14.117	14.675	2.2467	27.329	WW	ITAIPU	#	4
2	-1.7963	9.1831	9.3571	1.4615	19.197	WW	S Santiago	#	2
3	-2.0052	9.1695	9.3862	1.4594	21.363	DELT	FOZ AREIA	#	1
4	-0.06379	5.745	5.7453	0.9143	1.1102	WW	EQUIV SE	#	7
5	-6.384	5.023	8.1232	0.7994	78.59	EQ'	S Segredo	#	3
6	-0.6875	3.8757	3.9362	0.6168	17.467	DELT	ITAIPU	#	4
7	-7.2413	1.6383	7.4243	0.2607	97.535	ED''	EQUIV SE	#	7
8	-18.586	0.7874	18.603	0.1253	99.91	ED''	S Santiago	#	2
9	9.31E-06	0.00005	0.00005	8.48E-06	-17.226	DELT	ITAIPU	#	4
10	-29.242	0	29.242	0	100	ED''	S Segredo	#	3
11	-27.581	0	27.581	0	100	EQ'	ITAIPU	#	4
12	-27.207	0	27.207	0	100	EQ''	S Santiago	#	2
13	-26.363	0	26.363	0	100	EQ''	FOZ AREIA	#	1
14	-24.133	0	24.133	0	100	EQ''	S Segredo	#	3
15	-22.706	0	22.706	0	100	EQ'	ITAIPU	#	4
16	-20.32	0	20.32	0	100	x 0005	AVR-G7	#	7
17	-18.598	0	18.598	0	100	x 0005	AVR-G3	#	3
18	-12.727	0	12.727	0	100	ED''	FOZ AREIA	#	1
19	-7.9595	0	7.9595	0	100	ED''	ITAIPU	#	4
20	-3.8175	0	3.8175	0	100	EQ'	ITAIPU	#	4
21	-3.6597	0	3.6597	0	100	EQ'	ITAIPU	#	4
22	-1.3986	0	1.3986	0	100	EQ'	S Santiago	#	2
23	-1	0	1	0	100	x 0008	PSSDW	#	44
24	-0.8124	0	0.8124	0	100	EQ'	S Segredo	#	3
25	-0.3437	0	0.3437	0	100	x 0003	PSSDW	#	44
26	9.31E-06	-0.00005	0.00005	-8.48E-06	-17.226				
27	-18.586	-0.7874	18.603	-0.1253	99.91				
28	-7.2413	-1.6383	7.4243	-0.2607	97.535				
29	-0.6875	-3.8757	3.9362	-0.6168	17.467				
30	-6.384	-5.023	8.1232	-0.7994	78.59				
31	-0.06379	-5.745	5.7453	-0.9143	1.1102				
32	-2.0052	-9.1695	9.3862	-1.4594	21.363				
33	-1.7963	-9.1831	9.3571	-1.4615	19.197				
34	-4.0106	-14.117	14.675	-2.2467	27.329				

Table 7: Eigenvalues Calculated with PacDyn for the system with PSS at generators #1, #2, #3 and #4.

#	Real	Imaginary	Module	Freq. (Hz)	Damp(%)	Part. Factor
1	-2.7827	14.109	14.38	2.2454	19.351	WW S Santiago # 2
2	-4.0184	14.102	14.663	2.2444	27.404	WW ITAIPU # 4
3	-3.3327	12.57	13.004	2.0005	25.629	WW S Segredo # 3
4	-28.429	8.8787	29.783	1.4131	95.453	EQ'' S Santiago # 2
5	-3.5283	8.2603	8.9822	1.3147	39.28	WW FOZ AREIA # 1
6	-26.192	8.0512	27.401	1.2814	95.586	x 0005 AVR-G3 # 3
7	-0.7171	4.7415	4.7955	0.7546	14.953	WW EQUIV SE # 7
8	-1.1907	3.9232	4.1	0.6244	29.043	DELT ITAIPU # 4
9	-4.9686	3.8012	6.2559	0.605	79.423	x 0005 PSSDW # 22
10	-7.1289	1.7855	7.3491	0.2842	97.004	ED'' EQUIV SE # 7
11	-12.901	0.4999	12.911	0.07956	99.925	ED'' FOZ AREIA # 1
12	-0.5534	0.3732	0.6674	0.05939	82.91	DELT FOZ AREIA # 1
13	0.00221	0	0.00221	0	-100	DELT FOZ AREIA # 1
14	-77.952	0	77.952	0	100	x 0005 PSSDW # 11
15	-66.054	0	66.054	0	100	x 0005 PSSDW # 11
16	-30.454	0	30.454	0	100	ED'' S Segredo # 3
17	-27.619	0	27.619	0	100	EQ' ITAIPU # 4
18	-23.842	0	23.842	0	100	ED'' S Santiago # 2
19	-22.692	0	22.692	0	100	EQ' ITAIPU # 4
20	-20.596	0	20.596	0	100	ED'' S Santiago # 2
21	-20.424	0	20.424	0	100	x 0005 AVR-G7 # 7
22	-7.8752	0	7.8752	0	100	ED'' ITAIPU # 4
23	-6.6169	0	6.6169	0	100	EQ' FOZ AREIA # 1
24	-3.7955	0	3.7955	0	100	EQ' ITAIPU # 4
25	-3.6806	0	3.6806	0	100	EQ' ITAIPU # 4
26	-2.0577	0	2.0577	0	100	x 0008 PSSDW # 11
27	-1	0	1	0	100	x 0008 PSSDW # 33
28	-1	0	1	0	100	x 0008 PSSDW # 22
29	-1	0	1	0	100	x 0008 PSSDW # 33
30	-0.9468	0	0.9468	0	100	EQ' S Segredo # 3
31	-0.3843	0	0.3843	0	100	x 0003 PSSDW # 33
32	-0.3532	0	0.3532	0	100	x 0003 PSSDW # 22
33	-0.3401	0	0.3401	0	100	x 0003 PSSDW # 44
34	-0.00225	0	0.00225	0	100	DELT FOZ AREIA # 1
35	-0.5534	-0.3732	0.6674	-0.05939	82.91	
36	-12.901	-0.4999	12.911	-0.07956	99.925	
37	-7.1289	-1.7855	7.3491	-0.2842	97.004	
38	-4.9686	-3.8012	6.2559	-0.605	79.423	
39	-1.1907	-3.9232	4.1	-0.6244	29.043	
40	-0.7171	-4.7415	4.7955	-0.7546	14.953	
41	-26.192	-8.0512	27.401	-1.2814	95.586	
42	-3.5283	-8.2603	8.9822	-1.3147	39.28	
43	-28.429	-8.8787	29.783	-1.4131	95.453	
44	-3.3327	-12.57	13.004	-2.0005	25.629	
45	-4.0184	-14.102	14.663	-2.2444	27.404	
46	-2.7827	-14.109	14.38	-2.2454	19.351	

2.2.c) PSS/E Results

PSS®E auxiliary program PSSPLT[1] can estimate the dominant modes of a system by decomposing its oscillatory response. The following tables show the results using the Least Square decomposition method applied separately to time-domain responses of the speeds of machines #2 and #4.

Table 8 shows the "original" JCITA system eigenvalues. It can be seen that there is a complex pair with positive real part which characterizes an unstable mode. **Erro! Fonte de referência não encontrada.** and **Erro! Fonte de referência não encontrada.** show the system with PSS at the Itaipu Generator (#4), where the poor damping achieved is characterized. **Erro! Fonte de referência não encontrada.** and **Erro! Fonte de referência não encontrada.** show the system eigenvalues with PSSs in all machines (except the equivalent generator #7).

- **No PSS**

Table 8: Eigenvalues Calculated with PSS®E Program PSSPLT for the system without PSS.

```
     PTI INTERACTIVE POWER SYSTEM SIMULATOR--PSS/E      SUN, NOV 17 2013  13:38
IEEE BENCHMARK SYSTEM
BRAZILIAN 7-BUS EQUIVALENT SYSTEM

EIGENVALUES:

  NO.    REAL          IMAG          DAMP          FREQ
    1  -1.8470       9.1770       0.19731       1.4606
    2  -1.8470      -9.1770       0.19731       1.4606

    3  -2.0556       9.1654       0.21885       1.4587
    4  -2.0556      -9.1654       0.21885       1.4587

    5 -0.29081       5.8667       0.49508E-01  0.93371
    6 -0.29081      -5.8667       0.49508E-01  0.93371

    7  -6.4142       5.5609       0.75557      0.88505
    8  -6.4142      -5.5609       0.75557      0.88505

    9  0.69914       5.4366      -0.12755      0.86526
   10  0.69914      -5.4366      -0.12755      0.86526

   11  -6.6039       2.1971       0.94887      0.34967
   12  -6.6039      -2.1971       0.94887      0.34967

   13  -7.7453       1.1572       0.98902      0.18418
   14  -7.7453      -1.1572       0.98902      0.18418

   15  -18.587      0.80059       0.99907      0.12742
   16  -18.587     -0.80059       0.99907      0.12742

   17 -0.13523E-01  0.62574E-01  0.21123      0.99589E-02
   18 -0.13523E-01 -0.62574E-01  0.21123      0.99589E-02
```

[1] Provided as part of the PSS®E installation, for users with the proper license. Consult the software vendor if you are not sure about your license.

Table 9: Eigenvalues Calculated with PSS®E Program PSSPLT for the system without PSS. Results obtained processing generator #4 speed.

```
CHANNEL FILE: run_fault_bus_6_rea_50_pss_none.out

 IEEE BENCHMARK SYSTEM
 BRAZILIAN 7-BUS EQUIVALENT SYSTEM

 CHANNEL:  CHNL# 34: [SPD      4[ITAIPU      765.00]1]
 TIME INTERVAL:   1.2000  -  4.7000  SEC.

                            MODAL  COMPONENTS
 ------------------------------------------------------------------------------
 COMP.           EIGENVALUE                    EIGENVECTOR
  NO          REAL         IMAGINARY      MAGNITUDE        ANGLE        REMARKS
 ------------------------------------------------------------------------------
   1       0.707567        5.44299       0.16822E-04       67.30   FREQ.:   0.866 HZ.
   2       -2.46460          --          0.44952E-05        --     TCNST:   0.406 SC.
   3       -34.5179        182.730       0.66728E-05       43.62   FREQ.:  29.082 HZ.
   4       -9.14982        55.7144       0.36196E-05      -98.57   FREQ.:   8.867 HZ.
   5       -12.0880        114.826       0.26862E-05      -68.32   FREQ.:  18.275 HZ.
   6       -11.0529        138.551       0.20842E-05      -28.50   FREQ.:  22.051 HZ.
   7       -8.72382        85.4886       0.20348E-05      -67.37   FREQ.:  13.606 HZ.
   8      -0.234707        10.7970       0.19590E-05      -80.18   FREQ.:   1.718 HZ.
   9       -9.87398        175.272       0.14216E-05      -88.79   FREQ.:  27.895 HZ.

 PERC. ERROR:   1.922
 SIGNAL/NOISE:   34.70
 METHODS:  EIGENVALUE - LEAST SQUARE,  EIGENVECTOR - LEAST SQUARE
 ORDER: 30
```

Table 10: Eigenvalues Calculated with PSS®E Program PSSPLT for the system without PSS. Results obtained processing generator #2 speed.

```
CHANNEL FILE: run_fault_bus_6_rea_50_pss_none.out

 IEEE BENCHMARK SYSTEM
 BRAZILIAN 7-BUS EQUIVALENT SYSTEM

 CHANNEL:  CHNL# 32: [SPD      2[S. SANTIAGO 500.00]1]
 TIME INTERVAL:   1.2000  -  4.0000  SEC.

                            MODAL  COMPONENTS
 ------------------------------------------------------------------------------
 COMP.           EIGENVALUE                    EIGENVECTOR
  NO          REAL         IMAGINARY      MAGNITUDE        ANGLE        REMARKS
 ------------------------------------------------------------------------------
   1       -2.71953          --          0.49004E-05        --     TCNST:   0.368 SC.
   2       0.739907        5.48148       0.46626E-05      141.87   FREQ.:   0.872 HZ.
   3       -3.72779        10.1187       0.42710E-05       71.22   FREQ.:   1.610 HZ.
   4       -10.2605        61.3625       0.21551E-06       98.22   FREQ.:   9.766 HZ.
   5       -10.4198        121.613       0.12378E-06      155.86   FREQ.:  19.355 HZ.
   6       -7.84055        95.6032       0.11294E-06      116.46   FREQ.:  15.216 HZ.
   7       -8.23933        155.066       0.68604E-07     -179.76   FREQ.:  24.680 HZ.
   8       -7.56744        186.549       0.47514E-07     -148.40   FREQ.:  29.690 HZ.

 PERC. ERROR:   3.640
 SIGNAL/NOISE:   27.10
 METHODS:  EIGENVALUE - LEAST SQUARE,  EIGENVECTOR - LEAST SQUARE
 ORDER:  27
```

- **PSS at Itaipu**

Table 11: Eigenvalues Calculated with PSS®E Program PSSPLT for the system with PSS at generator #4. Results obtained processing generator #4 speed.

```
NUMBER OF SELECTED DATA POINTS IS    860 AND TIME STEP IS 0.008

 SELECT AN NPLT OF      8 TO REDUCE THE NUMBER OF POINTS TO ABOUT 100

 EFFECTIVE NUMBER OF  DATA POINTS IS    286 AND EFFECTIVE TIME STEP IS 0.025

 CHANNEL FILE: run_fault_bus_6_rea_50_pss_ita.out

 IEEE BENCHMARK SYSTEM
 BRAZILIAN 7-BUS EQUIVALENT SYSTEM

 CHANNEL:  CHNL# 34: [SPD      4[ITAIPU      765.00]1]
 TIME INTERVAL:   1.7833  -  8.9416  SEC.

                           MODAL  COMPONENTS
 ------------------------------------------------------------------------------
 COMP.           EIGENVALUE                    EIGENVECTOR
  NO         REAL        IMAGINARY      MAGNITUDE       ANGLE       REMARKS
 ------------------------------------------------------------------------------
   1     -0.700954        3.88240      0.31665E-05     -90.53   FREQ.:   0.618 HZ.
   2     -0.392241E-01    5.83679      0.14629E-05    -134.37   FREQ.:   0.929 HZ.
   3     -0.600196E-01      --         0.58355E-06       --     TCNST:  16.661 SC.
   4      -3.96201        14.1973      0.93869E-06    -172.52   FREQ.:   2.260 HZ.
   5      -132.750          --         0.18005E-07       --     TCNST:   0.008 SC.
   6      -6.11962        51.7513      0.56811E-08     -56.20   FREQ.:   8.236 HZ.
   7      -2.07211        17.2938      0.54852E-08     -34.19   FREQ.:   2.752 HZ.
   8      -3.02469        32.2951      0.33751E-08     -61.61   FREQ.:   5.140 HZ.
   9      -1.73617        26.4327      0.97554E-09    -105.83   FREQ.:   4.207 HZ.
  10      -1.65890        39.4505      0.91572E-09     -63.99   FREQ.:   6.279 HZ.
  11      -1.79492        48.1278      0.90750E-09    -163.90   FREQ.:   7.660 HZ.
  12      -1.61872        57.8029      0.82658E-09      41.91   FREQ.:   9.200 HZ.

 PERC. ERROR:   1.566
 SIGNAL/NOISE:   36.72
 METHODS:  EIGENVALUE - LEAST SQUARE,  EIGENVECTOR - LEAST SQUARE
 ORDER:  42
```

Table 12: Eigenvalues Calculated with PSS®E Program PSSPLT for the system with PSS at generator #4. Results obtained processing generator #2 speed.

```
NUMBER OF SELECTED DATA POINTS IS    967 AND TIME STEP IS 0.008

 SELECT AN NPLT OF      9 TO REDUCE THE NUMBER OF POINTS TO ABOUT 100

 EFFECTIVE NUMBER OF  DATA POINTS IS    322 AND EFFECTIVE TIME STEP IS 0.025

 CHANNEL FILE: run_fault_bus_6_rea_50_pss_ita.out

 IEEE BENCHMARK SYSTEM
 BRAZILIAN 7-BUS EQUIVALENT SYSTEM

 CHANNEL:  CHNL# 32: [SPD      2[S. SANTIAGO 500.00]1]
 TIME INTERVAL:   1.2833  -  9.3333  SEC.

                            MODAL  COMPONENTS
 ------------------------------------------------------------------------------
 COMP.           EIGENVALUE                    EIGENVECTOR
  NO          REAL        IMAGINARY      MAGNITUDE       ANGLE       REMARKS
 ------------------------------------------------------------------------------
   1     -0.417610E-01    5.83244       0.12416E-04     119.33   FREQ.:   0.928 HZ.
   2      -1.06764        3.85172       0.73100E-05     -41.44   FREQ.:   0.613 HZ.
   3      -1.94027        9.42923       0.37704E-05     118.90   FREQ.:   1.501 HZ.
   4      -4.06151        14.2612       0.24291E-05     -38.81   FREQ.:   2.270 HZ.
   5     -0.154238           --         0.85108E-06       --     TCNST:   6.483 SC.
   6      -3.26438        44.6039       0.59773E-07      24.10   FREQ.:   7.099 HZ.
   7      -2.56384        42.0519       0.44050E-07     -89.75   FREQ.:   6.693 HZ.
   8      -2.17107        32.4173       0.23673E-07     -47.05   FREQ.:   5.159 HZ.
   9      -2.24696        52.2368       0.18447E-07      34.81   FREQ.:   8.314 HZ.
  10      -2.15622        57.1731       0.13831E-07      90.55   FREQ.:   9.099 HZ.
  11     -0.877513        25.2768       0.10091E-07     -31.63   FREQ.:   4.023 HZ.

 PERC. ERROR:   1.582
 SIGNAL/NOISE:   34.92
 METHODS:  EIGENVALUE - LEAST SQUARE,  EIGENVECTOR - LEAST SQUARE
 ORDER:  41
```

- **PSS at All Machines**

Table 13: Eigenvalues Calculated with PSS®E Program PSSPLT for the system with PSS at generator1 #1, #2, #3 and #4. Results obtained processing generator #4 speed.

```
NUMBER OF SELECTED DATA POINTS IS    693 AND TIME STEP IS 0.008

 SELECT AN NPLT OF      6 TO REDUCE THE NUMBER OF POINTS TO ABOUT 100

 EFFECTIVE NUMBER OF  DATA POINTS IS    231 AND EFFECTIVE TIME STEP IS 0.025

 CHANNEL FILE: run_fault_bus_6_rea_50_pss_all.out

 IEEE BENCHMARK SYSTEM
 BRAZILIAN 7-BUS EQUIVALENT SYSTEM

 CHANNEL:  CHNL# 34: [SPD      4[ITAIPU      765.00]1]
 TIME INTERVAL:   1.8250  -  7.5916  SEC.

                           MODAL  COMPONENTS
 ------------------------------------------------------------------------------
 COMP.            EIGENVALUE                    EIGENVECTOR
  NO          REAL         IMAGINARY      MAGNITUDE       ANGLE       REMARKS
 ------------------------------------------------------------------------------
   1      -0.437235        4.88936      0.31565E-05    -104.73   FREQ.:   0.778 HZ.
   2       -1.29290        3.41596      0.12155E-05     -52.41   FREQ.:   0.544 HZ.
   3       -4.29502        14.2399      0.80381E-06    -143.46   FREQ.:   2.266 HZ.
   4     -0.486911E-01       --         0.35360E-06       --     TCNST:  20.538 SC.
   5       -2.05888        17.9331      0.45370E-08     119.05   FREQ.:   2.854 HZ.
   6       -2.73865        23.1637      0.16747E-08     172.61   FREQ.:   3.687 HZ.
   7       -2.09055        37.2507      0.12660E-08     169.77   FREQ.:   5.929 HZ.
   8       -2.01404        56.5822      0.75808E-09    -154.29   FREQ.:   9.005 HZ.
   9       -1.00134        43.9675      0.43750E-09    -167.74   FREQ.:   6.998 HZ.
  10       -1.05279        49.7804      0.38606E-09    -159.99   FREQ.:   7.923 HZ.
  11      -0.741519        31.0985      0.29546E-09     114.03   FREQ.:   4.949 HZ.

 PERC. ERROR:  0.8675
 SIGNAL/NOISE:   41.29
 METHODS:  EIGENVALUE - LEAST SQUARE,  EIGENVECTOR - LEAST SQUARE
 ORDER:  43
```

Table 14: Eigenvalues Calculated with PSS®E Program PSSPLT for the system with PSS at generator1 #1, #2, #3 and #4. Results obtained processing generator #2 speed.

```
NUMBER OF SELECTED DATA POINTS IS    783 AND TIME STEP IS 0.008

 SELECT AN NPLT OF      7 TO REDUCE THE NUMBER OF POINTS TO ABOUT 100

 EFFECTIVE NUMBER OF  DATA POINTS IS    261 AND EFFECTIVE TIME STEP IS 0.025

 CHANNEL FILE: run_fault_bus_6_rea_50_pss_all.out

 IEEE BENCHMARK SYSTEM
 BRAZILIAN 7-BUS EQUIVALENT SYSTEM

 CHANNEL:  CHNL# 32: [SPD      2[S. SANTIAGO 500.00]1]
 TIME INTERVAL:   1.6000  -  8.1166  SEC.

                           MODAL  COMPONENTS
 ------------------------------------------------------------------------------
 COMP.          EIGENVALUE                    EIGENVECTOR
  NO         REAL        IMAGINARY      MAGNITUDE       ANGLE       REMARKS
 ------------------------------------------------------------------------------
   1     -0.402555        4.83123      0.71027E-05     -85.37   FREQ.:   0.769 HZ.
   2      -3.40692          --        -0.29306E-05       --     TCNST:   0.294 SC.
   3      -14.2885          --         0.25267E-05       --     TCNST:   0.070 SC.
   4      -3.64382        9.44457      0.26045E-05     -88.77   FREQ.:   1.503 HZ.
   5     -0.182164          --         0.58536E-06       --     TCNST:   5.490 SC.
   6      -2.08941        14.5850      0.36719E-06     -38.58   FREQ.:   2.321 HZ.
   7      -3.32931        43.3634      0.75991E-07    -147.84   FREQ.:   6.902 HZ.
   8      -2.86408        21.1938      0.69333E-07    -155.02   FREQ.:   3.373 HZ.
   9      -3.60589        36.7381      0.69062E-07     175.95   FREQ.:   5.847 HZ.
  10      -2.17182        46.6651      0.35010E-07     -58.67   FREQ.:   7.427 HZ.
  11      -1.76623        29.7095      0.25797E-07     174.11   FREQ.:   4.728 HZ.
  12      -1.97827        54.9647      0.15864E-07    -100.68   FREQ.:   8.748 HZ.
  13      -2.15861        61.6569      0.13529E-07     -78.28   FREQ.:   9.813 HZ.

 PERC. ERROR:   4.590
 SIGNAL/NOISE:   27.24
 METHODS:  EIGENVALUE - LEAST SQUARE,  EIGENVECTOR - LEAST SQUARE
 ORDER:  42
```

References

[1] MARTINS, Nelson; LIMA, L. T. G. "Eigenvalue and Frequency Domain Analysis of Small-Signal Electromechanical Stability Problems", *IEEE Symposium on Application of Eigenanalysis and Frequency Domain Method for System Dynamic Performance*, 1989, .p. 17-33.

[2] CEPEL, "ANATEM Users Manual V10.04.06 (in Portuguese)", March 2012.

[3] Siemens PTI, "PSS/E 32.0 Online Documentation", June 2009.

[4] IEEE Recommended Practice for Excitation System Models for Power System Stability Studies, IEEE Standard 421.5(2005), April 2006.