IEEE PES Task Force on Benchmark Systems for Stability Controls

Report on the 2-area, 4-generator system

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The present report refers to the data setup and nonlinear stability study carried over with the 4-generators, two-areas, system proposed in [1] using the Siemens PTI's PSS/E software [2]. The main objectives of this report are to document the data setup and to provide some validation of such data, comparing (to the extent possible) the results obtained with a time-domain nonlinear simulation with the eigenvalue analysis shown in [1].

It should be noted that simplified versions of this system have been used in the past [3-4], but the data shown in this report corresponds to that presented in Example 12.6 of [1].

1. Power Flow

The power flow solution is shown in Figure 1, with the one line diagram of the system. The bus data, including the voltage magnitudes and angles from the power flow solution, are shown in Table 1.

The transmission line data is shown in Table 2. The data is provided in percent considering a system MVA base of 100 MVA. All transmission lines are 230 kV lines. The lines are represented by π sections and the charging shown in Table 2 corresponds to the total line charging.

The only difference regarding the data as presented in [1] is the introduction of multiple parallel circuits, so results considering weaker transmission system conditions might be investigated.

The generator step-up transformers (GSU) are explicitly represented in the case. The GSUs are all rated 900 MVA and have a leakage reactance of 15% on the transformer base. Winding resistance and magnetizing currents are neglected. Table 3 presents the GSU data.

There are two loads, directly connected to the 230 kV buses 7 and 9. The associated data is given in Table 4. These loads are represented, in the dynamic simulation, with a constant current characteristic for the active power and a constant admittance characteristic for the reactive power (100%I, 100%Z for P and Q, respectively).

Capacitor banks are also connected to the 230 kV buses 7 and 9. The values for these capacitors at nominal voltage (1.0 pu voltage) are shown in Table 5.

The complete PSS/E [2] report with all power flows for this system is given in Table 6.

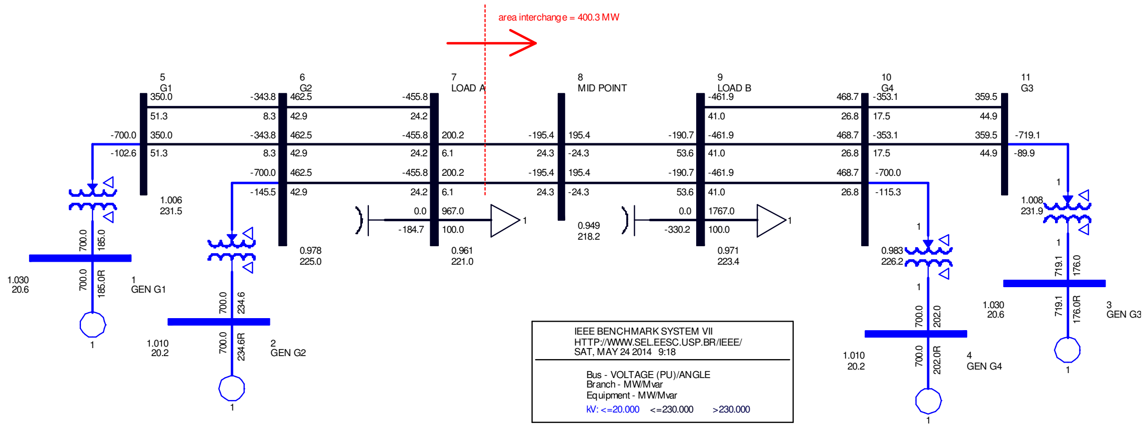

Figure 1: Case 1 Power Flow Solution

Table 1: Bus Data and Power Flow Solution

Bus Number	Bus Name	Base kV	Bus type	Voltage (pu)	Angle (deg)
1	GEN G1	20.0	PV	1.0300	20.07
2	GEN G2	20.0	PV	1.0100	10.31
3	GEN G3	20.0	swing	1.0300	-7.00
4	GEN G4	20.0	PV	1.0100	-17.19
5	G1	230.0	PQ	1.0065	13.61
6	G2	230.0	PQ	0.9781	3.52
7	LOAD A	230.0	PQ	0.9610	-4.89
8	MID POINT	230.0	PQ	0.9486	-18.76
9	LOAD B	230.0	PQ	0.9714	-32.35
10	G4	230.0	PQ	0.9835	-23.94
11	G3	230.0	PQ	1.0083	-13.63

Table 2: Transmission Line Data

From Bus	To Bus	ckt id	R (%)	X (%)	Charging (%)	Length (km)
5	6	1	0.50	5.0	2.1875	25
5	6	2	0.50	5.0	2.1875	25
6	7	1	0.30	3.0	0.5833	10
6	7	2	0.30	3.0	0.5833	10
6	7	3	0.30	3.0	0.5833	10
7	8	1	1.10	11.0	19.2500	110
7	8	2	1.10	11.0	19.2500	110
8	9	1	1.10	11.0	19.2500	110
8	9	2	1.10	11.0	19.2500	110
9	10	1	0.30	3.0	0.5833	10
9	10	2	0.30	3.0	0.5833	10
9	10	3	0.30	3.0	0.5833	10
10	11	1	0.50	5.0	2.1875	25
10	11	2	0.50	5.0	2.1875	25

Table 3: Generator Step- Up Transformer Data (on Transformer MVA Base)

From Bus	To Bus	R (%)	X (%)	MVA Base	tap (pu)
1	5	0	15	900	1
2	6	0	15	900	1
3	11	0	15	900	1
4	10	0	15	900	1

Table 4: Load Data

Bus	P (MW)	Q (MVAr)
7	967	100
9	1767	100

Table 5: Capacitor Bank Data

Bus	Q (MVAr)
7	200
9	350

Table 6: PSS/E Power Flow Results

X---- FROM BUS ---X BUS#	X-- NAME --X	VOLT PU/KV	ANGLE	GEN MW/MVAR	LOAD MW/MVAR	SHUNT MW/MVAR	X---- TO BUS -----X BUS#	X-- NAME --X	CKT	MW	MVAR	TRANSFORMER RATIO
1	GEN G1	1.0300	20.1	700.0	0.0	0.0						
		20.600		185.0R	0.0	0.0	5	G1	1	700.0	185.0	1.000UN
2	GEN G2	1.0100	10.3	700.0	0.0	0.0						
		20.200		234.6R	0.0	0.0	6	G2	1	700.0	234.6	1.000UN
3	GEN G3	1.0300	-7.0	719.1	0.0	0.0						
		20.600		176.0R	0.0	0.0	11	G3	1	719.1	176.0	1.000UN
4	GEN G4	1.0100	-17.2	700.0	0.0	0.0						
		20.200		202.0R	0.0	0.0	10	G4	1	700.0	202.0	1.000UN
5	G1	1.0065	13.6	0.0	0.0	0.0						
		231.49		0.0	0.0	0.0	1	GEN G1	1	-700.0	-102.6	1.000LK
							6	G2	1	350.0	51.3	
							6	G2	2	350.0	51.3	
6	G2	0.9781	3.5	0.0	0.0	0.0						
		224.97		0.0	0.0	0.0	2	GEN G2	1	-700.0	-145.5	1.000LK
							5	G1	1	-343.8	8.3	
							5	G1	2	-343.8	8.3	
							7	LOAD A	1	462.5	42.9	
							7	LOAD A	2	462.5	42.9	
							7	LOAD A	3	462.5	42.9	
7	LOAD A	0.9610	-4.9	0.0	967.0	0.0						
		221.04		0.0	100.0	-184.7	6	G2	1	-455.8	24.2	
							6	G2	2	-455.8	24.2	
							6	G2	3	-455.8	24.2	
							8	MID POINT	1	200.2	6.1	
							8	MID POINT	2	200.2	6.1	
8	MID POINT	0.9486	-18.8	0.0	0.0	0.0						
		218.18		0.0	0.0	0.0	7	LOAD A	1	-195.4	24.3	
							7	LOAD A	2	-195.4	24.3	
							9	LOAD B	1	195.4	-24.3	
							9	LOAD B	2	195.4	-24.3	
9	LOAD B	0.9714	-32.4	0.0	1767.0	0.0						
		223.42		0.0	100.0	-330.2	8	MID POINT	1	-190.7	53.6	
							8	MID POINT	2	-190.7	53.6	
							10	G4	1	-461.9	41.0	
							10	G4	2	-461.9	41.0	
							10	G4	3	-461.9	41.0	
10	G4	0.9835	-23.9	0.0	0.0	0.0						
		226.20		0.0	0.0	0.0	4	GEN G4	1	-700.0	-115.3	1.000LK
							9	LOAD B	1	468.7	26.8	
							9	LOAD B	2	468.7	26.8	
							9	LOAD B	3	468.7	26.8	
							11	G3	1	-353.1	17.5	
							11	G3	2	-353.1	17.5	
11	G3	1.0083	-13.6	0.0	0.0	0.0						
		231.90		0.0	0.0	0.0	3	GEN G3	1	-719.1	-89.9	1.000LK
							10	G4	1	359.5	44.9	
							10	G4	2	359.5	44.9	

2. Dynamic Simulation Models

The models and associated parameters for the dynamic simulation models used in this PSS/E setup are described in this Section. All generation units are considered identical and will be represented by the same dynamic models and parameters, with exception of the inertias.

2.1 Synchronous Machines

The generator model to represent the round rotor units is the PSS/E model GENROE, shown in the block diagram in Figure 2. Details about the implementation of the model are available in the software documentation [2]. This is a 6^{th} order dynamic model with the saturation function represented as a geometric (exponential) function. Table 7 provides the parameters for this model and, with the exception of the inertia constants, all data are the same for all generators in the system.

The representation of the saturation of the generators has some impact on 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. Figure 3 presents the calculated generator open circuit saturation curve, based on the data in Table 7. As mentioned before, the saturation function is represented by a geometric function in the PSS/E GENROE model.

The calculated rated field current for this generator model is 2.66 pu (considering 0.85 rated power factor). This calculation comprises the initialization of the generator model at full (rated) power output, considering their rated power factor. It should be noted that in PSS/E models, due to the choice of base values for generator field voltage and generator field current, these variables are numerically the same, in steady state, when expressed in pu.

Figure 4 shows the calculated capability curve for the generators, based on the data in Table 7.

Table 7: Dynamic Model Data for Round Rotor Units (PSS/E Model GENROE)

PARAMETERS			
Description	**Symbol**	**Value**	**Unit**
Rated apparent power	MBASE	900	MVA
d-axis open circuit transient time constant	T'_{do}	8.0	s
d-axis open circuit sub-transient time constant	T''_{do}	0.03	s
q-axis open circuit transient time constant	T'_{qo}	0.4	s
q-axis open circuit sub-transient time constant	T''_{qo}	0.05	s
Inertia	H	†	MW.s/MVA
Speed damping	D	0	pu
d-axis synchronous reactance	X_d	1.8	pu
q-axis synchronous reactance	X_q	1.70	pu
d-axis transient reactance	X'_d	0.3	pu
q-axis transient reactance	X'_q	0.55	pu
sub-transient reactance	$X''_d = X''_q$	0.25	pu
Leakage reactance	X_ℓ	0.20	pu
Saturation factor at 1.0 pu voltage	S(1.0)	0.0392	–
Saturation factor at 1.2 pu voltage	S(1.2)	0.2672	–

Notes:

† Units 1 and 2 have inertias H = 6.50, while units 3 and 4 have inertias H = 6.175

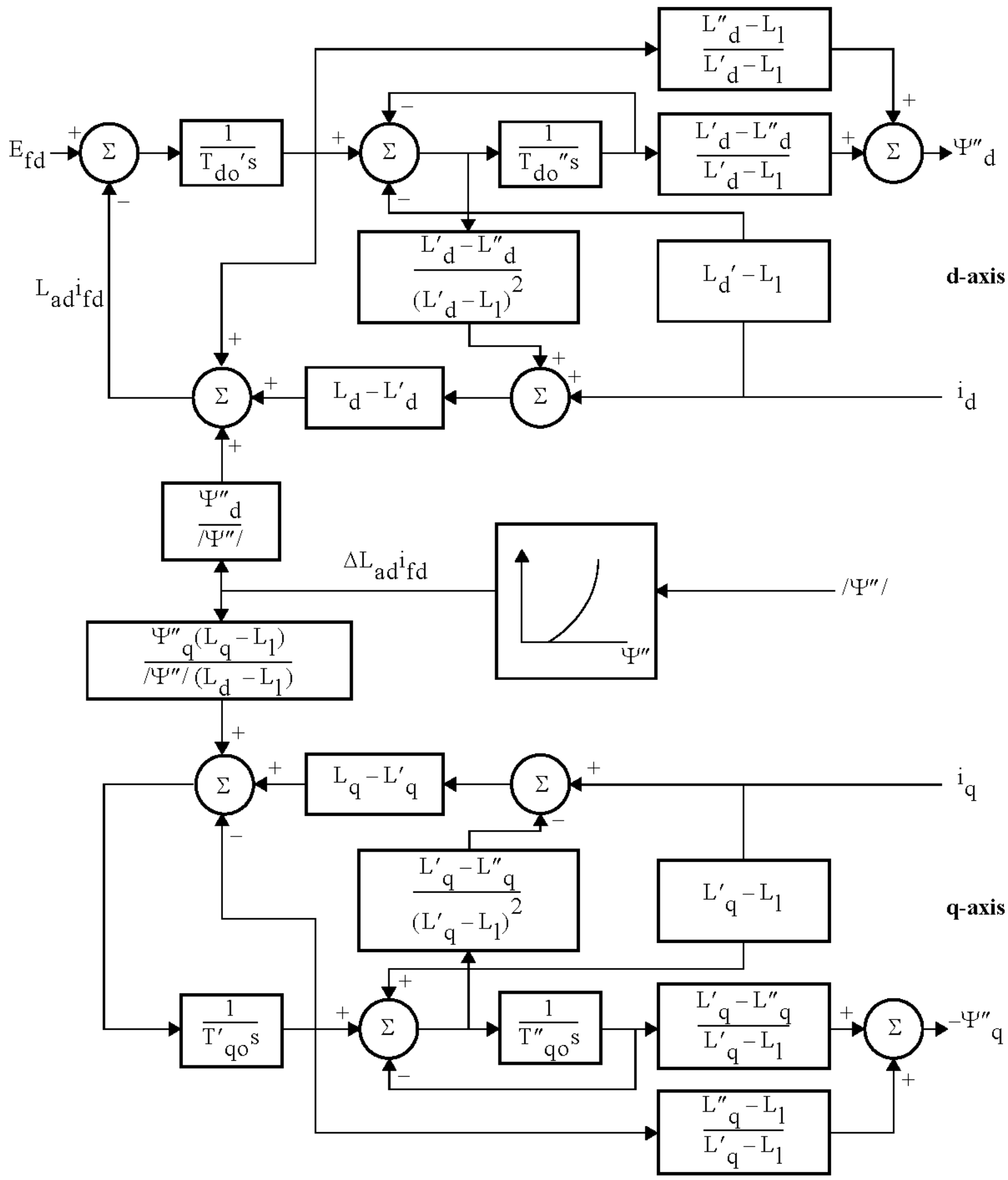

Figure 2: Block Diagram for the PSS/E Model GENROE

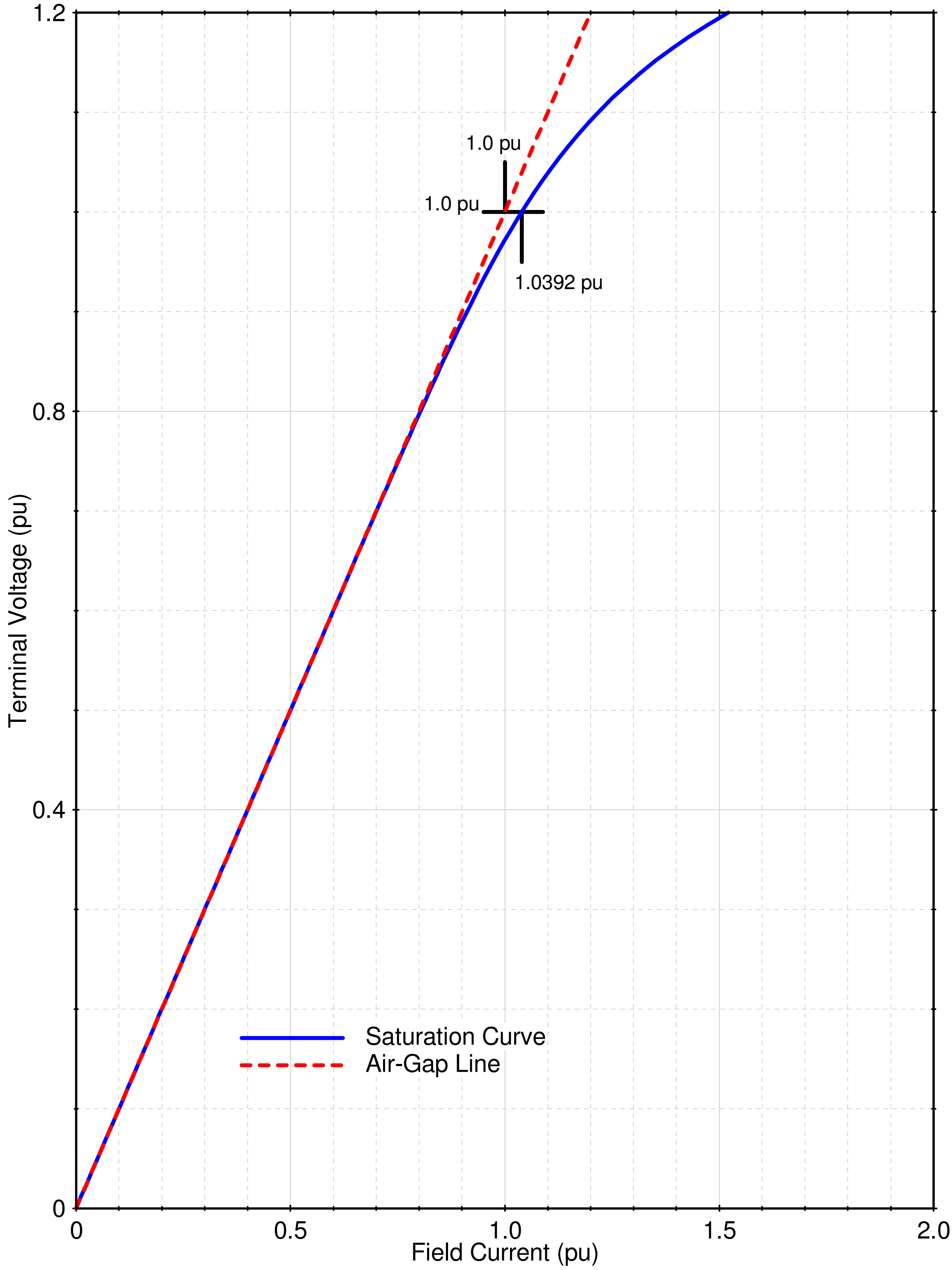

Figure 3: Generator Open Circuit Saturation Curve

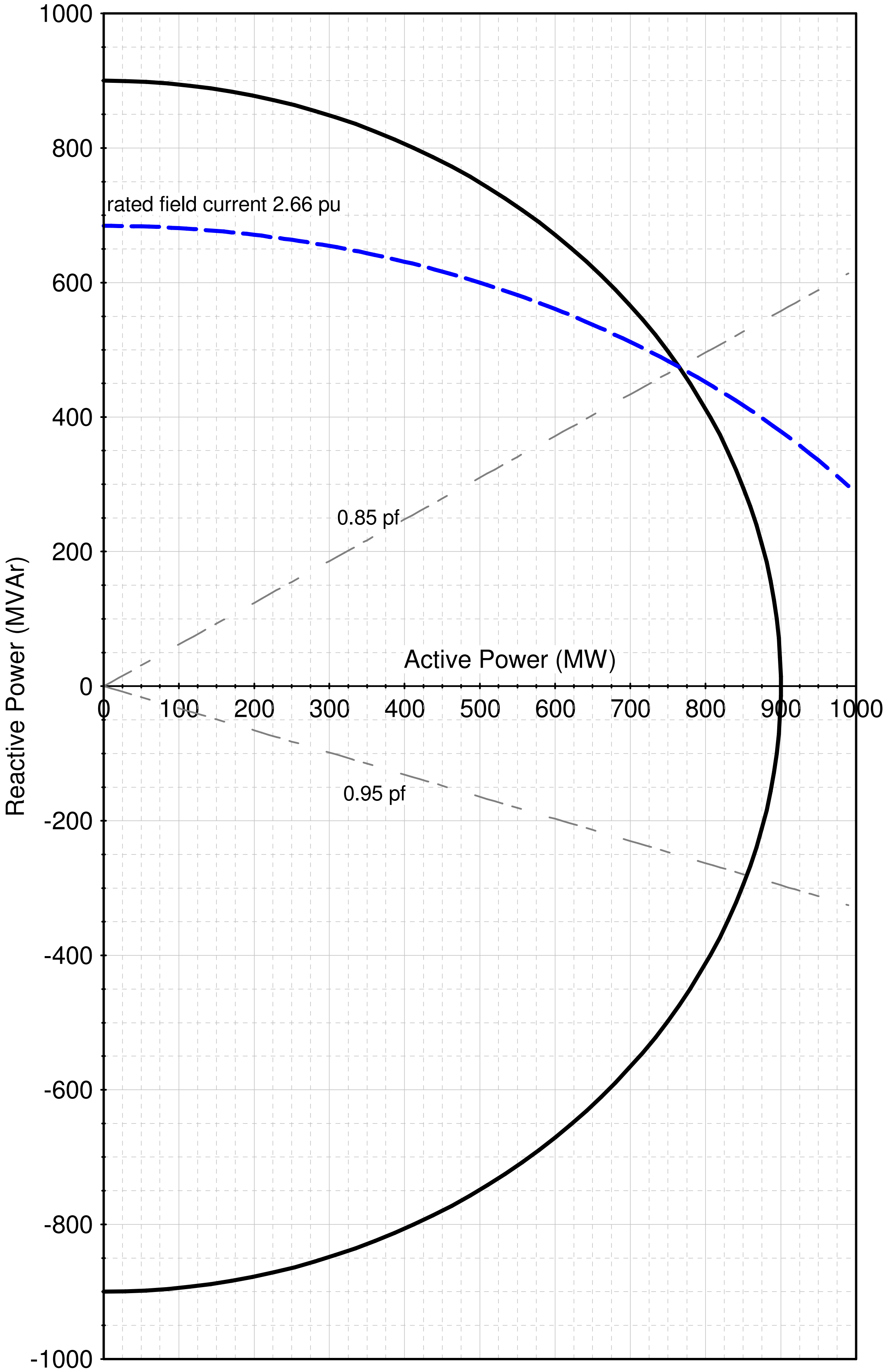

Figure 4: Generator Capability Curve

2.2 Excitation Systems

Following the results presented in [1], this report will present simulation results with different representations/models for the excitation system of the generators.

The first set of results is associated with all generators in manual control (constant generator field voltage). Therefore, in PSS/E there will be no explicit excitation system model, as PSS/E assumes constant generator field voltage when no dynamic model for the excitation system is available.

The second set of results is related to a low gain, relatively slow DC rotating exciter. This excitation system is represented by the IEEE Std. 421.5(2005) DC1A [5], corresponding to the PSS/E model ESDC1A [1]. A variation regarding the results in [1] will be introduced in this report, where the steady state gain of the AVR in this DC rotating excitation system is increased tenfold.

A relatively fast (high initial response) static excitation system will be used in the next three sets of results: an AVR with transient gain reduction, then the AVR without such transient gain reduction, and finally the AVR without transient gain reduction with an active power system stabilizer (PSS).

2.2.1 DC Rotating Excitation System

The block diagram of the PSS/E model ESDC1A [2] is shown in Figure 5. The parameters for the model are presented in

Table **8**.

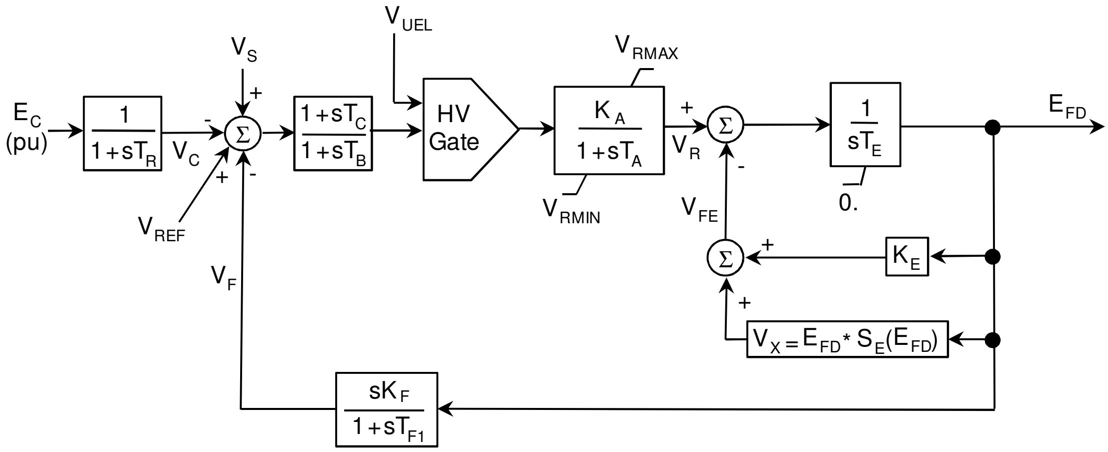

Figure 5: Block Diagram for the PSS/E Model ESDC1A

Table 8: Dynamic Model Data for DC Rotating Excitation Systems (PSS/E Model ESDC1A)

PARAMETERS			
Description	**Symbol**	**Value**	**Unit**
Voltage transducer time constant	T_R	0.05	s
AVR steady state gain	K_A	20†	pu
AVR equivalent time constant	T_A	0.055	s
TGR block 1 denominator time constant	T_B	0	s
TGR block 2 numerator time constant	T_C	0	s
Max. AVR output	V_{Rmax}	5	pu
Min. AVR output	V_{Rmin}	–3	pu
Exciter feedback time constant	K_E	1	pu
Exciter time constant	T_E	0.36	s
Stabilizer feedback gain	K_F	0.125	pu
Stabilizer feedback time constant	T_{F1}	1.8	s
Switch		0††	
Exciter saturation point 1	E_1	3†††	pu
Exciter saturation factor at point 1	$S_E(E_1)$	0.1	–
Exciter saturation point 2	E_2	4	pu
Exciter saturation factor at point 2	$S_E(E_2)$	0.3	–

Notes:

† Results will be presented with gain K_A=20 and also K_A=200.

†† The parameter "switch" is specific to the PSS/E implementation of this model and it is not part of the Standard definition of the DC1A model. It might not be needed in other software.

††† Saturation for the rotating DC exciter was not provided in [1]. Typical saturation values are assumed.

2.2.2 Static Excitation System

The block diagram of the PSS/E model ESST1A [2] is shown in Figure 6. The transient gain reduction will be implemented by the lead-lag block with parameters T_C and T_B, so the parameters T_{C1}, T_{B1}, K_F and T_F are not applicable and have been set accordingly. Similarly, the generator field current limit represented by the parameters K_{LR} and I_{LR} is not considered in the results presented in this report. The parameters for the ESST1A model are presented in Table 9.

The limits (parameters V_{Imax}, V_{Imin}, V_{Amax}, V_{Amin}, V_{Rmax} and V_{Rmin}) in the model were set to typical values corresponding to the expected ceilings of such static excitation system. These limits are irrelevant for the small-signal analysis of the system dynamic response. On the other hand, these limits are a critical part of the model and the expected response of the excitation system following large system disturbances such as faults.

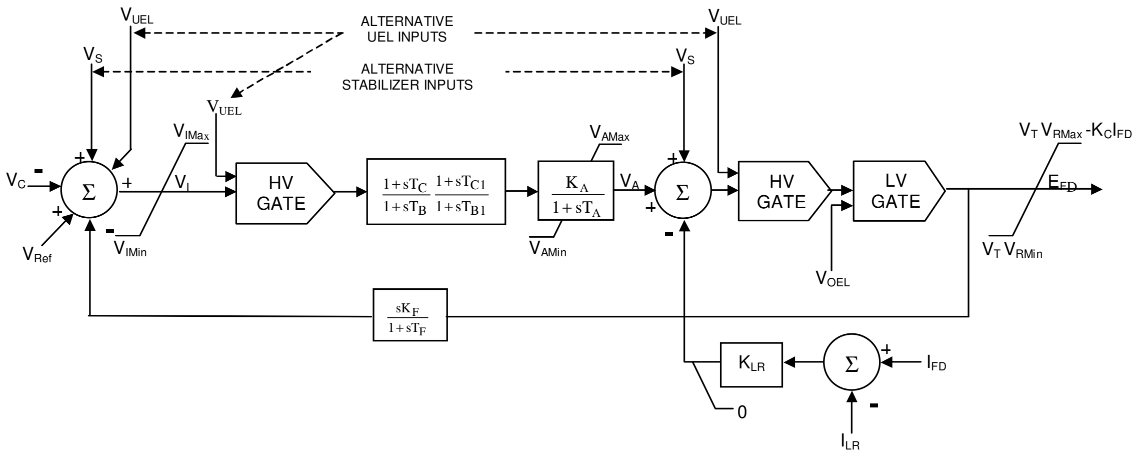

Figure 6: Block Diagram for the PSS/E Model ESST1A

Table 9: Dynamic Model Data for Static Excitation Systems (PSS/E Model ESST1A)

PARAMETERS			
Description	**Symbol**	**Value**	**Unit**
Voltage transducer time constant	T_R	0.01	s
Max. voltage error	V_{Imax}	99	pu
Min. voltage error	V_{Imin}	–99	pu
TGR block 1 numerator time constant	T_C	1	s
TGR block 1 denominator time constant	T_B	1†	s
TGR block 2 numerator time constant	T_{C1}	0	s
TGR block 1 denominator time constant	T_{B1}	0	s
AVR steady state gain	K_A	200	pu
Rectifier bridge equivalent time constant	T_A	0	s
Max. AVR output	V_{Amax}	4	pu
Min. AVR output	V_{Amin}	–4	pu
Max. rectifier bridge output	V_{Rmax}	4	pu
Min. rectifier bridge output	V_{Rmin}	–4	pu
Commutation factor for rectifier bridge	K_C	0	pu
Stabilizer feedback gain	K_F	0	pu
Stabilizer feedback time constant	T_F	1	s
Field current limiter gain	K_{LR}	0	pu
Field current instantaneous limit	I_{LR}	3	pu

Notes:

† This data corresponds to the case without transient gain reduction (TGR). The parameter T_B should be set to 10 seconds for the cases considering transient gain reduction.

2.3 Power System Stabilizers

The IEEE Std. 421.5(2005) model PSS1A [5] will be used to represent the power system stabilizers. The block diagram of the PSS/E model IEEEST [2] is shown in Figure 7. The parameters for the IEEEST model are presented in Table 10.

The output limits were set to +/– 5%, while the logic to switch off the PSS for voltages outside a normal operation range has been ignored (parameters V_{CU} and V_{CL} set to zero).

These stabilizers are used with the excitation system represented by the ESST1A model without transient gain reduction (TGR). The PSS transfer function and, in particular, the phase compensation would have to be adjusted for application with any of the other excitation system models presented in this benchmark system.

Figure 8 presents the calculated phase requirement for the PSS (the phase characteristic of the GEP(s) transfer function [6]), and the phase characteristic of the PSS proposed in [1]. It can be seen that the original PSS does not provide sufficient phase lead, particularly at the frequencies associated with the local mode of oscillation of the generator (above 1 Hz). This is consistent with the results presented in [1], where the frequency of the local mode of oscillation increases when the PSS is in service.

A modified tuning for the PSS transfer function is proposed here, with significant more phase lead particularly in the frequency range associated with the local mode of oscillation. Figure 8 shows that this new PSS transfer function is a much closer match to the actual phase requirement given by GEP(s), within ±30° of the actual compensation requirement as suggested in [6].

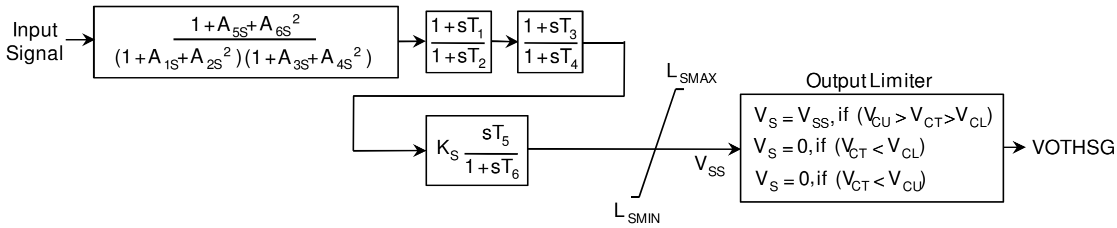

Figure 7: Block Diagram for the PSS/E Model IEEEST

Table 10: Dynamic Model Data for Power System Stabilizers (PSS/E Model IEEEST)

PARAMETERS				
Description	**Symbol**	**Original Values**	**New Values**	**Unit**
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	0.05	0.08	s
1st lead-lag denominator time constant	T_2	0.02	0.015	s
2nd lead-lag numerator time constant	T_3	3	0.08	s
2nd lead-lag denominator time constant	T_4	5.4	0.015	s
Washout block numerator time constant	T_5	10	10	s
Washout block denominator time constant	T_6	10	10	s
PSS gain	K_S	20	10	pu
PSS max. output	L_{Smax}	0.05	0.05	pu
PSS min. output	L_{Smin}	–0.05	–0.05	pu
Upper voltage limit for PSS operation	V_{CU}	0	0	pu
Lower voltage limit for PSS operation	V_{CL}	0	0	pu

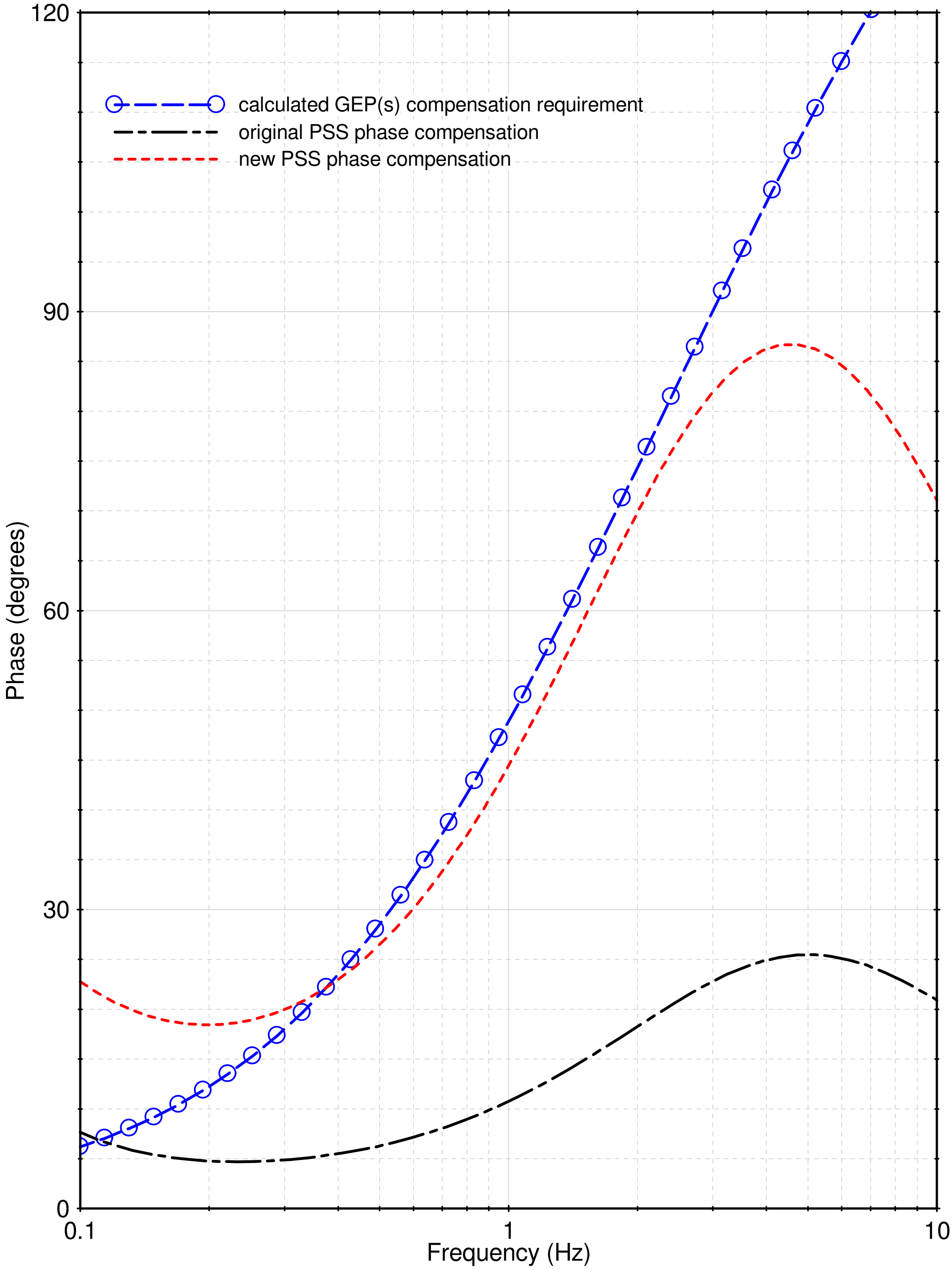

Figure 8: PSS Phase Compensation Characteristics

3. Simulation Results

The results presented in this report correspond to time-domain simulations of different disturbances. The main objective associated with the selection of these disturbances was to assess the system damping and the effectiveness of the proposed stabilizers in providing damping to these oscillations.

The first set of simulations comprise the connection of a 50 MVAr reactor at the mid-point of the system (bus #8) at t=1.0 second. The reactor is disconnected 100 ms later, without any changes in the system topology. This is a very small disturbance, and as such leads to results that correspond to the linear response of the system. Furthermore, given the location where the disturbance is applied, it tends to excite primarily the inter-area oscillation.

The second set of simulations correspond to simultaneous changes in voltage reference in all generator units, applied at t=1.0 second. The applied step changes are as follows:

GENERATOR	STEP IN V_{ref}
G1	+3%
G2	–1%
G3	–3%
G4	+1%

These changes in voltage reference were selected in order to excite not only the inter-area oscillation mode but also the other electromechanical modes in the system.

3.1 System without AVR – Constant Field Voltage

The results in this Section correspond to the results in [1] with a manual excitation control. Since there is no automatic voltage regulator (AVR), the steps in voltage reference cannot be applied, so only the results corresponding to the 50 MVAr reactor at the mid-point are presented.

3.1.1 50 MVAr Reactor at Mid-Point

Figure 9 presents the PSS/E results (time domain simulation) of the 50 MVAr reactor disturbance, when the excitation systems are operated in manual control (constant field voltage). The results in Figure 9 are the electrical power outputs of the four machines, in per unit of the system MVA base (100 MVA).

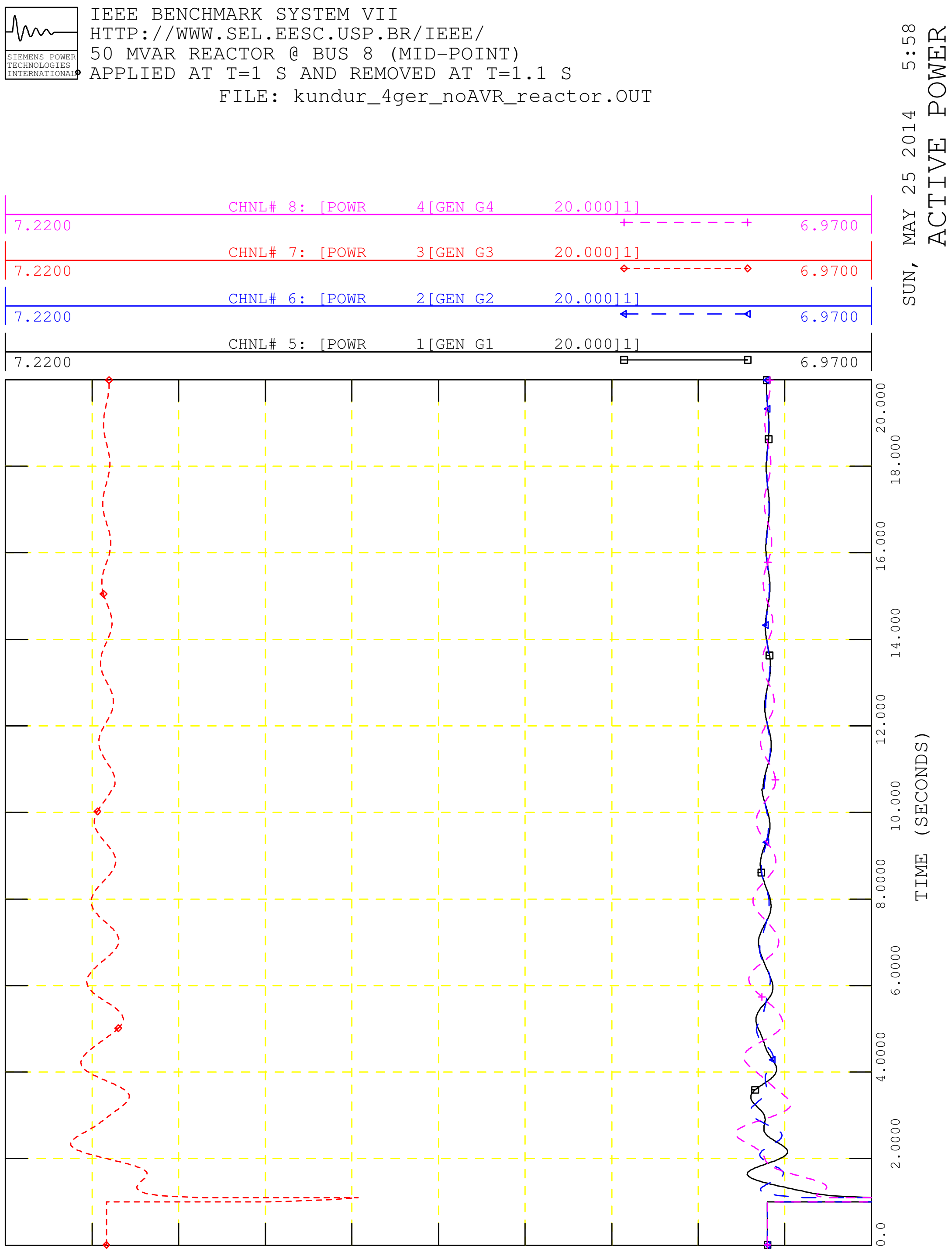

Figure 9: 50 MVAr Reactor Disturbance with Manual Excitation Control

3.2 ESDC1A with K_A=20

The results in this Section correspond to the results in [1] with the self-excited dc exciter, represented in PSS/E by the ESDC1A model presented in Section 2.2.1 (gain K_A=20 pu).

3.2.1 50 MVAr Reactor at Mid-Point

Figure 10 shows the electrical power output of the generators (100 MVA base) for the 50 MVAr reactor disturbance (ESDC1A model with K_A=20 pu).

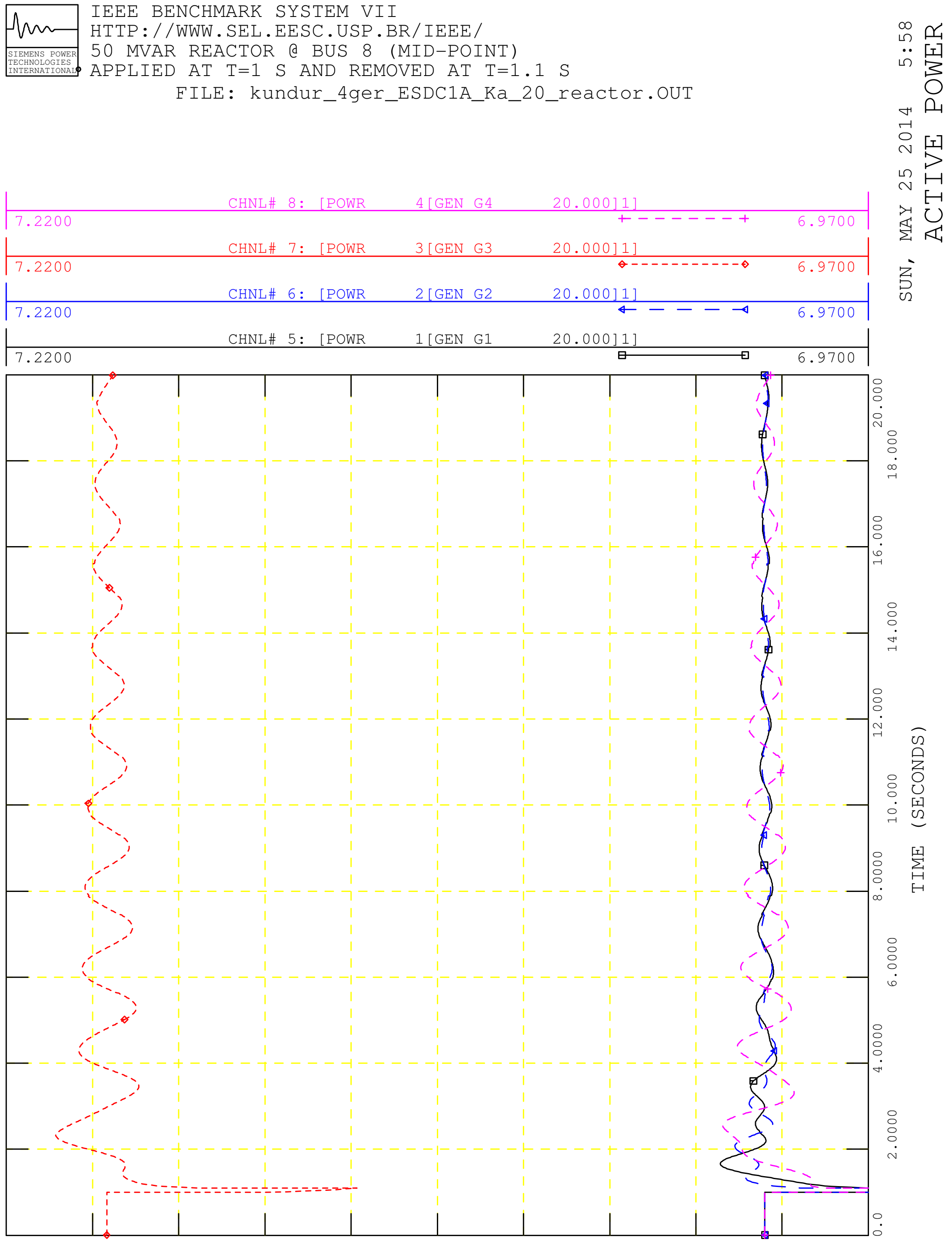

Figure 10: 50 MVAr Reactor Disturbance with ESDC1A Model (K_A=20)

3.2.2 Steps in V_{ref}

Figure 11 shows the electrical power output of the generators (100 MVA base) for the step changes in voltage reference, when the excitation systems represented by the ESDC1A model, considering the gain K_A=20 pu.

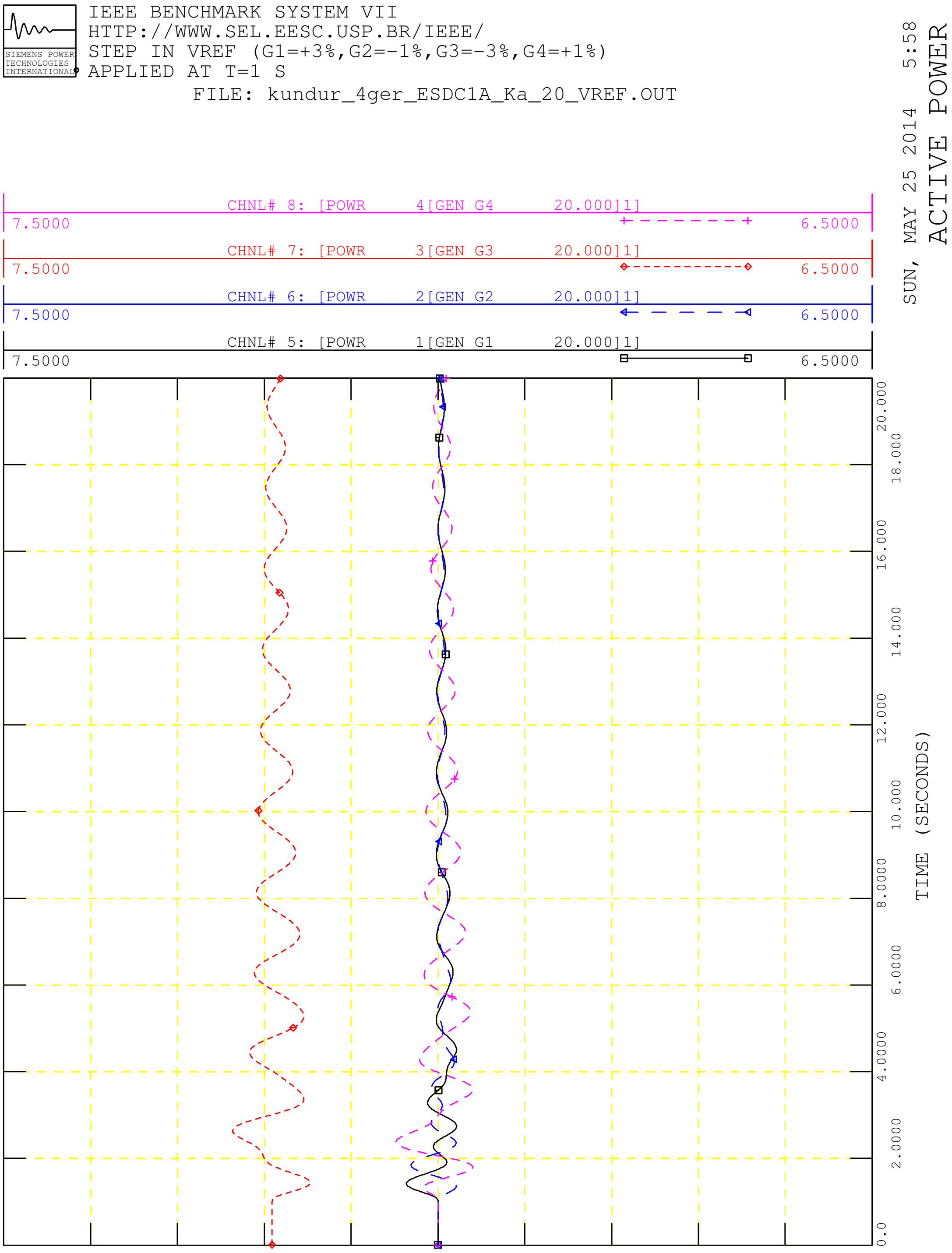

Figure 11: Step in Voltage References with ESDC1A Model (K_A=20)

3.3 ESDC1A with K_A=200

The results in this Section correspond to the results in [1] with the self-excited dc exciter, represented in PSS/E by the ESDC1A model presented in Section 2.2.1 (gain K_A=200 pu).

3.3.1 50 MVAr Reactor at Mid-Point

Figure 12 shows the electrical power output of the generators (100 MVA base) for the 50 MVAr reactor disturbance (ESDC1A model with K_A=200 pu).

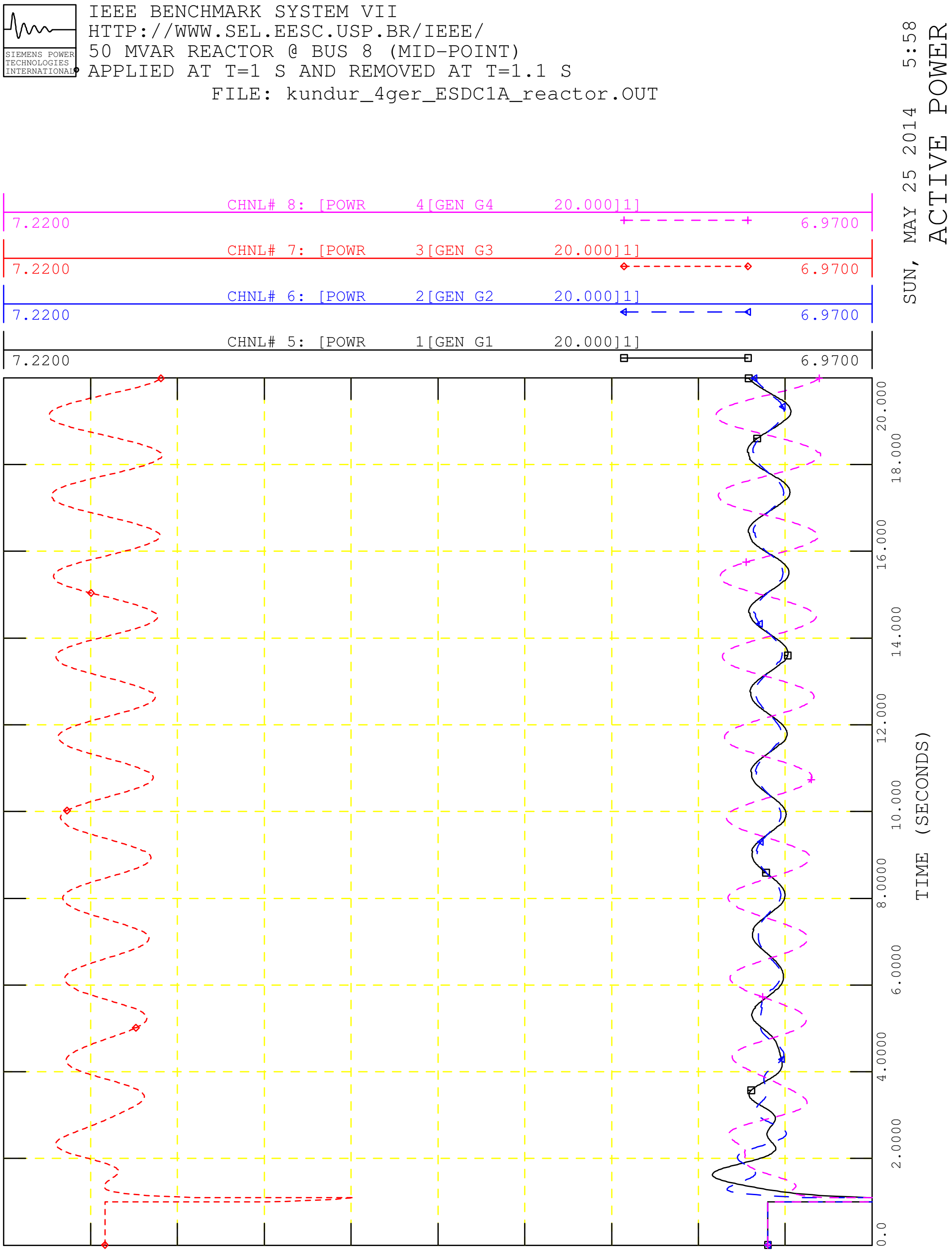

Figure 12: 50 MVAr Reactor Disturbance with ESDC1A Model (K_A=200)

3.3.2 Steps in V_{ref}

Figure 13 shows the electrical power output of the generators (100 MVA base) for the step changes in voltage reference, when the excitation systems represented by the ESDC1A model, considering the gain K_A=200 pu.

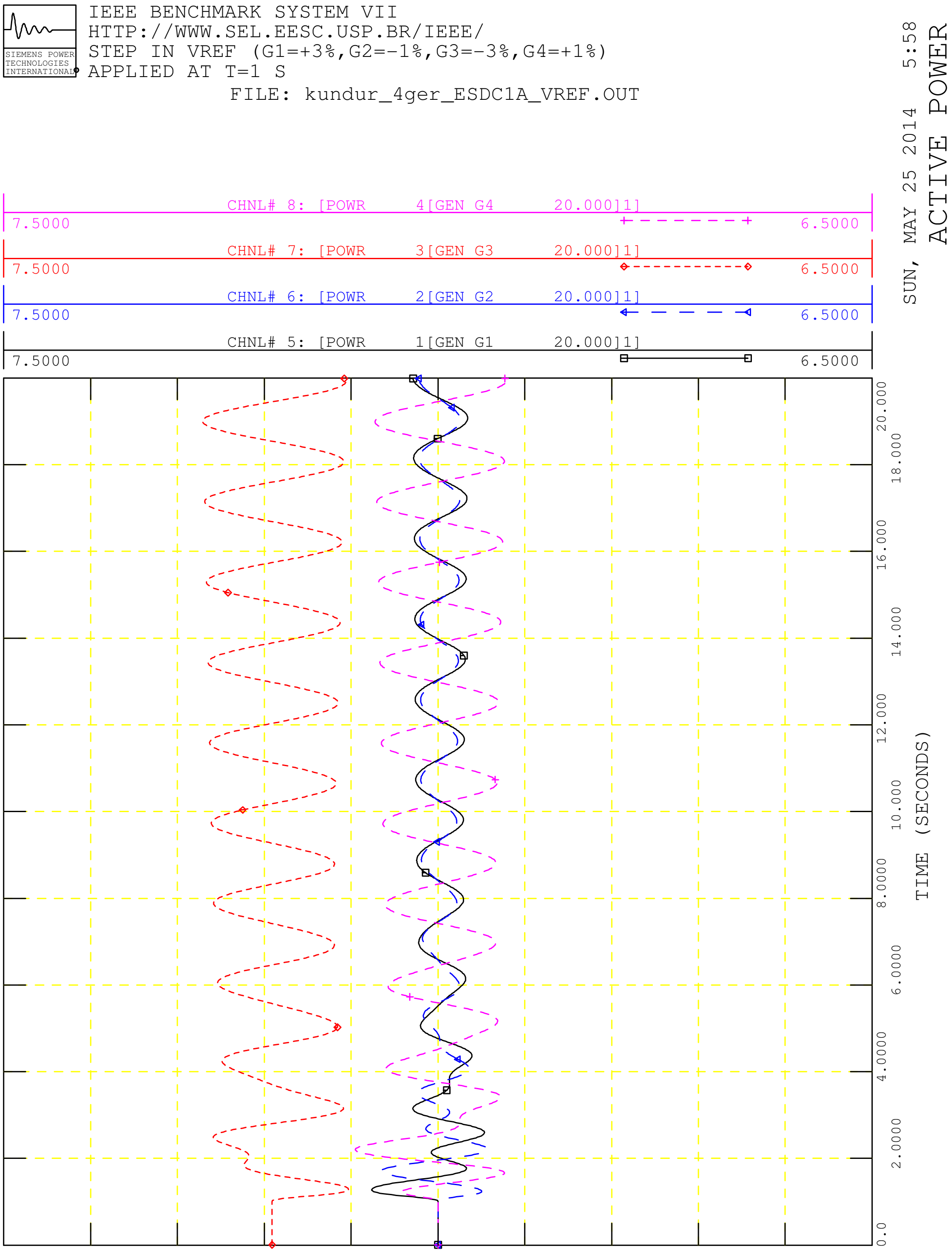

Figure 13: Step in Voltage References with ESDC1A Model (K_A=200)

3.4 ESST1A with TGR

The results in this Section correspond to the results in [1] with the static excitation system, represented in PSS/E by the ESST1A model presented in Section 2.2.2 (time constant T_B=10 s).

3.4.1 50 MVAr Reactor at Mid-Point

Figure 14 shows the electrical power output of the generators (100 MVA base) for the 50 MVAr reactor disturbance (ESST1A model with T_B=10 s).

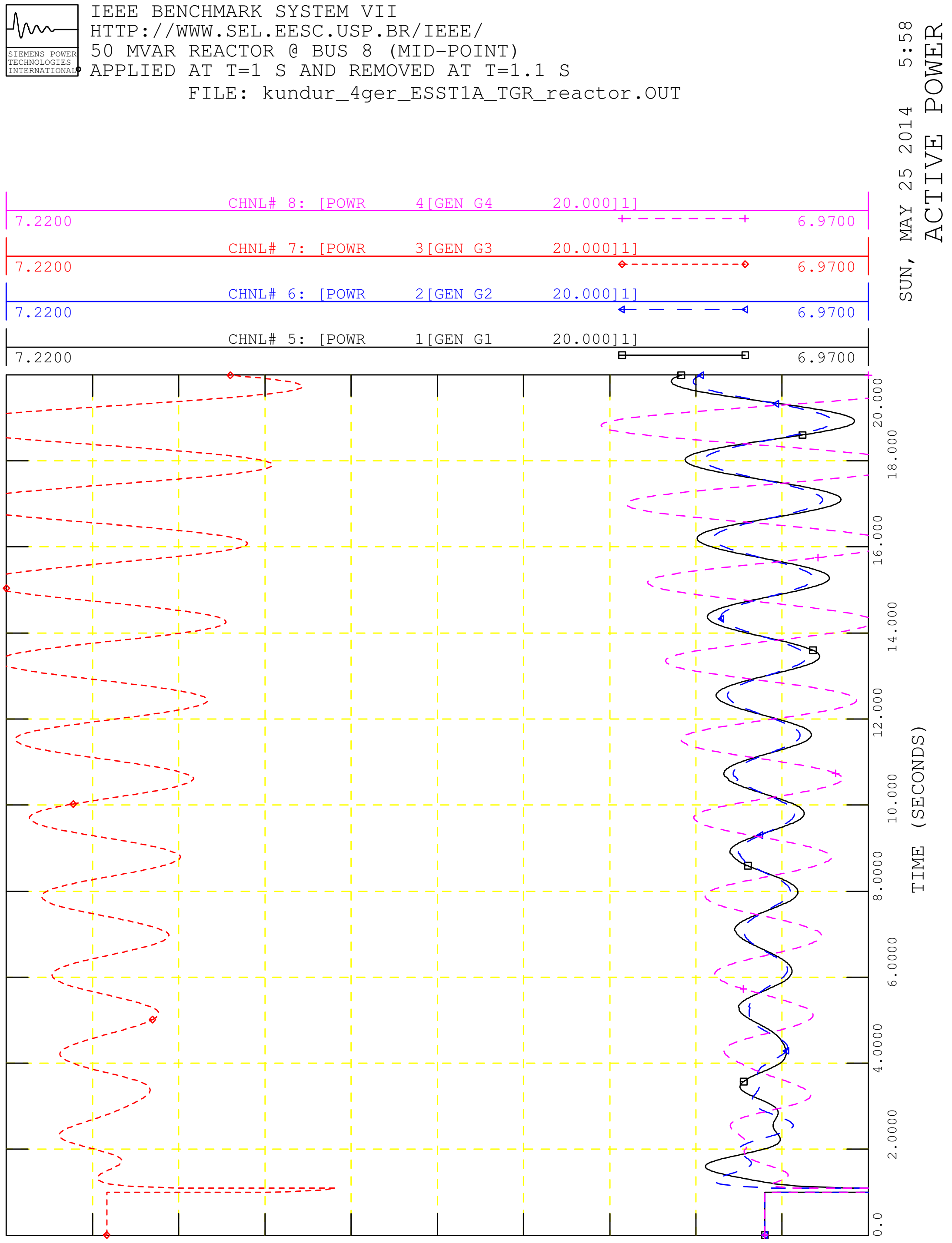

Figure 14: 50 MVAr Reactor Disturbance with ESST1A Model with TGR

3.4.2 Steps in V_{ref}

Figure 15 shows the electrical power output of the generators (100 MVA base) for the step changes in voltage reference, when the excitation systems represented by the ESST1A model, considering the gain T_B=10 s.

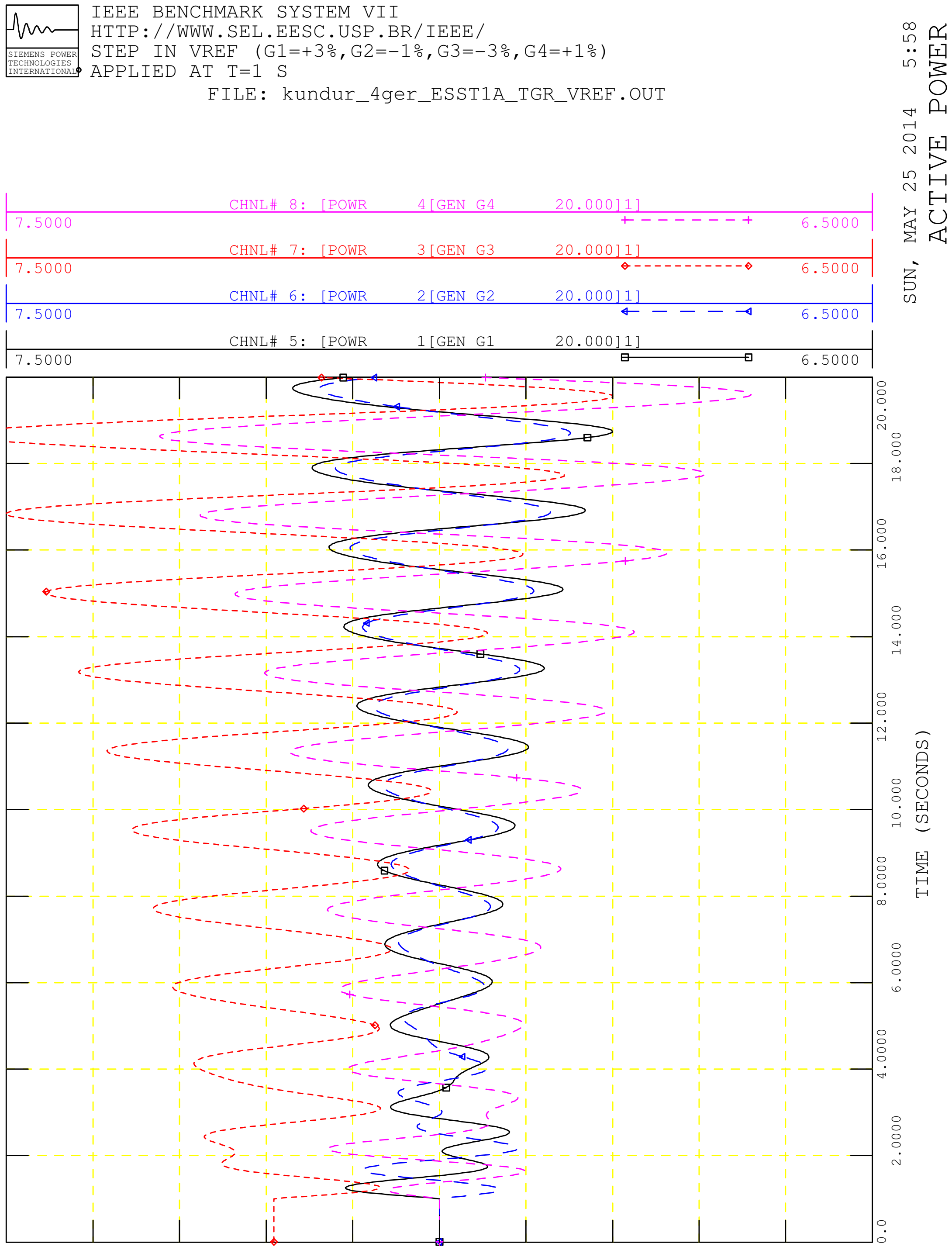

Figure 15: Step in Voltage References with ESST1A Model with TGR

3.5 ESST1A without TGR

The results in this Section correspond to the results in [1] with the static excitation system, represented in PSS/E by the ESST1A model presented in Section 2.2.2 (time constant T_B=1 s).

3.5.1 50 MVAr Reactor at Mid-Point

Figure 16 shows the electrical power output of the generators (100 MVA base) for the 50 MVAr reactor disturbance (ESST1A model with T_B=1 s).

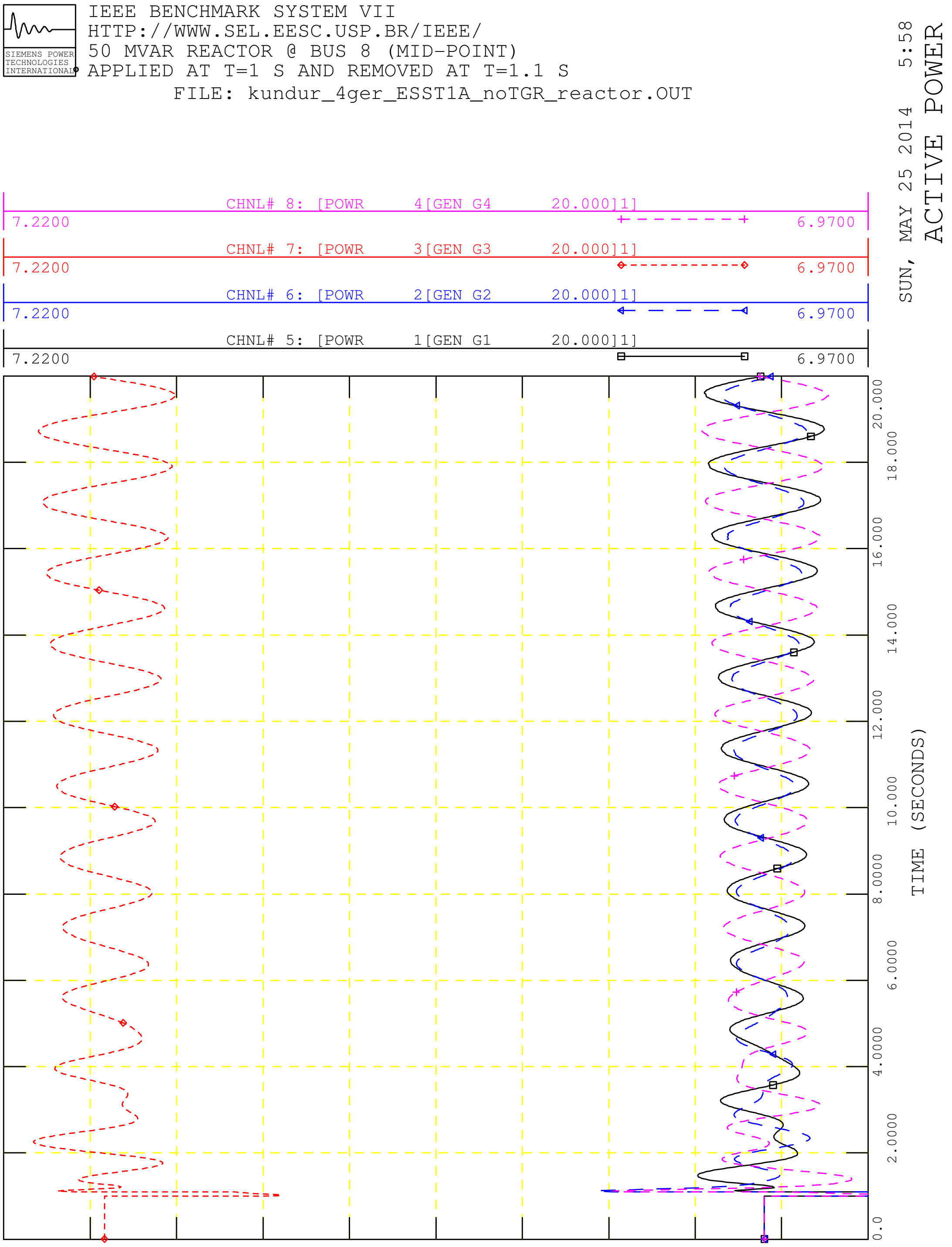

Figure 16: 50 MVAr Reactor Disturbance with ESST1A Model without TGR

3.5.2 Steps in V_{ref}

Figure 17 shows the electrical power output of the generators (100 MVA base) for the step changes in voltage reference, when the excitation systems represented by the ESST1A model, considering the gain T_B=1 s.

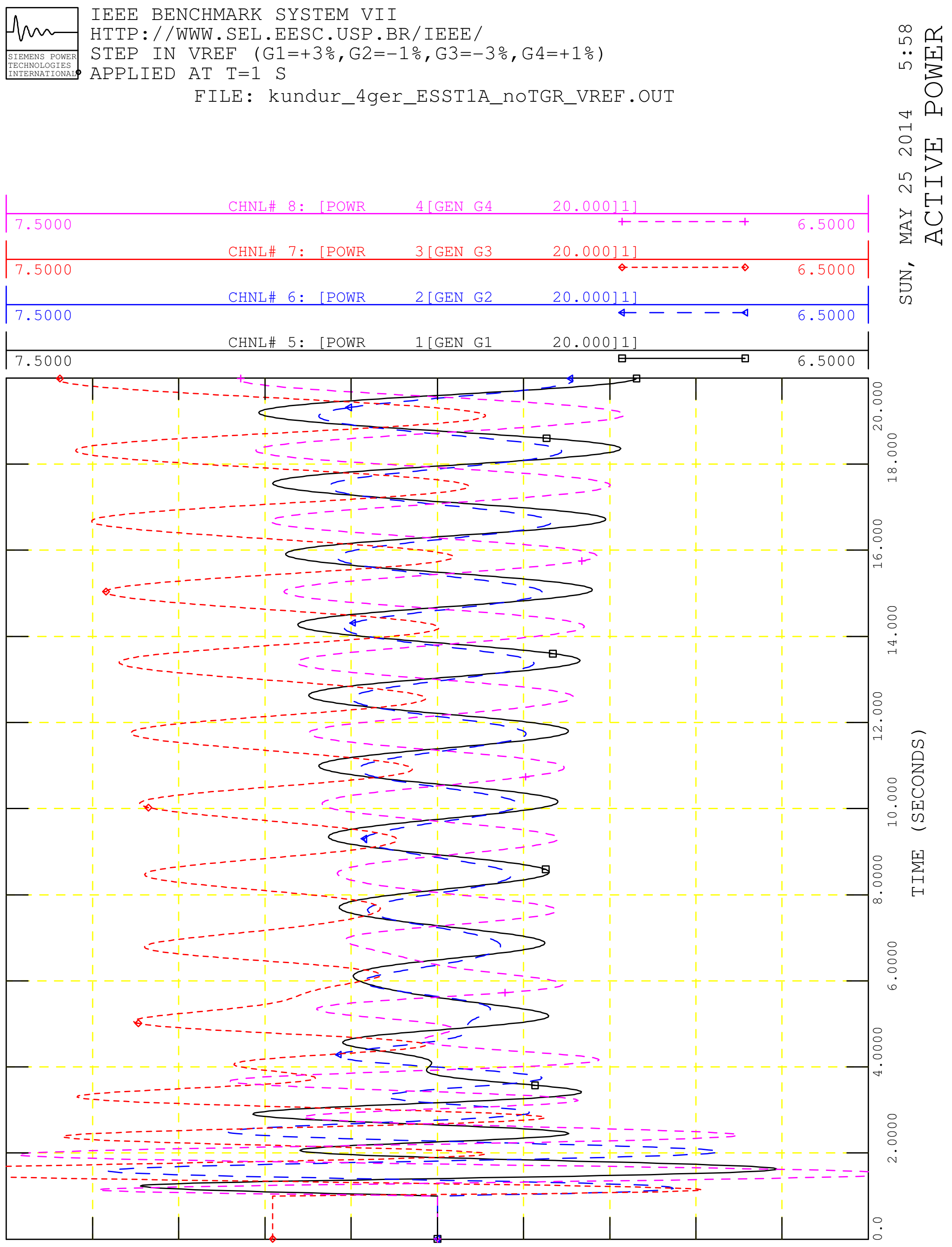

Figure 17: Step in Voltage References with ESST1A Model without TGR

3.6 ESST1A without TGR with Original PSS

The results in this Section correspond to the results in [1] with the static excitation system, represented in PSS/E by the ESST1A model presented in Section 2.2.2 (time constant T_B=1 s) and considering the original PSS parameters as described in Section 2.3.

3.6.1 50 MVAr Reactor at Mid-Point

Figure 16 shows the power output of the generators for the 50 MVAr reactor disturbance.

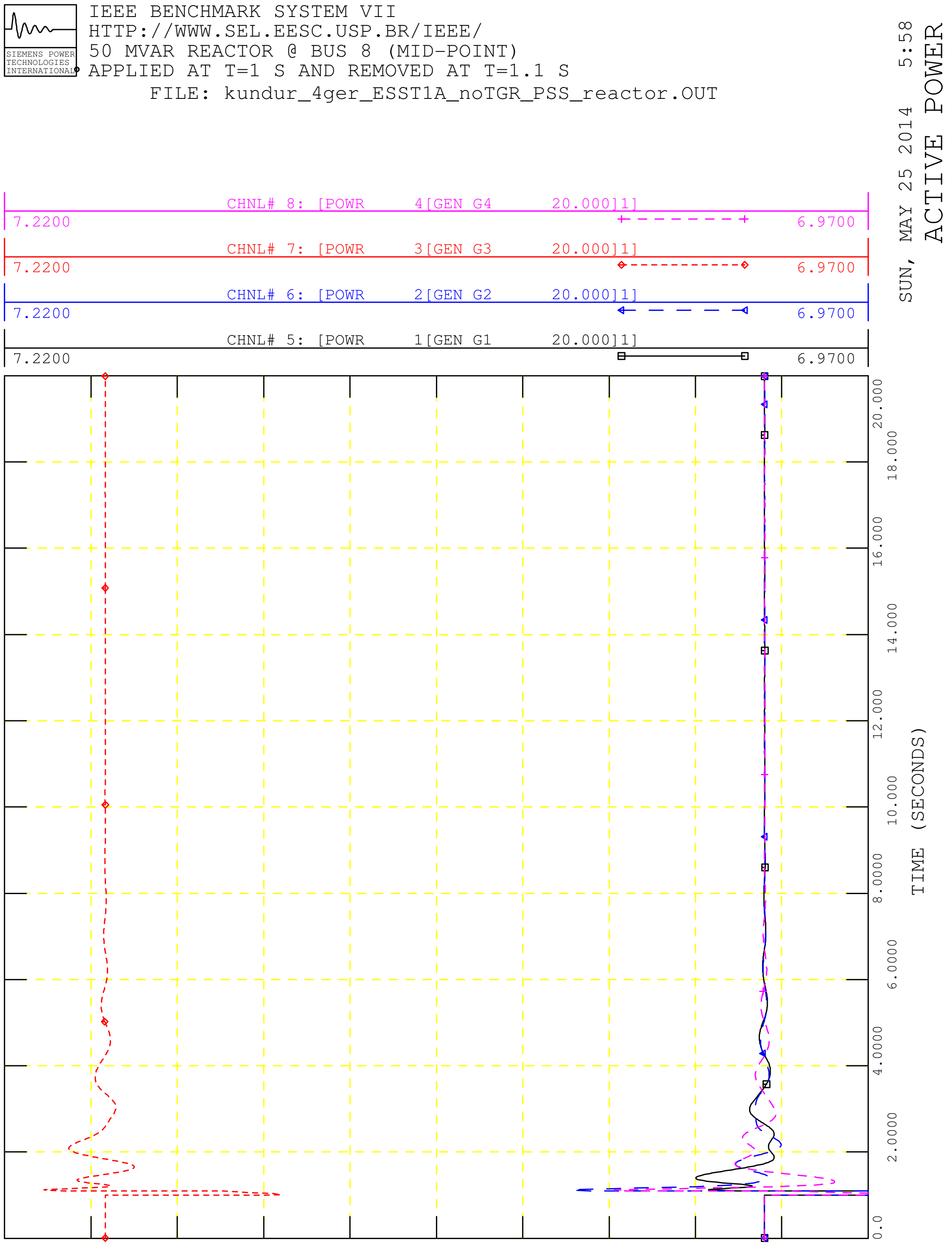

Figure 18: 50 MVAr Reactor Disturbance with ESST1A Model without TGR and Original PSS

3.6.2 Steps in V_{ref}

Figure 19 shows the electrical power output of the generators (100 MVA base) for the step changes in voltage reference.

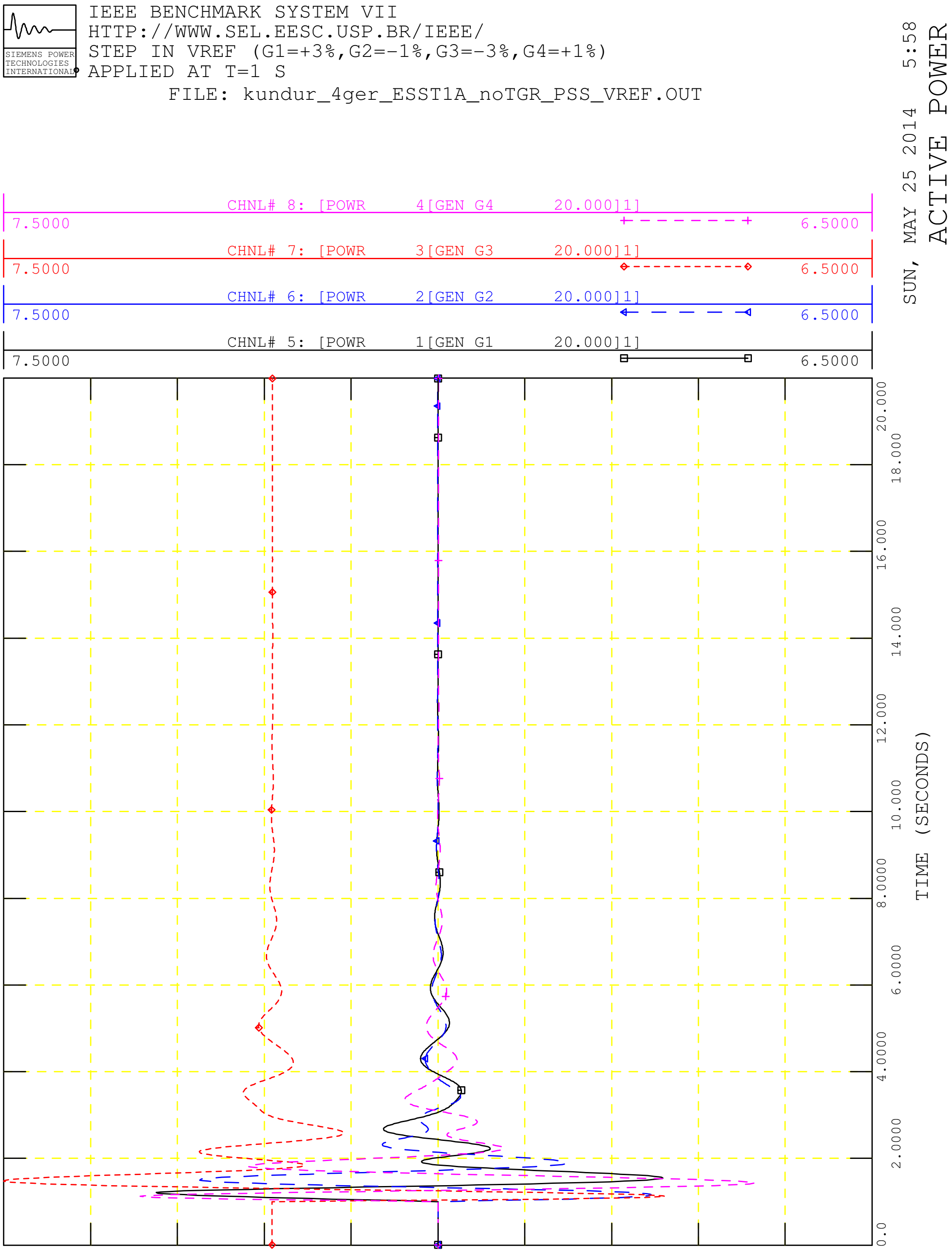

Figure 19: Step in Voltage References with ESST1A Model without TGR and Original PSS

3.7 ESST1A without TGR with Modified PSS

The results in this Section correspond to the results in [1] with the static excitation system, represented in PSS/E by the ESST1A model presented in Section 2.2.2 (time constant T_B=1 s) and considering the modified PSS parameters proposed in Section 2.3.

3.7.1 50 MVAr Reactor at Mid-Point

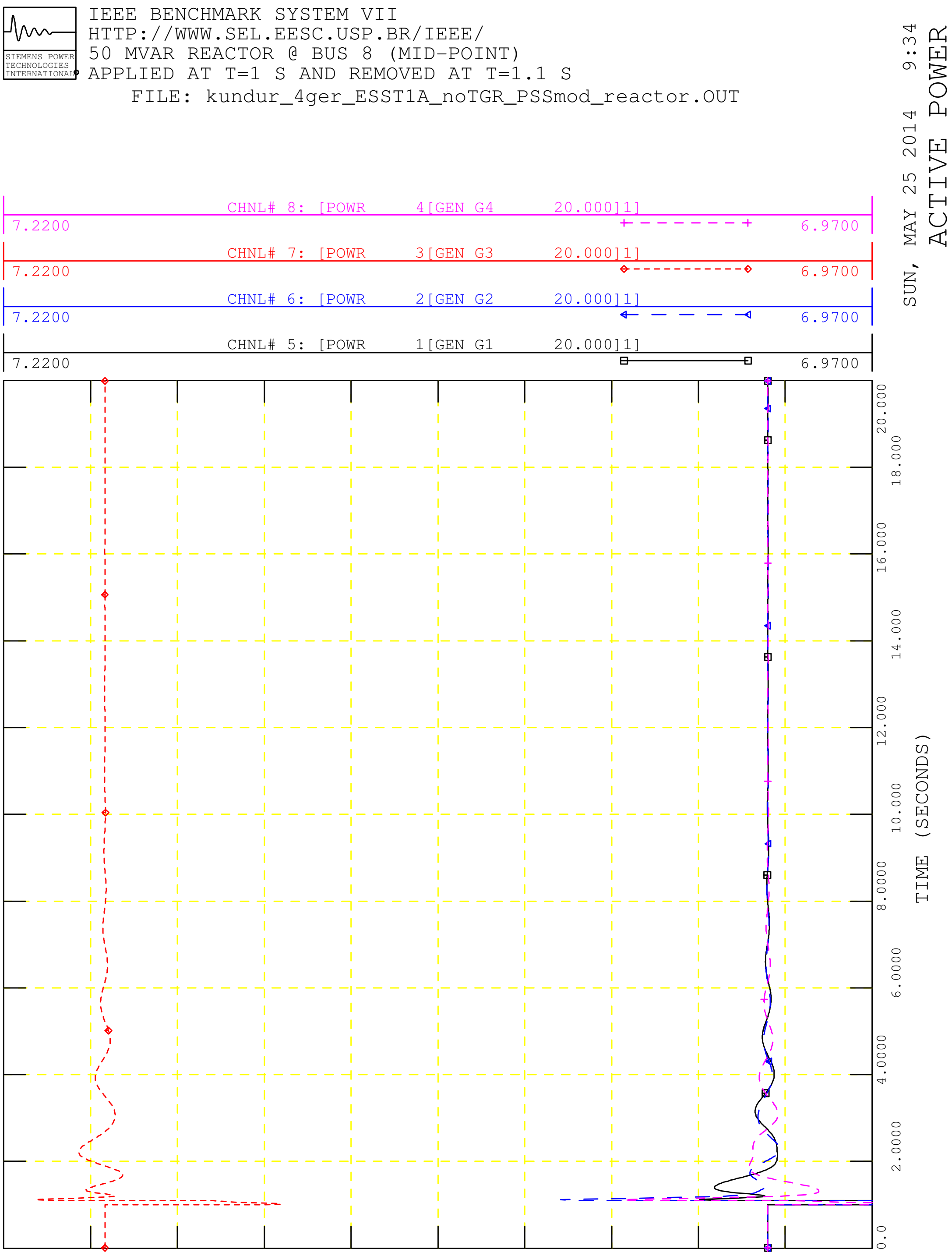

Figure 20: 50 MVAr Reactor Disturbance with ESST1A Model without TGR and Modified PSS

3.7.2 Steps in Vref

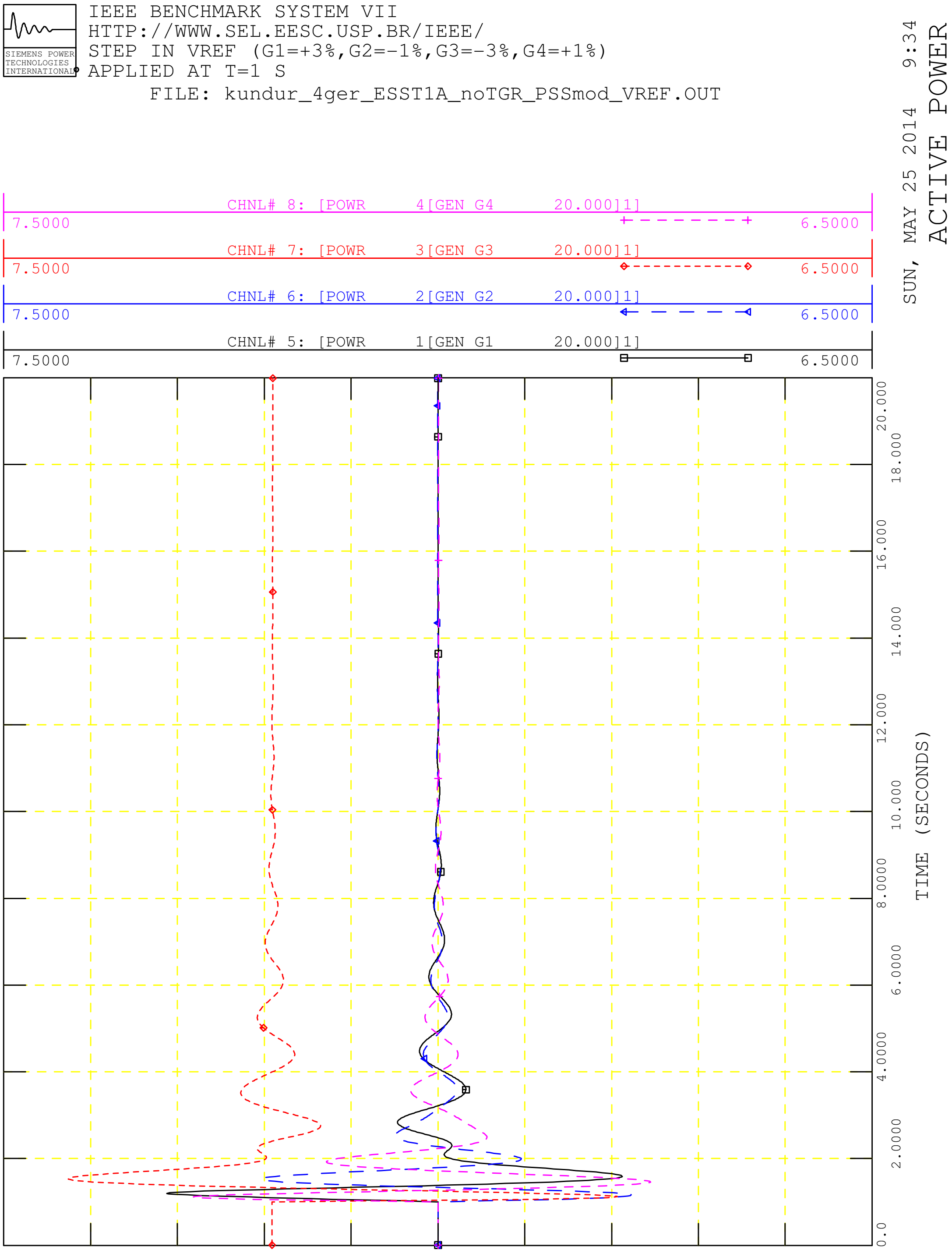

Figure 21: Step in Voltage References with ESST1A Model without TGR and Modified PSS

3.8 Modal Analysis

3.8.1 PSS/E LSYSAN

PSS/E can build a numerical approximation for the linearized system model. This approximation is obtained by numerical disturbances applied to the states of the nonlinear model, so the resulting precision of the numerical approximation is a function of the applied disturbance.

The results obtained with this tool might not be as accurate as the results that can be obtained from linearized models built with analytical linearization techniques, so the results (eigenvalues and eigenvectors) presented in this section cannot be taken as an absolute (precise) reference. On the other hand, it would be an interesting exercise to compare these results with those obtained from analytical methods.

The PSS/E activity ASTR allows the definition of the disturbance to be used, and also the state variables and input/output variables that will be used in building a (linearized) state equation for modal analysis, as shown in Figure 22.

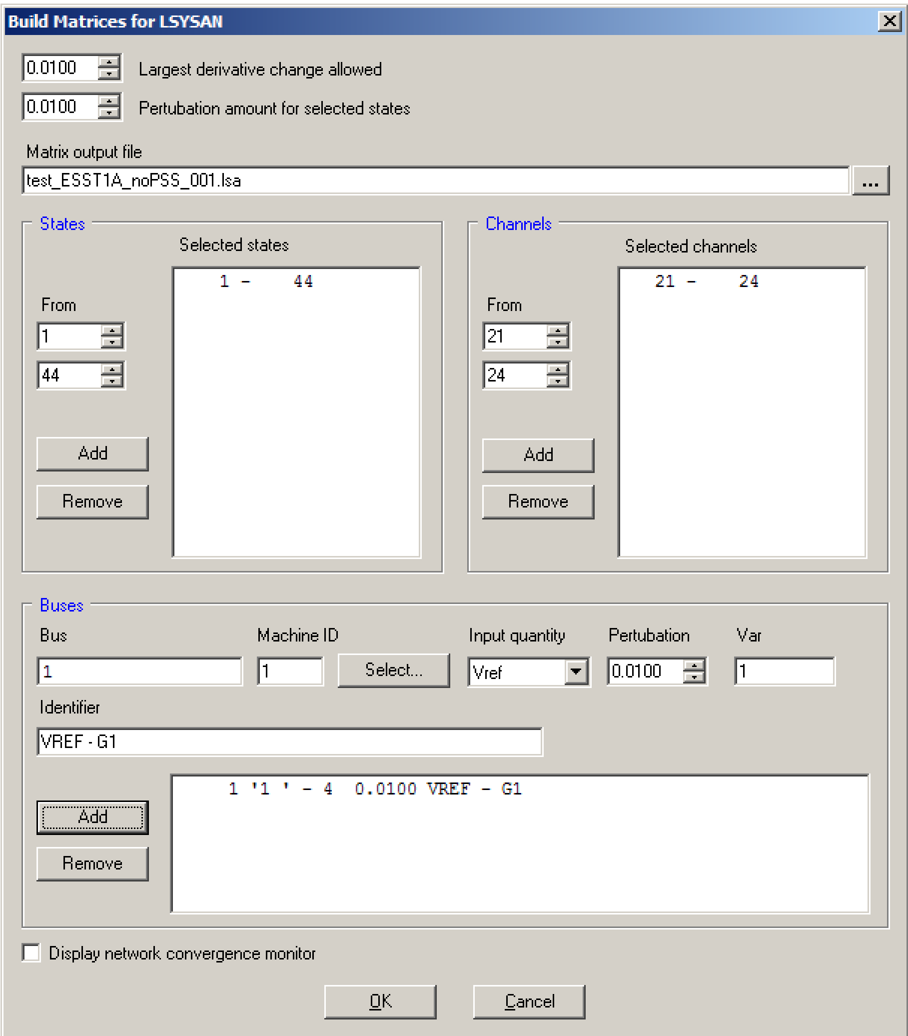

Figure 22: PSS/E Window for Activity ASTR (Linearized State Equation)

Once the linearized state equations have been numerically calculated, the auxiliary program LSYSAN[1] can be used for the modal analysis.

It should be noted that the PSS/E case associated with Section 3.5 (ESST1A model without TGR, no PSS) has 44 states, corresponding to 6 states per generator, plus 5 states per excitation system (ESST1A model). On the other hand, the data for the ESST1A model has been set (see Table 9) with T_A=T_{C1}=T_{B1}=K_F=0, so only two state variables in each ESST1A model are "active", i.e., are part of the system dynamic response: the state associated with the voltage measurement time constant T_R and the state associated with the lead-lag block with parameters T_C and T_B.

The program LSYSAN was able to automatically identify (and eliminate from the linearized state equations) the state variables associated with the time constant T_A in the four ESST1A models in the system. Thus, LSYSAN calculated the eigenvalues of a linearized system of order 40, as shown Table 11. The other state variables that are redundant (not active due to the selected values for the parameters in the model) are still part of the state equations. Each of these redundant states will result in an eigenvalue equal to –1, as highlighted in Table 11 .

Also, it is important to notice that the system data does not contain an infinite bus and PSS/E uses angles referred to the synchronous frame of reference (absolute angles), not relative angles between machines, or between machines and an infinite bus. Furthermore, there are no speed governor models in the system data, so all generators are represented as having constant mechanical power from the turbine. Therefore, the linearized system model contains two eigenvalues at the origin, associated with the rigid-body motion of the system [7]. Numerical calculations, both in the determination of the linearized state equations and the EISPACK routines for the QR method, result in a pair of eigenvalues close to the origin, but not exactly zero (highlighted in Table 11). Sometimes these eigenvalues, due to the numerical issues described above, are even shown with a positive real part, which might be misinterpreted as an unstable mode. These modes should be ignored and cannot be misinterpreted as an electromechanical oscillation mode, particularly an unstable mode. All it takes is to determine the speed mode-shape for this mode (eigenvector elements associated with the rotor speed deviation of the generators) and the analyst will see that the mode-shape shows all components with the same phase and magnitude, clearly indicating that this is the rigid-body motion of the system, all units accelerating together.

Table 12 presents the eigenvector associated with mode #5 in Table 11. The components of the eigenvector associated with the rotor speed deviation of the generators (state K+4 of the model GENROE) are highlighted. It can be seen that this mode is related with machines 1 and 4 oscillating in phase opposition to machines 2 and 3. Moreover, the relative magnitudes of these eigenvector components indicate that this mode corresponds (mostly) to the oscillation between machines 3 and 4. The fact that this mode is an oscillation between machines 3 and 4 becomes obvious when looking at the relative participation factors for this mode, shown in

[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 **13**.

Table **14** presents the eigenvector associated with mode #7 in Table 11. The components of the eigenvector associated with the rotor speed deviation of the generators (state K+4 of the model GENROE) are highlighted. It can be seen that this mode is (mostly) the oscillation between machines 1 and 2, as clearly shown by the participation factors in

Table **15**.

Table 16 presents the eigenvector associated with mode #9 in Table 11. The components of the eigenvector associated with the rotor speed deviation of the generators (state K+4 of the model GENROE) are highlighted. It can be seen that this mode is the inter-area mode, with machines 1 and 2 oscillating against machines 3 and 4. Considering the relative magnitudes of these eigenvector components, the inter-area mode is somewhat more observable in the importing area (generators 3 and 4). The relative participation factors in Table 17 show that all four units participate in this oscillation mode, with slightly more observability and controlability on the units in the importing area.

Table 18 corresponds to the eigenvector associated with mode #11 in Table 11 and it can be seen that the components of the eigenvector associated with rotor speed deviation of the generators (highlighted) have practically the same phase, the indication that this is the rigid body mode, as described above.

Table 11: Eigenvalues Calculated with PSS/E Program LSYSAN

```
COMPLEX EIGENVALUES:

  NO.     REAL          IMAG          DAMP          FREQ
    1  -18.119        22.262       0.63124        3.5431
    2  -18.119       -22.262       0.63124        3.5431

    3  -19.167        16.532       0.75724        2.6311
    4  -19.167       -16.532       0.75724        2.6311

    5 -0.66058        7.2907       0.90236E-01    1.1604
    6 -0.66058       -7.2907       0.90236E-01    1.1604

    7 -0.65639        7.0881       0.92210E-01    1.1281
    8 -0.65639       -7.0881       0.92210E-01    1.1281

    9  0.64617E-03    3.8361      -0.16840E-03   0.61054
   10  0.64617E-03   -3.8361      -0.16840E-03   0.61054

   11 -0.28446E-01  0.80374E-01   0.33364       0.12792E-01
   12 -0.28446E-01 -0.80374E-01   0.33364       0.12792E-01

REAL EIGENVALUES:

  NO.     REAL      TIME CONSTANT
   13  -97.447      0.10262E-01
   14  -97.389      0.10268E-01
   15  -95.600      0.10460E-01
   16  -94.467      0.10586E-01
   17  -36.297      0.27550E-01
   18  -36.200      0.27625E-01
   19  -31.617      0.31628E-01
   20  -30.678      0.32597E-01
   21  -25.254      0.39598E-01
   22  -24.357      0.41057E-01
   23  -16.818      0.59461E-01
   24  -15.953      0.62682E-01
   25  -3.6304      0.27545
   26  -3.5340      0.28296
   27  -3.3135      0.30179
   28  -3.2842      0.30449
   29  -1.0000       1.0000
   30  -1.0000       1.0000
   31  -1.0000       1.0000
   32  -1.0000       1.0000
   33  -1.0000       1.0000
   34  -1.0000       1.0000
   35  -1.0000       1.0000
   36  -1.0000       1.0000
   37  -1.0000       1.0000
```

38	-1.0000	1.0000
39	-1.0000	1.0000
40	-1.0000	1.0000

Table 12: Eigenvector Calculated with PSS/E Program LSYSAN for Mode #5

```
EIGENVALUE      5: REAL=  -0.66058      IMAG=     7.2907
                   DAMP=    0.90236E-01 FREQ=     1.1604
```

ROW	X--- VECTOR MAGNITUDE	ELEMENT ---X PHASE	STATE	MODEL	BUS	X----- NAME	-----X	ID
1	0.19592E-01	-23.884	K	GENROE	1	GEN G1	20.000	1
2	0.34422E-01	-61.870	K+1	GENROE	1	GEN G1	20.000	1
3	0.12763E-01	-176.57	K+2	GENROE	1	GEN G1	20.000	1
4	0.59303E-01	-30.047	K+3	GENROE	1	GEN G1	20.000	1
5	0.33976E-02	86.700	K+4	GENROE	1	GEN G1	20.000	1
6	0.17497	-8.4770	K+5	GENROE	1	GEN G1	20.000	1
7	0.55303E-01	-146.60	K	GENROE	2	GEN G2	20.000	1
8	0.38783E-01	102.49	K+1	GENROE	2	GEN G2	20.000	1
9	0.25895E-01	-124.26	K+2	GENROE	2	GEN G2	20.000	1
10	0.66405E-01	139.87	K+3	GENROE	2	GEN G2	20.000	1
11	0.42271E-02	-86.616	K+4	GENROE	2	GEN G2	20.000	1
12	0.21768	178.21	K+5	GENROE	2	GEN G2	20.000	1
13	0.21400	-175.06	K	GENROE	3	GEN G3	20.000	1
14	0.11930	112.51	K+1	GENROE	3	GEN G3	20.000	1
15	0.54508E-01	175.54	K+2	GENROE	3	GEN G3	20.000	1
16	0.22165	147.92	K+3	GENROE	3	GEN G3	20.000	1
17	0.17545E-01	-88.884	K+4	GENROE	3	GEN G3	20.000	1
18	0.90351	175.94	K+5	GENROE	3	GEN G3	20.000	1
19	0.11370	103.45	K	GENROE	4	GEN G4	20.000	1
20	0.24404	-66.045	K+1	GENROE	4	GEN G4	20.000	1
21	0.19437	134.07	K+2	GENROE	4	GEN G4	20.000	1
22	0.39142	-32.350	K+3	GENROE	4	GEN G4	20.000	1
23	0.19418E-01	95.177	K+4	GENROE	4	GEN G4	20.000	1
24	1.0000	0.0000	K+5	GENROE	4	GEN G4	20.000	1
25	0.65227E-02	-131.75	K	ESST1A	1	GEN G1	20.000	1
26	0.0000	0.0000	K+1	ESST1A	1	GEN G1	20.000	1
27	0.0000	0.0000	K+2	ESST1A	1	GEN G1	20.000	1
28	0.0000	0.0000	K+4	ESST1A	1	GEN G1	20.000	1
29	0.15153E-01	117.79	K	ESST1A	2	GEN G2	20.000	1
30	0.0000	0.0000	K+1	ESST1A	2	GEN G2	20.000	1
31	0.0000	0.0000	K+2	ESST1A	2	GEN G2	20.000	1
32	0.0000	0.0000	K+4	ESST1A	2	GEN G2	20.000	1
33	0.62847E-01	87.260	K	ESST1A	3	GEN G3	20.000	1
34	0.0000	0.0000	K+1	ESST1A	3	GEN G3	20.000	1
35	0.0000	0.0000	K+2	ESST1A	3	GEN G3	20.000	1
36	0.0000	0.0000	K+4	ESST1A	3	GEN G3	20.000	1
37	0.24736E-01	26.409	K	ESST1A	4	GEN G4	20.000	1
38	0.0000	0.0000	K+1	ESST1A	4	GEN G4	20.000	1
39	0.0000	0.0000	K+2	ESST1A	4	GEN G4	20.000	1
40	0.0000	0.0000	K+4	ESST1A	4	GEN G4	20.000	1

Table 13: Relative Participation Factors Calculated with PSS/E Program LSYSAN for Mode #5

NORMALIZED PARTICIPATION FACTORS FOR MODE 5: -0.66058 7.2907

FACTOR	ROW	STATE	MODEL	BUS	X----- NAME -----X	ID
1.00000	23	K+4	GENROE	4	GEN G4 20.000	1
0.99928	24	K+5	GENROE	4	GEN G4 20.000	1
0.82994	17	K+4	GENROE	3	GEN G3 20.000	1
0.82930	18	K+5	GENROE	3	GEN G3 20.000	1
0.13109	20	K+1	GENROE	4	GEN G4 20.000	1
0.11943	13	K	GENROE	3	GEN G3 20.000	1
0.11232	22	K+3	GENROE	4	GEN G4 20.000	1
0.06230	19	K	GENROE	4	GEN G4 20.000	1
0.05871	14	K+1	GENROE	3	GEN G3 20.000	1
0.05824	16	K+3	GENROE	3	GEN G3 20.000	1
0.04037	11	K+4	GENROE	2	GEN G2 20.000	1
0.04034	12	K+5	GENROE	2	GEN G2 20.000	1
0.01833	5	K+4	GENROE	1	GEN G1 20.000	1
0.01832	6	K+5	GENROE	1	GEN G1 20.000	1
0.01189	21	K+2	GENROE	4	GEN G4 20.000	1
0.00880	33	K	ESST1A	3	GEN G3 20.000	1
0.00629	7	K	GENROE	2	GEN G2 20.000	1
0.00364	8	K+1	GENROE	2	GEN G2 20.000	1
0.00340	37	K	ESST1A	4	GEN G4 20.000	1
0.00340	15	K+2	GENROE	3	GEN G3 20.000	1
0.00332	10	K+3	GENROE	2	GEN G2 20.000	1
0.00193	2	K+1	GENROE	1	GEN G1 20.000	1
0.00178	4	K+3	GENROE	1	GEN G1 20.000	1
0.00111	1	K	GENROE	1	GEN G1 20.000	1
0.00043	29	K	ESST1A	2	GEN G2 20.000	1
0.00033	9	K+2	GENROE	2	GEN G2 20.000	1
0.00009	25	K	ESST1A	1	GEN G1 20.000	1
0.00008	3	K+2	GENROE	1	GEN G1 20.000	1
0.00000	31	K+2	ESST1A	2	GEN G2 20.000	1
0.00000	30	K+1	ESST1A	2	GEN G2 20.000	1
0.00000	28	K+4	ESST1A	1	GEN G1 20.000	1
0.00000	27	K+2	ESST1A	1	GEN G1 20.000	1
0.00000	26	K+1	ESST1A	1	GEN G1 20.000	1
0.00000	40	K+4	ESST1A	4	GEN G4 20.000	1
0.00000	39	K+2	ESST1A	4	GEN G4 20.000	1
0.00000	38	K+1	ESST1A	4	GEN G4 20.000	1
0.00000	36	K+4	ESST1A	3	GEN G3 20.000	1
0.00000	35	K+2	ESST1A	3	GEN G3 20.000	1
0.00000	34	K+1	ESST1A	3	GEN G3 20.000	1
0.00000	32	K+4	ESST1A	2	GEN G2 20.000	1

Table 14: Eigenvector Calculated with PSS/E Program LSYSAN for Mode #7

```
EIGENVALUE      7: REAL=  -0.65639      IMAG=     7.0881
                   DAMP=   0.92210E-01 FREQ=     1.1281

  ROW   X--- VECTOR  ELEMENT ---X  STATE  MODEL       BUS  X----- NAME -----X   ID
         MAGNITUDE        PHASE
    1    0.18930       -170.48     K     GENROE         1  GEN G1       20.000   1
    2    0.14218        116.04     K+1   GENROE         1  GEN G1       20.000   1
    3    0.33462E-01   -159.24     K+2   GENROE         1  GEN G1       20.000   1
    4    0.25376        150.20     K+3   GENROE         1  GEN G1       20.000   1
    5    0.17559E-01   -86.802     K+4   GENROE         1  GEN G1       20.000   1
    6    0.92993        177.91     K+5   GENROE         1  GEN G1       20.000   1
    7    0.10921        84.714     K     GENROE         2  GEN G2       20.000   1
    8    0.23755       -65.703     K+1   GENROE         2  GEN G2       20.000   1
    9    0.16242        129.42     K+2   GENROE         2  GEN G2       20.000   1
   10    0.38205       -32.365     K+3   GENROE         2  GEN G2       20.000   1
   11    0.18882E-01    95.291     K+4   GENROE         2  GEN G2       20.000   1
   12     1.0000        0.0000     K+5   GENROE         2  GEN G2       20.000   1
   13    0.42190E-01   -143.53     K     GENROE         3  GEN G3       20.000   1
   14    0.22907E-01    144.52     K+1   GENROE         3  GEN G3       20.000   1
   15    0.11378E-01   -152.44     K+2   GENROE         3  GEN G3       20.000   1
   16    0.42333E-01    179.42     K+3   GENROE         3  GEN G3       20.000   1
   17    0.34616E-02   -57.699     K+4   GENROE         3  GEN G3       20.000   1
   18    0.18333       -152.99     K+5   GENROE         3  GEN G3       20.000   1
   19    0.24313E-01    159.85     K     GENROE         4  GEN G4       20.000   1
   20    0.31238E-01   -33.506     K+1   GENROE         4  GEN G4       20.000   1
   21    0.32708E-01    166.02     K+2   GENROE         4  GEN G4       20.000   1
   22    0.48241E-01 -0.40388     K+3   GENROE         4  GEN G4       20.000   1
   23    0.21223E-02    130.85     K+4   GENROE         4  GEN G4       20.000   1
   24    0.11240        35.564     K+5   GENROE         4  GEN G4       20.000   1
   25    0.53270E-01    90.079     K     ESST1A         1  GEN G1       20.000   1
   26     0.0000        0.0000     K+1   ESST1A         1  GEN G1       20.000   1
   27     0.0000        0.0000     K+2   ESST1A         1  GEN G1       20.000   1
   28     0.0000        0.0000     K+4   ESST1A         1  GEN G1       20.000   1
   29    0.21164E-01 -0.68033     K     ESST1A         2  GEN G2       20.000   1
   30     0.0000        0.0000     K+1   ESST1A         2  GEN G2       20.000   1
   31     0.0000        0.0000     K+2   ESST1A         2  GEN G2       20.000   1
   32     0.0000        0.0000     K+4   ESST1A         2  GEN G2       20.000   1
   33    0.12050E-01    118.79     K     ESST1A         3  GEN G3       20.000   1
   34     0.0000        0.0000     K+1   ESST1A         3  GEN G3       20.000   1
   35     0.0000        0.0000     K+2   ESST1A         3  GEN G3       20.000   1
   36     0.0000        0.0000     K+4   ESST1A         3  GEN G3       20.000   1
   37    0.64398E-02    79.346     K     ESST1A         4  GEN G4       20.000   1
   38     0.0000        0.0000     K+1   ESST1A         4  GEN G4       20.000   1
   39     0.0000        0.0000     K+2   ESST1A         4  GEN G4       20.000   1
   40     0.0000        0.0000     K+4   ESST1A         4  GEN G4       20.000   1
```

Table 15: Relative Participation Factors Calculated with PSS/E Program LSYSAN for Mode #7

```
NORMALIZED PARTICIPATION FACTORS FOR MODE     7: -0.65639       7.0881

 FACTOR   ROW  STATE  MODEL     BUS  X-- NAME --X  ID
1.00000    11   K+4   GENROE               2  GEN G2      20.000  1
0.99926    12   K+5   GENROE               2  GEN G2      20.000  1
0.85261     5   K+4   GENROE               1  GEN G1      20.000  1
0.85199     6   K+5   GENROE               1  GEN G1      20.000  1
0.12671     8   K+1   GENROE               2  GEN G2      20.000  1
0.10786    10   K+3   GENROE               2  GEN G2      20.000  1
0.09957     1   K     GENROE               1  GEN G1      20.000  1
0.06985     2   K+1   GENROE               1  GEN G1      20.000  1
0.06596     4   K+3   GENROE               1  GEN G1      20.000  1
0.05868     7   K     GENROE               2  GEN G2      20.000  1
0.04558    17   K+4   GENROE               3  GEN G3      20.000  1
0.04554    18   K+5   GENROE               3  GEN G3      20.000  1
0.01862    23   K+4   GENROE               4  GEN G4      20.000  1
0.01861    24   K+5   GENROE               4  GEN G4      20.000  1
0.00948     9   K+2   GENROE               2  GEN G2      20.000  1
0.00703    25   K     ESST1A               1  GEN G1      20.000  1
0.00622    13   K     GENROE               3  GEN G3      20.000  1
0.00319    14   K+1   GENROE               3  GEN G3      20.000  1
0.00311    16   K+3   GENROE               3  GEN G3      20.000  1
0.00285    29   K     ESST1A               2  GEN G2      20.000  1
0.00280    20   K+1   GENROE               4  GEN G4      20.000  1
0.00228    22   K+3   GENROE               4  GEN G4      20.000  1
0.00203    19   K     GENROE               4  GEN G4      20.000  1
0.00191     3   K+2   GENROE               1  GEN G1      20.000  1
0.00045    33   K     ESST1A               3  GEN G3      20.000  1
0.00030    21   K+2   GENROE               4  GEN G4      20.000  1
0.00018    15   K+2   GENROE               3  GEN G3      20.000  1
0.00013    37   K     ESST1A               4  GEN G4      20.000  1
0.00000    31   K+2   ESST1A               2  GEN G2      20.000  1
0.00000    30   K+1   ESST1A               2  GEN G2      20.000  1
0.00000    28   K+4   ESST1A               1  GEN G1      20.000  1
0.00000    27   K+2   ESST1A               1  GEN G1      20.000  1
0.00000    26   K+1   ESST1A               1  GEN G1      20.000  1
0.00000    40   K+4   ESST1A               4  GEN G4      20.000  1
0.00000    39   K+2   ESST1A               4  GEN G4      20.000  1
0.00000    38   K+1   ESST1A               4  GEN G4      20.000  1
0.00000    36   K+4   ESST1A               3  GEN G3      20.000  1
0.00000    35   K+2   ESST1A               3  GEN G3      20.000  1
0.00000    34   K+1   ESST1A               3  GEN G3      20.000  1
0.00000    32   K+4   ESST1A               2  GEN G2      20.000  1
```

Table 16: Eigenvector Calculated with PSS/E Program LSYSAN for Mode #9

EIGENVALUE 9: REAL= 0.64617E-03 IMAG= 3.8361
DAMP= -0.16840E-03 FREQ= 0.61054

ROW	X--- VECTOR MAGNITUDE	ELEMENT ---X PHASE	STATE	MODEL	BUS	X----- NAME	-----X	ID
1	0.15161	173.09	K	GENROE	1	GEN G1	20.000	1
2	0.16606E-01	14.014	K+1	GENROE	1	GEN G1	20.000	1
3	0.95891E-01	165.58	K+2	GENROE	1	GEN G1	20.000	1
4	0.17763E-01	81.067	K+3	GENROE	1	GEN G1	20.000	1
5	0.83922E-02	-100.94	K+4	GENROE	1	GEN G1	20.000	1
6	0.82473	169.07	K+5	GENROE	1	GEN G1	20.000	1
7	0.25589	158.66	K	GENROE	2	GEN G2	20.000	1
8	0.82312E-01	-64.728	K+1	GENROE	2	GEN G2	20.000	1
9	0.19836	144.92	K+2	GENROE	2	GEN G2	20.000	1
10	0.95749E-01	-53.104	K+3	GENROE	2	GEN G2	20.000	1
11	0.59052E-02	-89.479	K+4	GENROE	2	GEN G2	20.000	1
12	0.58033	-179.47	K+5	GENROE	2	GEN G2	20.000	1
13	0.30072E-01	90.912	K	GENROE	3	GEN G3	20.000	1
14	0.82204E-01	-51.165	K+1	GENROE	3	GEN G3	20.000	1
15	0.55905E-01	134.61	K+2	GENROE	3	GEN G3	20.000	1
16	0.12286	-32.017	K+3	GENROE	3	GEN G3	20.000	1
17	0.10176E-01	89.990	K+4	GENROE	3	GEN G3	20.000	1
18	1.0000	0.0000	K+5	GENROE	3	GEN G3	20.000	1
19	0.73132E-01	130.31	K	GENROE	4	GEN G4	20.000	1
20	0.10633	-56.573	K+1	GENROE	4	GEN G4	20.000	1
21	0.10084	134.98	K+2	GENROE	4	GEN G4	20.000	1
22	0.15149	-38.018	K+3	GENROE	4	GEN G4	20.000	1
23	0.93171E-02	87.142	K+4	GENROE	4	GEN G4	20.000	1
24	0.91562	-2.8485	K+5	GENROE	4	GEN G4	20.000	1
25	0.24354E-01	70.038	K	ESST1A	1	GEN G1	20.000	1
26	0.0000	0.0000	K+1	ESST1A	1	GEN G1	20.000	1
27	0.0000	0.0000	K+2	ESST1A	1	GEN G1	20.000	1
28	0.0000	0.0000	K+4	ESST1A	1	GEN G1	20.000	1
29	0.42509E-01	59.639	K	ESST1A	2	GEN G2	20.000	1
30	0.0000	0.0000	K+1	ESST1A	2	GEN G2	20.000	1
31	0.0000	0.0000	K+2	ESST1A	2	GEN G2	20.000	1
32	0.0000	0.0000	K+4	ESST1A	2	GEN G2	20.000	1
33	0.14633E-02	19.536	K	ESST1A	3	GEN G3	20.000	1
34	0.0000	0.0000	K+1	ESST1A	3	GEN G3	20.000	1
35	0.0000	0.0000	K+2	ESST1A	3	GEN G3	20.000	1
36	0.0000	0.0000	K+4	ESST1A	3	GEN G3	20.000	1
37	0.10261E-01	49.336	K	ESST1A	4	GEN G4	20.000	1
38	0.0000	0.0000	K+1	ESST1A	4	GEN G4	20.000	1
39	0.0000	0.0000	K+2	ESST1A	4	GEN G4	20.000	1
40	0.0000	0.0000	K+4	ESST1A	4	GEN G4	20.000	1

Table 17: Relative Participation Factors Calculated with PSS/E Program LSYSAN for Mode #9

```
NORMALIZED PARTICIPATION FACTORS FOR MODE     9:  0.64617E-03   3.8361

 FACTOR   ROW  STATE  MODEL     BUS  X-- NAME --X  ID
1.00000    18    K+5  GENROE                3  GEN G3      20.000  1
0.99986    17    K+4  GENROE                3  GEN G3      20.000  1
0.84740    24    K+5  GENROE                4  GEN G4      20.000  1
0.84729    23    K+4  GENROE                4  GEN G4      20.000  1
0.84029     6    K+5  GENROE                1  GEN G1      20.000  1
0.84018     5    K+4  GENROE                1  GEN G1      20.000  1
0.52350    12    K+5  GENROE                2  GEN G2      20.000  1
0.52344    11    K+4  GENROE                2  GEN G2      20.000  1
0.11696     7    K    GENROE                2  GEN G2      20.000  1
0.05480     1    K    GENROE                1  GEN G1      20.000  1
0.05069    20    K+1  GENROE                4  GEN G4      20.000  1
0.04270    14    K+1  GENROE                3  GEN G3      20.000  1
0.03779     8    K+1  GENROE                2  GEN G2      20.000  1
0.03522    22    K+3  GENROE                4  GEN G4      20.000  1
0.03111    16    K+3  GENROE                3  GEN G3      20.000  1
0.02695    19    K    GENROE                4  GEN G4      20.000  1
0.02143    10    K+3  GENROE                2  GEN G2      20.000  1
0.00927    13    K    GENROE                3  GEN G3      20.000  1
0.00878     2    K+1  GENROE                1  GEN G1      20.000  1
0.00587     9    K+2  GENROE                2  GEN G2      20.000  1
0.00485    29    K    ESST1A                2  GEN G2      20.000  1
0.00458     4    K+3  GENROE                1  GEN G1      20.000  1
0.00241    21    K+2  GENROE                4  GEN G4      20.000  1
0.00225     3    K+2  GENROE                1  GEN G1      20.000  1
0.00220    25    K    ESST1A                1  GEN G1      20.000  1
0.00112    15    K+2  GENROE                3  GEN G3      20.000  1
0.00094    37    K    ESST1A                4  GEN G4      20.000  1
0.00011    33    K    ESST1A                3  GEN G3      20.000  1
0.00000    31    K+2  ESST1A                2  GEN G2      20.000  1
0.00000    30    K+1  ESST1A                2  GEN G2      20.000  1
0.00000    28    K+4  ESST1A                1  GEN G1      20.000  1
0.00000    27    K+2  ESST1A                1  GEN G1      20.000  1
0.00000    26    K+1  ESST1A                1  GEN G1      20.000  1
0.00000    40    K+4  ESST1A                4  GEN G4      20.000  1
0.00000    39    K+2  ESST1A                4  GEN G4      20.000  1
0.00000    38    K+1  ESST1A                4  GEN G4      20.000  1
0.00000    36    K+4  ESST1A                3  GEN G3      20.000  1
0.00000    35    K+2  ESST1A                3  GEN G3      20.000  1
0.00000    34    K+1  ESST1A                3  GEN G3      20.000  1
0.00000    32    K+4  ESST1A                2  GEN G2      20.000  1
```

Table 18: Eigenvector Calculated with PSS/E Program LSYSAN for Mode #11

EIGENVALUE 11: REAL= -0.28446E-01 IMAG= 0.80374E-01
DAMP= 0.33364 FREQ= 0.12792E-01

ROW	X--- VECTOR ELEMENT ---X MAGNITUDE	PHASE	STATE	MODEL	BUS	X----- NAME -----X		ID
1	0.58873E-02	-0.62087	K	GENROE	1	GEN G1	20.000	1
2	0.40065E-02	178.61	K+1	GENROE	1	GEN G1	20.000	1
3	0.52644E-02	-0.90546	K+2	GENROE	1	GEN G1	20.000	1
4	0.49813E-02	178.96	K+3	GENROE	1	GEN G1	20.000	1
5	0.22615E-03	109.48	K+4	GENROE	1	GEN G1	20.000	1
6	1.0000	0.0000	K+5	GENROE	1	GEN G1	20.000	1
7	0.68345E-02	-0.59659	K	GENROE	2	GEN G2	20.000	1
8	0.45170E-02	178.61	K+1	GENROE	2	GEN G2	20.000	1
9	0.60773E-02	-0.87527	K+2	GENROE	2	GEN G2	20.000	1
10	0.56001E-02	178.96	K+3	GENROE	2	GEN G2	20.000	1
11	0.22550E-03	109.49	K+4	GENROE	2	GEN G2	20.000	1
12	0.99714	0.50360E-03	K+5	GENROE	2	GEN G2	20.000	1
13	0.24227E-02	-0.68215	K	GENROE	3	GEN G3	20.000	1
14	0.16116E-02	178.68	K+1	GENROE	3	GEN G3	20.000	1
15	0.21571E-02	-0.93353	K+2	GENROE	3	GEN G3	20.000	1
16	0.19979E-02	179.04	K+3	GENROE	3	GEN G3	20.000	1
17	0.22589E-03	109.49	K+4	GENROE	3	GEN G3	20.000	1
18	0.99877	-0.71651E-02	K+5	GENROE	3	GEN G3	20.000	1
19	0.12133E-02	-0.49801E-02	K	GENROE	4	GEN G4	20.000	1
20	0.87161E-03	179.38	K+1	GENROE	4	GEN G4	20.000	1
21	0.10347E-02	-0.19490	K+2	GENROE	4	GEN G4	20.000	1
22	0.11019E-02	179.76	K+3	GENROE	4	GEN G4	20.000	1
23	0.22592E-03	109.48	K+4	GENROE	4	GEN G4	20.000	1
24	0.99892	-0.92475E-02	K+5	GENROE	4	GEN G4	20.000	1
25	0.11317E-03	-170.09	K	ESST1A	1	GEN G1	20.000	1
26	0.0000	0.0000	K+1	ESST1A	1	GEN G1	20.000	1
27	0.0000	0.0000	K+2	ESST1A	1	GEN G1	20.000	1
28	0.0000	0.0000	K+4	ESST1A	1	GEN G1	20.000	1
29	0.78409E-04	-163.16	K	ESST1A	2	GEN G2	20.000	1
30	0.0000	0.0000	K+1	ESST1A	2	GEN G2	20.000	1
31	0.0000	0.0000	K+2	ESST1A	2	GEN G2	20.000	1
32	0.0000	0.0000	K+4	ESST1A	2	GEN G2	20.000	1
33	0.43968E-04	-169.49	K	ESST1A	3	GEN G3	20.000	1
34	0.0000	0.0000	K+1	ESST1A	3	GEN G3	20.000	1
35	0.0000	0.0000	K+2	ESST1A	3	GEN G3	20.000	1
36	0.0000	0.0000	K+4	ESST1A	3	GEN G3	20.000	1
37	0.18509E-04	-167.22	K	ESST1A	4	GEN G4	20.000	1
38	0.0000	0.0000	K+1	ESST1A	4	GEN G4	20.000	1
39	0.0000	0.0000	K+2	ESST1A	4	GEN G4	20.000	1
40	0.0000	0.0000	K+4	ESST1A	4	GEN G4	20.000	1

3.8.2 PSSPLT

The plotting package PSSPLT provided with the PSS/E installation [2] has a modal analysis function that can be used to obtain a numerical approximation of the oscillation modes observed in a time domain curve, such as the time domain simulation results from PSS/E. This modal analysis tool has a Prony method as well as a least square curve fit. The user has to select a time domain curve to be used for the analysis, as well as the time interval for the analysis and the order of the approximation, via the window shown in Figure 23.

The least square methods allow a scan for different orders of linear approximation, a useful tool to determine the best possible approximation. Figure 23 shows the options to be selected to determine the best fit from a 15th order equivalent to a 45th order equivalent, while Figure 24 presents the options related with the modal analysis calculation for the chosen equivalent system order.

Table 19 shows the results of the modal analysis scan, searching for the best fit as a function of the order of the equivalent system. It can be seen that the minimum error is associated with a 36th–order system.

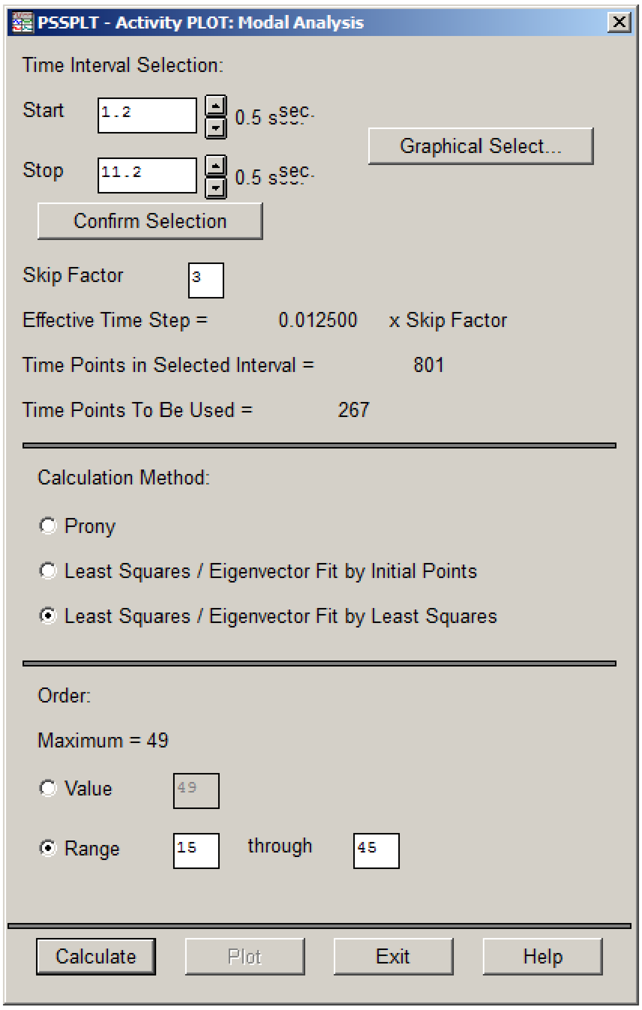

Figure 23: PSSPLT Window for Modal Analysis Scan to Determine Order of Best Equivalent

Table 20 shows the results of the modal analysis calculations with a given equivalent system order, usually the best fit determined by as shown above.

The user should always remember that this is a numerical approach, therefore the results are sensitive to numerical issues and user selections. The mode highlighted in blue is a good example, as it is associated with a pole in the origin, representing a step function in the time domain. This mode is always present, when the initial and final points of the selected curve, in the given time window (time range) are not identical. The curve fit procedure would understand (and represent) this change as a step change in the response and, as such, introduce this mode at the origin, with the appropriate magnitude to match the difference between the values of initial and final points. This mode should be disregarded, for all practical purposes.

The two modes highlighted in yellow are reasonable (numerical) approximations to the modes #5 and #9, obtained with LSYSAN and shown in Table 11. It is also notable that mode #7 in Table 11 is not present in these results: generator G1 has limited participation in that mode, thus the observability of that mode in the electrical power output of generator G1 (selected trace for this analysis) is quite small.

The remaining modes have relatively small magnitudes, with exception of the the 3rd component. This 3rd component has a relatively high frequency (above 3 Hz) and is very well damped, corresponding to a time domain response that disappears very fast.

The time domain response of the equivalent system can be generated and plotted on top of the original curve, the selected curve for the modal analysis. Figure 25 shows the PSSPLT interface for selecting the modes for plotting. In this example, only the highlighted modes in Table 20 were selected. Figure 26 presents the time domain response of the reduced order equivalent system (5th order system) in blue, with the original trace from the nonlinear time domain simulation in PSS/E shown in black. It is a very good match, with some error introduced at the very beginning of the plot (less than 0.5 seconds).

Despite the difficulties associated with numerical methods, particularly potential inaccuracies, the results obtained with these tools are quite consistent and provide the correct qualitative information regarding oscillation frequencies, damping or these modes, and relative participation factors.

Table 19: PSSPLT Scan of Modal Equivalents

```
NUMBER OF SELECTED DATA POINTS IS    801 AND TIME STEP IS 0.012

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

 EFFECTIVE NUMBER OF  DATA POINTS IS    267 AND EFFECTIVE TIME STEP IS 0.037

 ORDER       % ERROR     SIGNAL/NOISE
 ------------------------------------
   15        93.71           0.07
   16        82.46           1.54
   17        78.88           1.63
   18        56.34           4.47
   19        40.91           7.08
   20        25.30          11.07
   21        14.17          14.99
   22        19.40          12.96
   23        8.716          20.20
   24        11.22          18.00
   25        11.89          17.58
   26        5.465          24.58
   27        9.238          20.06
   28        3.963          27.85
   29        4.116          26.95
   30        7.888          21.71
   31        3.037          30.04
   32        14.31          16.65
   33        9.399          20.08
   34        7.099          22.73
   35        3.631          28.64
   36        2.112          32.61
   37        3.826          27.42
   38        3.258          29.38
   39        3.287          29.30
   40        9.174          20.37
   41        2.163          32.41
   42        6.183          23.84
   43        4.771          26.03
   44        3.276          29.35
   45        2.317          32.61
```

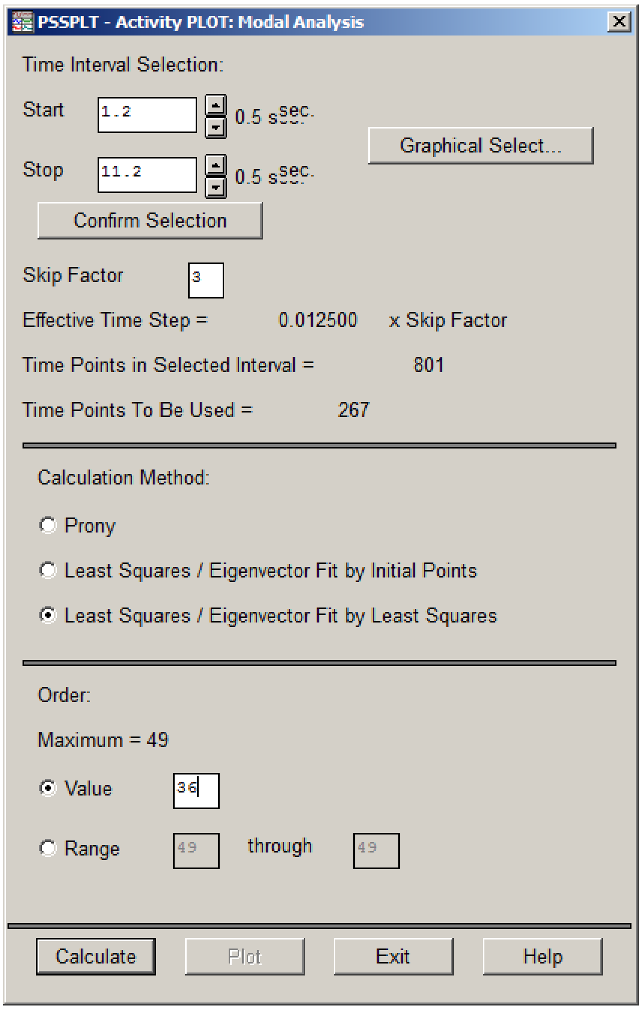

Figure 24: PSSPLT Window for Modal Analysis Calculation with a Specific Equivalent System Order

Table 20: Results of the Modal Analysis Calculations with the Equivalent System of 36th Order

```
CHANNEL:  CHNL# 5:  [POWR     1[GEN G1      20.000]1]
 TIME INTERVAL:    1.2000  - 11.1998  SEC.

                            MODAL  COMPONENTS
 --------------------------------------------------------------------------------
 COMP.           EIGENVALUE                      EIGENVECTOR
  NO          REAL         IMAGINARY      MAGNITUDE        ANGLE         REMARKS
 --------------------------------------------------------------------------------
   1      0.635793E-05       --           6.9996           --
   2     -0.575326         7.05087      0.12623E-01    -112.24   FREQ.:   1.122 HZ.
   3      -15.1229        19.9601      0.91841E-02      97.49   FREQ.:   3.177 HZ.
   4      0.376434E-01     3.82388      0.87685E-02     -67.89   FREQ.:   0.609 HZ.
   5      -1.88157        13.5899      0.26695E-03      60.48   FREQ.:   2.163 HZ.
   6      -1.96054        24.1774      0.15576E-03     -63.89   FREQ.:   3.848 HZ.
   7     -0.999003        29.2507      0.56638E-04      51.75   FREQ.:   4.655 HZ.
   8      -1.53119        19.2763      0.52868E-04    -166.83   FREQ.:   3.068 HZ.
   9     -0.669758        34.8902      0.31107E-04     143.42   FREQ.:   5.553 HZ.
  10      -1.15286        41.5950      0.17379E-04    -150.87   FREQ.:   6.620 HZ.

 PERC. ERROR:    2.112
 SIGNAL/NOISE:    32.61
 METHODS:  EIGENVALUE - LEAST SQUARE,   EIGENVECTOR - LEAST SQUARE
 ORDER:   36
```

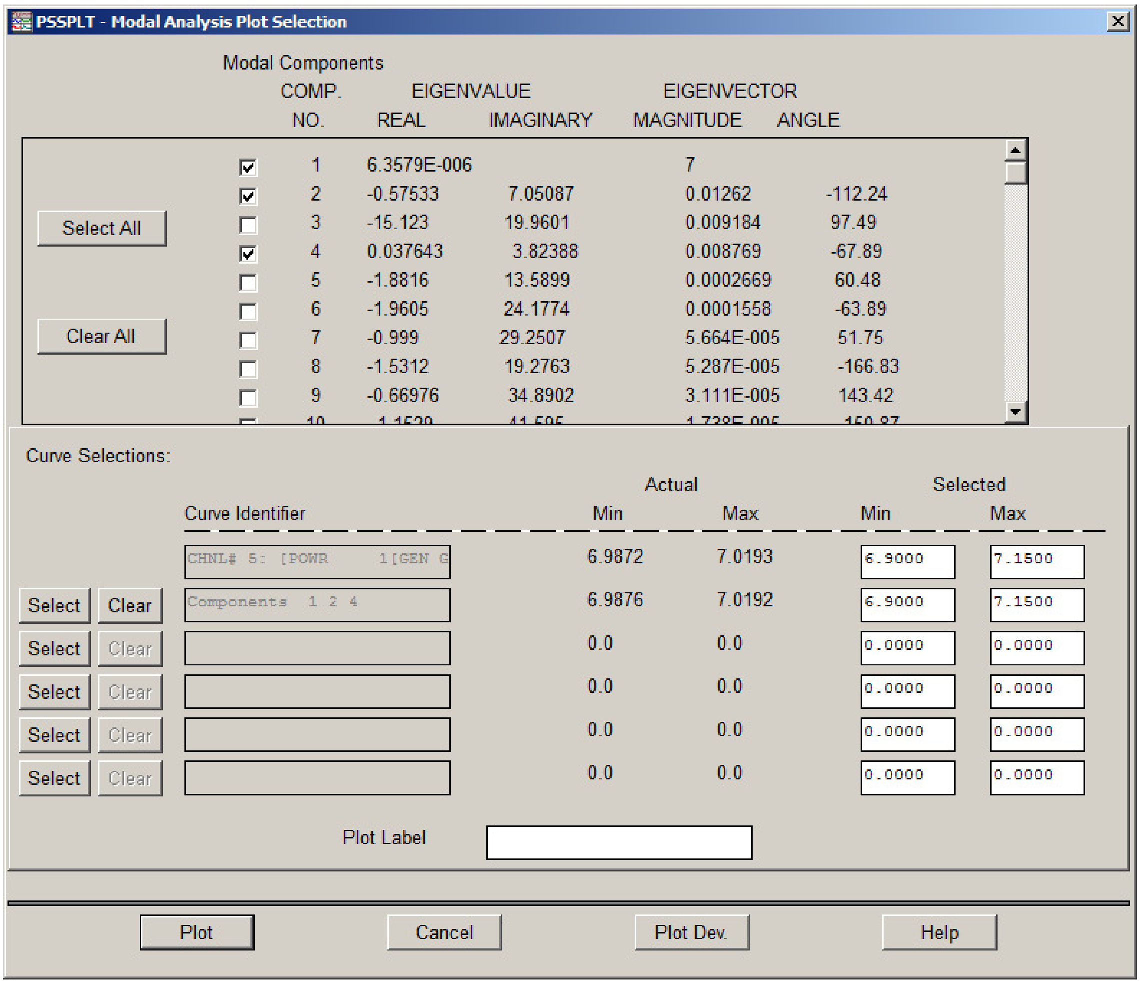

Figure 25: PSSPLT Window for Time Domain Plot of Modal Analysis Equivalent Response

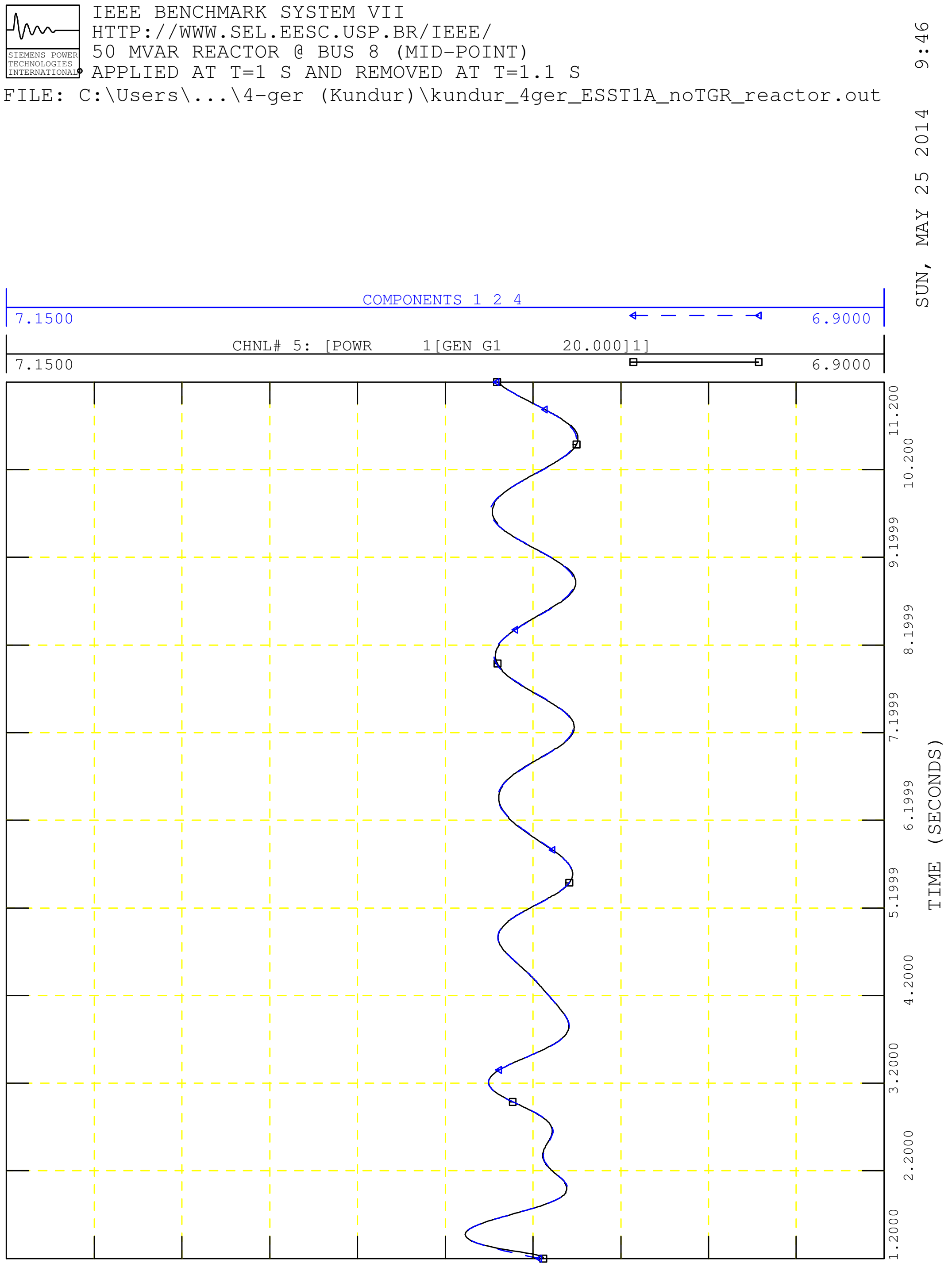

Figure 26: Time Domain Plot of Original Curve and Modal Analysis Equivalent Response

3.9 Impact of Generator Saturation

As mentioned in Section 2.1, the representation of the magnetic saturation in the synchronous machine impacts the small-signal stability results.

To show the impact of the magnetic saturation in the small-signal stability results, the simulations with the ESST1A model without TGR (see Sections 3.5, 3.6, and 3.7) were repeated with the magnetic saturation of the generator models being ignored.

Figure 27 presents the electrical power output of the four generators in the case, for the disturbance considering the 50 MVAr reactor applied at the mid-point of the system, for the case without PSS (see Section 3.5.1). The black traces correspond to the original simulation, considering the magnetic saturation as described in Section 2.1. The blue traces are the simulation results when the magnetic saturation is neglected on all machines. It can be seen that the damping and even the frequency of the inter-area electromechanical mode of oscillation has been affected by this modeling decision. This impact is even more visible in the rotor speed deviations shown in Figure 28.

On the other hand, the impact of neglecting magnetic saturation almost vanishes in the case where the PSS are in service. The power output of the generators following the step changes in voltage references, for the case where the PSS are in service (see Section 3.6.2), is shown in Figure 29.

Thus, two basic conclusions can be drawn:

a) Modeling differences, such as the representation of the magnetic saturation in the synchronous machine, will have some impact on the small-signal stability results. Moreover, this impact is way more visible and significant for unstable or poorly damped oscillation modes (critical modes);
b) These differences in modeling, leading to differences in numerical values for the calculated eigenvalues, do not affect the overall conceptual analysis (relative mode-shapes and participation factors, for instance) and do not significantly impact the tuning and performance of the PSS. With properly tuned PSS, resulting in better damping for all electromechanical modes, the modeling differences are practically negligible.

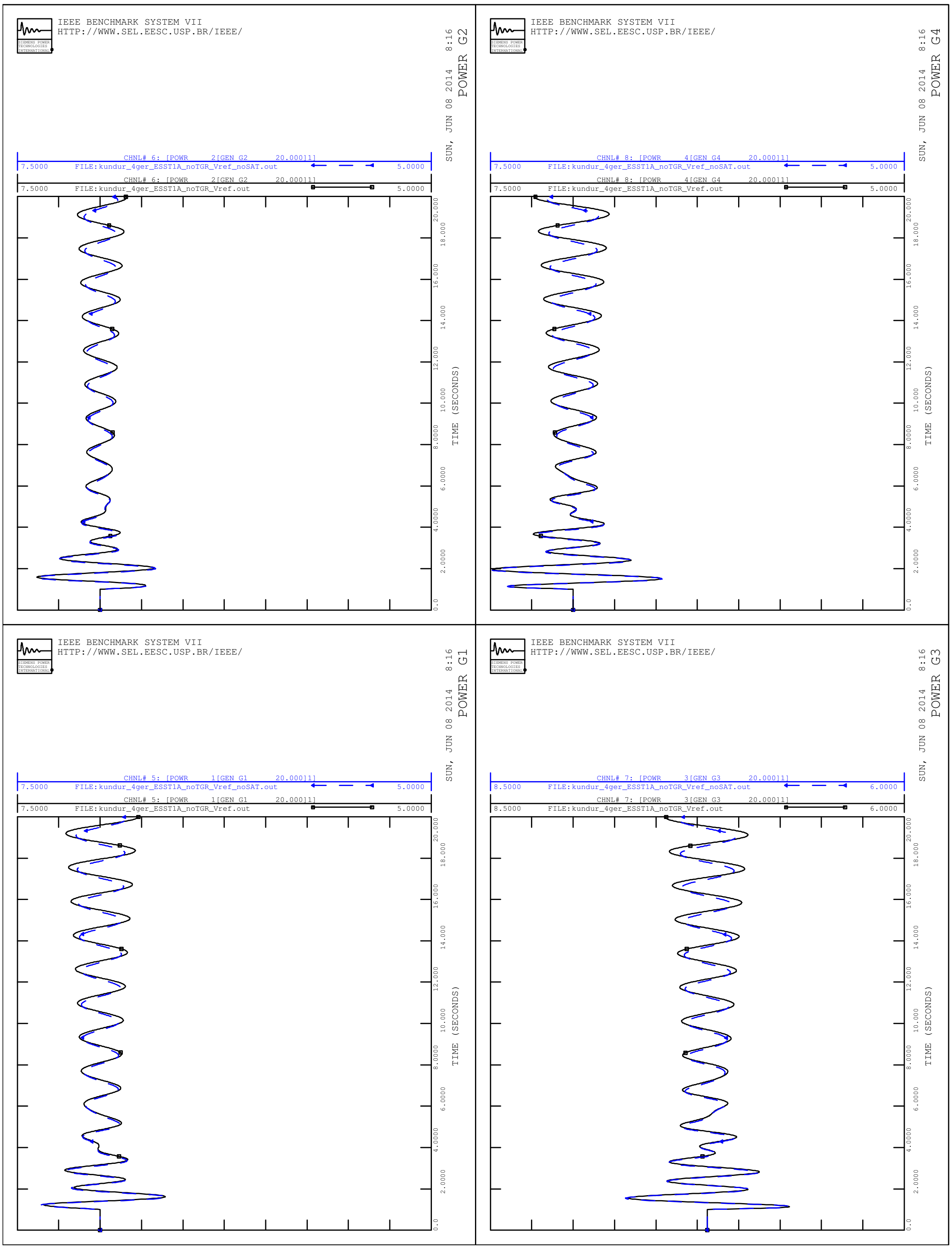

Figure 27: Electrical Power Output Comparison (50 MVAr Reactor Disturbance)

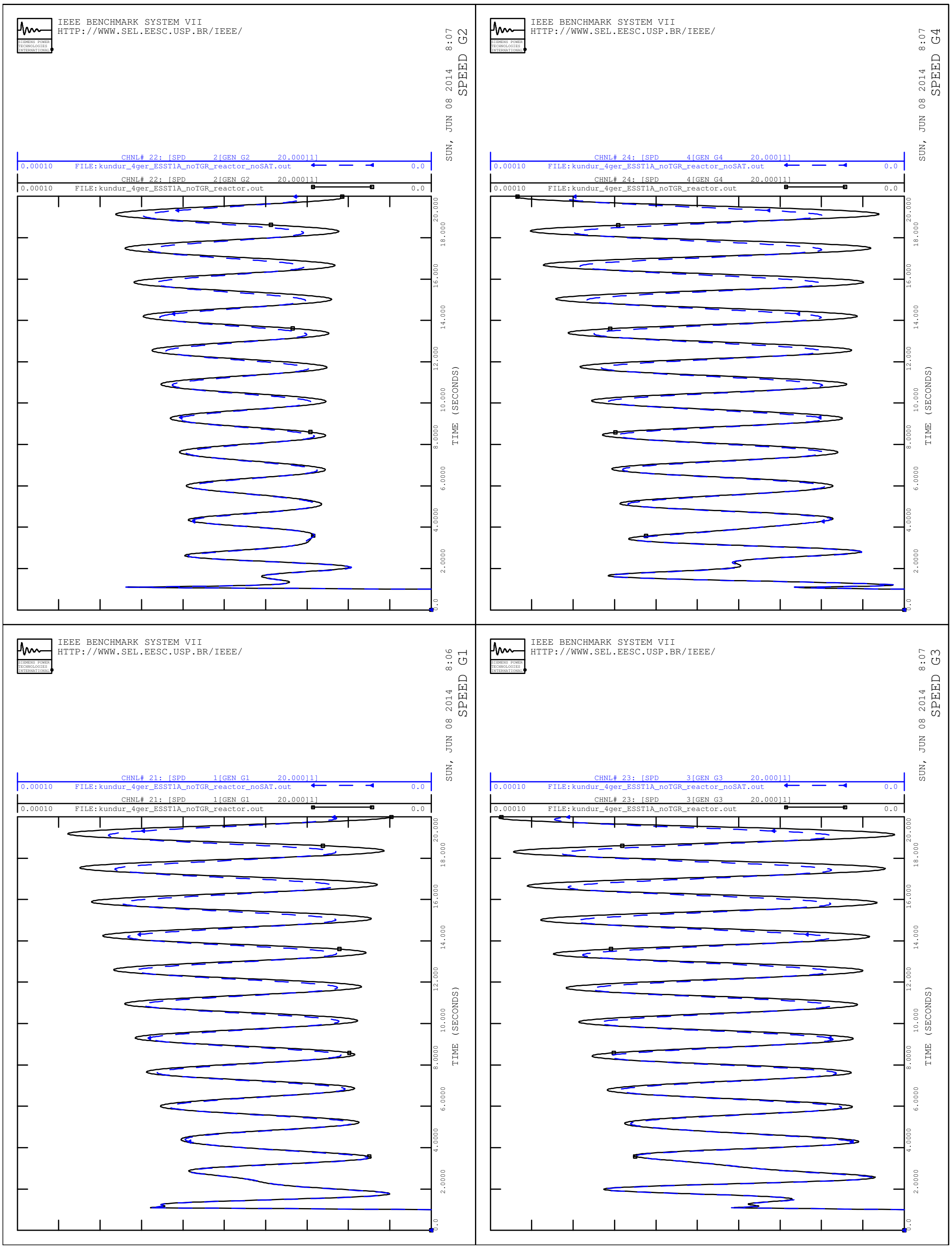

Figure 28: Speed Deviation Comparison (50 MVAr Reactor Disturbance)

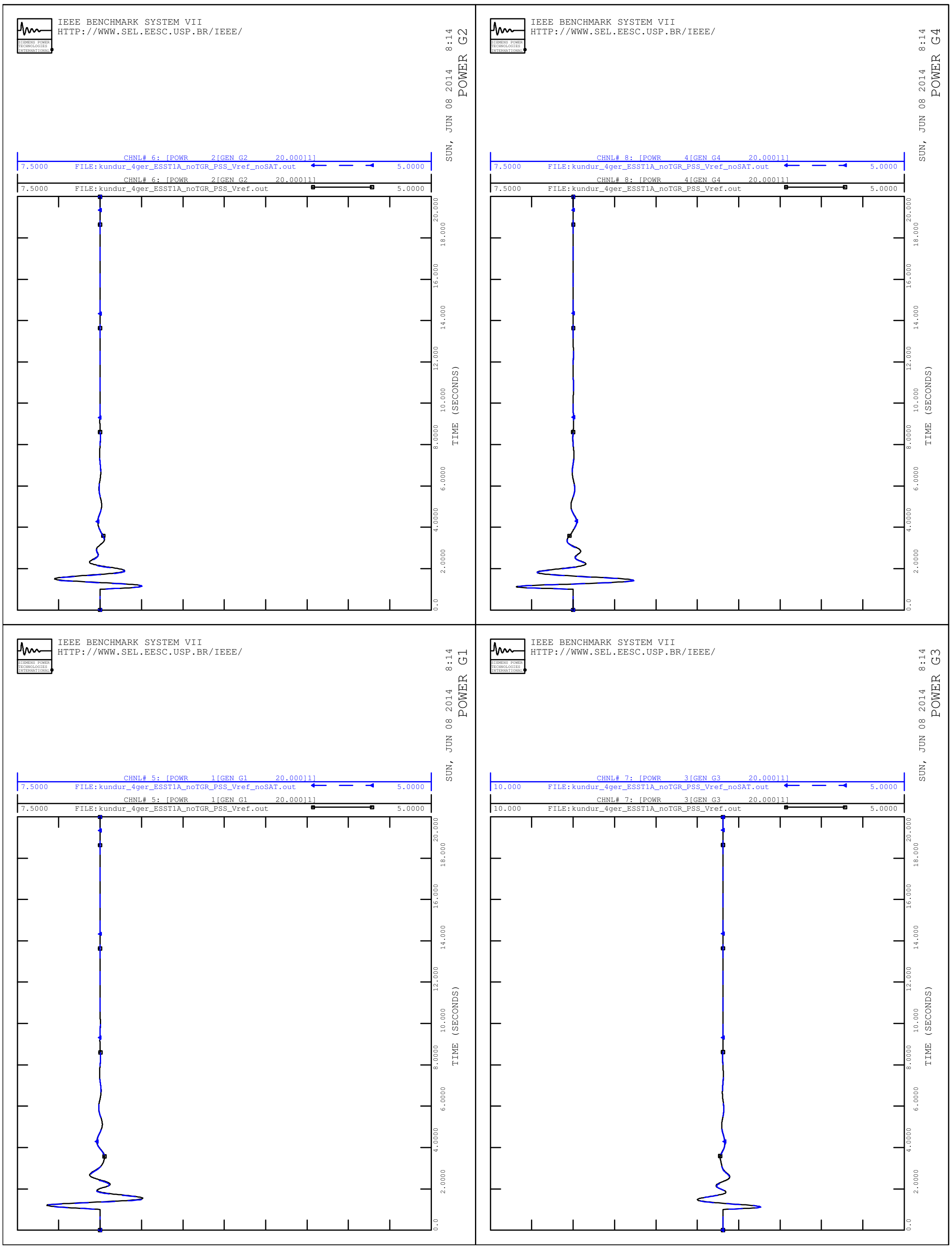

Figure 29: Electrical Power Output Comparison with PSS (Voltage Reference Disturbance)