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Relating the Microcosm Simulations to Full-Scale Grid Simulations

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Relating the Microcosm Simulations to Full-Scale Grid Simulations

Prepared for the
Office of Electric Reliability
Federal Energy Regulatory Commission

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All opinions, errors, and omissions remain the responsibility of the authors. All reference URLs were accurate as of February 2018.

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Acronyms and Abbreviations

CCGT	Combined-cycle gas turbine
CCST	Combined-cycle steam turbine
ERCOT	Electric Reliability Council of Texas
FMW	Fleet MW of the grouping; the total real power produced, in MW
GT	gas turbine
GVA	Generator electrical capability
HRSG	Heat Recovery Steam Generator
Hz	Hertz
LBNL	Lawrence Berkeley National Laboratory
MVAT	Total connected generator, complex power capability, MVA
MW	Megawatt
MWCT	Total connected prime mover capability, MW
MWST	Stored inertial energy at rated speed, MW-sec
Rfrac, Rf	Responsive fraction
Sfrac, Sf	Responsive-sustaining fraction
WECC	Western Electricity Coordinating Council

1. Objective

This report in an addendum to Undrill 2018b1. It compares simulations made with the microcosm power system model described in Undrill 2018a2 and Undrill 2018b, with full scale grid simulation programs made with the PSS/E and PSLF simulation programs.

2. Relationship of the Microcosm Model to Large-Scale Simulation Models

2.1 The Microcosm Simulation Model

The microcosm model described in the accompanying report (Undrill 2018a) considers the dynamic behavior of eleven classes of generation connected to a single-point electric system as shown in Figure 1. The generation in each class is represented by a single generator, excitation system, prime mover and plant level secondary controller. Renewable generation is treated as contributing constant real power but no inertial response to the system and, accordingly, is represented as negative electrical load.

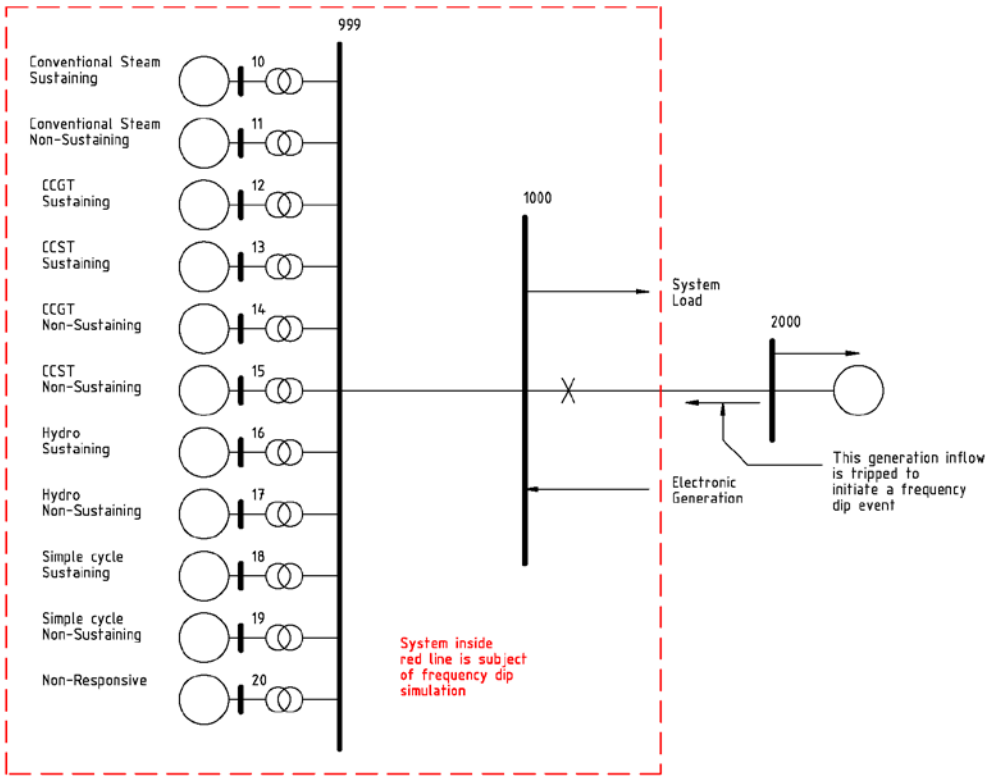


Figure 1. Generation elements of the microcosm model

[1] Undrill, J.M. (2018b): *Primary Frequency Response and Control of Power System Frequency.*
[2] Undrill, J.M. (2018a): *Microcosm Model for Simulation of Power System Frequency Dip Transients: Program Manual.*

Each of the first ten synchronous generating units represents the totalized behavior of a particular type of synchronous generating unit in a particular operating mode. The types and operating modes are shown in Figure 2.

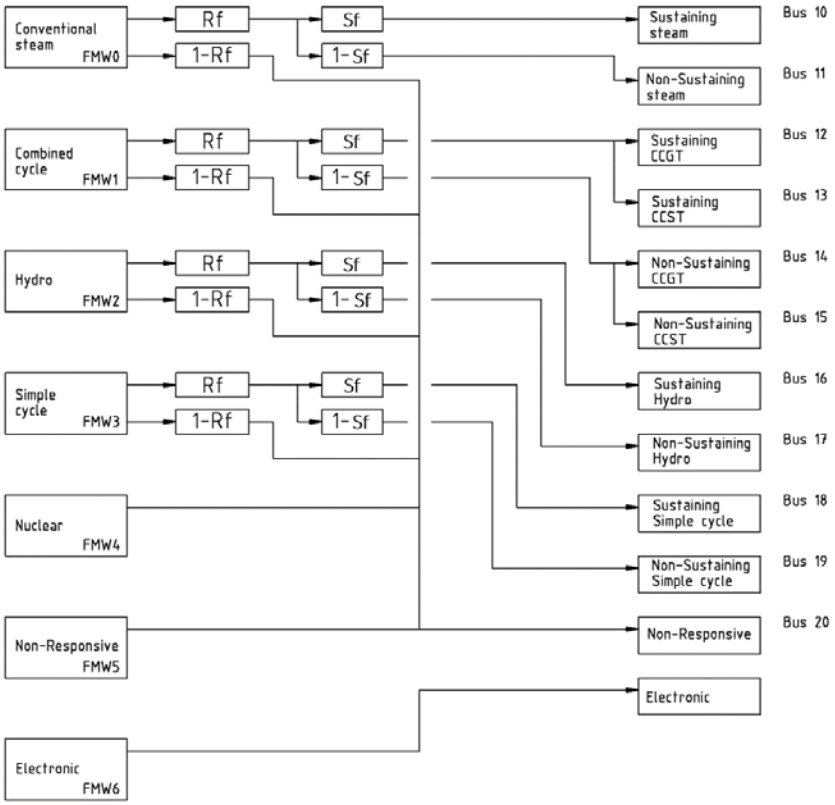


Figure 2. Construction of the microcosm model from fleet makeup data

The electrical parameters of the generators and electrical system are assigned *pro forma* values chosen to ensure that:

- the eleven turbine generators are firmly synchronized with one-another
- there is sufficient electric power transfer capacity to convey the power produced by the prime movers to the load

The MVA ratings, MW ratings, and inertia constants of the turbine-generators and the frequency dependence characteristics of load are important parameters in the simulation model; other electrical characteristics are important only in relation to the assurances noted above.

The prime-mover and secondary control models assigned to the eleven classes of prime mover are the focus of interest in simulations made with the microcosm model. The model is implemented in the PSLF program and uses the standard prime-mover and control models available in that program. In keeping with the minimal electric system modeling, the description of the model is made in terms of real power

generation; transmission losses are considered to be part of the total system load.

The individual prime mover models in the microcosm system model are populated by preassigned parameters that are typical of the classes of power plant that they represent, but contain only *pro forma* values of turbine capability, inertia constant, and generator MVA. These pro-forma characterizations of size and operating mode are replaced each time a simulation is executed by reading and applying fleet description parameters as described below.

After the simulation has been prepared, details of the individual dynamic models can be viewed and modified by the standard facilities of the PSLF program and its EPCL programming language.

2.2 Matching a Microcosm Simulation to Standard System-Wide Simulations

The setup of the microcosm model is based on the grouping of generation types as follows:

0	steam (conventional)
1	combined cycle (including GT and ST parts)
2	hydro
3	simple cycle
4	nuclear
5	nonresponsive (synchronous)
6	electronic

The generation fleet is described by stating the fraction of the total real power production, including that of electronically coupled generations, provided by each of the seven generation types. The power fractions assigned to these classes must add up unity.

For each class of turbine-generator there must be specified:

FMW	The fraction of the total real power produced by the generation assigned to the group
Rfrac	Responsive fraction. The fraction of the generation in the class that is initially responsive to change of frequency
Sfrac	Sustaining fraction. The fraction of the responsive generation in the class that sustains its initial change in power output

The relationship between the groupings of generation by type and the generation classes of the microcosm model is illustrated by Figure 2.

The steps required to relate the microcosm model to a large-scale simulation, or to reality are:

a. Work from a data base that describes to real power output and type of every generating unit that is on-line in the system condition of interest.

b. Identify the type, such as conventional steam, combined cycle, or hydro, of each generating unit.

c. Group the generating units by type, into the seven generation groupings identified above, and obtain the following for each grouping:
    - Total real power produced, MW
    - Total connected generator MVA capability
    - Total connected prime mover real power capability, MW
    - Stored inertial energy at rated speed, MW-sec

d. Determine by examination of parameters, if possible, or otherwise estimate the fraction of the generation in each grouping that is responsive to change of system frequency. This fraction is referred to as the Responsive fraction (Rfrac, or Rf).

e. Determine by examination of parameters, if possible, or otherwise estimate the fraction of the responsive part of each grouping's generation that sustains its initial response to a discrete disturbance of frequency. This fraction is referred to as the Sustaining fraction (Sfrac, or Sf).

f. Enter the values gleaned for the above parameters into the fleet data file (described in the accompanying manual).

g. Execute the control program to run a simulation.

Sample fleet data files containing the above data for the three interconnections are shown in Table 2, Table 4, and Table 6. The details of the file format are described in the operating manual of the microcosm model (Undrill 2018a).

2.3 Sources of Data

Simulations of each of the three U.S. interconnections were made with the microcosm simulation model and compared with large-scale simulations made with the PSS/E and PSLF grid simulation programs. The parameters used in the microcosm model were based, to the extent that proved to be possible and meaningful, on data gleaned from the PSS/E and PSLF base cases cited Table 1.

The totals of generator electrical capability (GVA) and turbine real power capability (GW) shown in the table were gleaned from examination of the load flow cases and of the associated dynamic simulation data files.

The table shows the system level values of the Responsive fractions (Rfrac) and Sustaining fractions (Sfrac) used to describing the overall operating modes of the generation in each system. These overall fractions were calculated from the values assigned to these fractions for each of the seven generation classes. The PSS/E and PSLF data bases provide only minimal information on power plant operating modes.

Accordingly, the Responsive and Sustaining fractions for the generation groups had to be estimated initially and then tuned in trial simulations with the microcosm model. Initial estimates of the fractions, Rfrac and Sfrac, allocating generation to responsive, and responsive-sustaining operation were made on the basis of experience with the several types of plants.

It must be noted that the parameters shown in Table 1 do not purport to indicate the totals and fractions that exist in the interconnections in reality. Rather, these totals and fractions describe the simulations that have been made with the two full-scale programs.

Table 1. Summary of base case models used for large-scale simulations

	Year	File	Total Synch Gen GVA D	Total Real Power GW E	Total Synch Power GW F	Total Synch Capac. GW G	Synch Reserve GW H	Rf	Sf	Nf	Ef	Gen Loss
EI	2018	MMWG_2016SUM_2015	878.0	665.6	657.7	unclear	unclear	0.67	0.66	0.32	0.01	0.007
ERCOT	2018	NT2018-2015	56.8	43.3	28.2	52.2	24.0	0.65	0.52	0.05	0.30	0.0625
WECC	2018	18LW2	168.6	99.0	4.0	120.0	17.0	0.79	0.57	0.17	0.04	0.0276

2.3.1 The Texas Interconnection (ERCOT)

Generation types were deduced from the names of governor dynamic models associated with the generators. The PSS/E data base does not include explicit identification of prime mover type and so the deduction was based on assumed correspondence with dynamic models with the types of interest. For example, it was assumed that ERCOT uses the ggov1 model for steam turbines and that the ucbgt model (which is a 'user written' model) is indicative of a gas turbine in a combined cycle.

Examination of the wind turbine models in the ERCOT data base indicated that a large fraction of the wind power plants in Texas are type 1 machines and, accordingly, that the wind fleet contributes a significant, but unknown, amount of rotating inertia to the ERCOT system. The system inertia constant used for the rotating synchronous part of the ERCOT fleet is 3.8 seconds, (see Figure 4). This inertia constant value has been augmented by trial-and-error to achieve a fair match between the initial rate of frequency decline and the timing of the frequency nadir as indicated by the microcosm model and by the simulation in PSS/E.

2.3.2 The Western Interconnection (WECC)

Generation types were deduced on the basis of the turbine governor model name as follows:

conventional steam	ieeeg1, tgov1
gas turbine and combined cycle	ggov1, ggov3
hydro	hygov, hygov4, hygovr, ieeeg3, hyg3, gpwscc, pidgov, g2wscc

2.3.3 The Eastern Interconnection

Generation type was determined on the basis of the turbine governor model names. There was a high degree of uncertainty in the identification of prime mover types and operating modes. It is suspected that the data base indicates larger fraction of generation to be responsive and responsive-sustaining than exists in reality. (This point is addressed further in Section 3.3.2.)

3. Comparisons of Microcosm and Large-Scale Simulations

3.1 Texas Interconnection

Simulations of the Texas Interconnection in the PSS/E program consider the instantaneous loss of 2750 MW, resulting from the trip of both units of the South Texas Nuclear plant. The response of frequency as simulated by PSS/E is shown by the dashed trace in Figure 3.

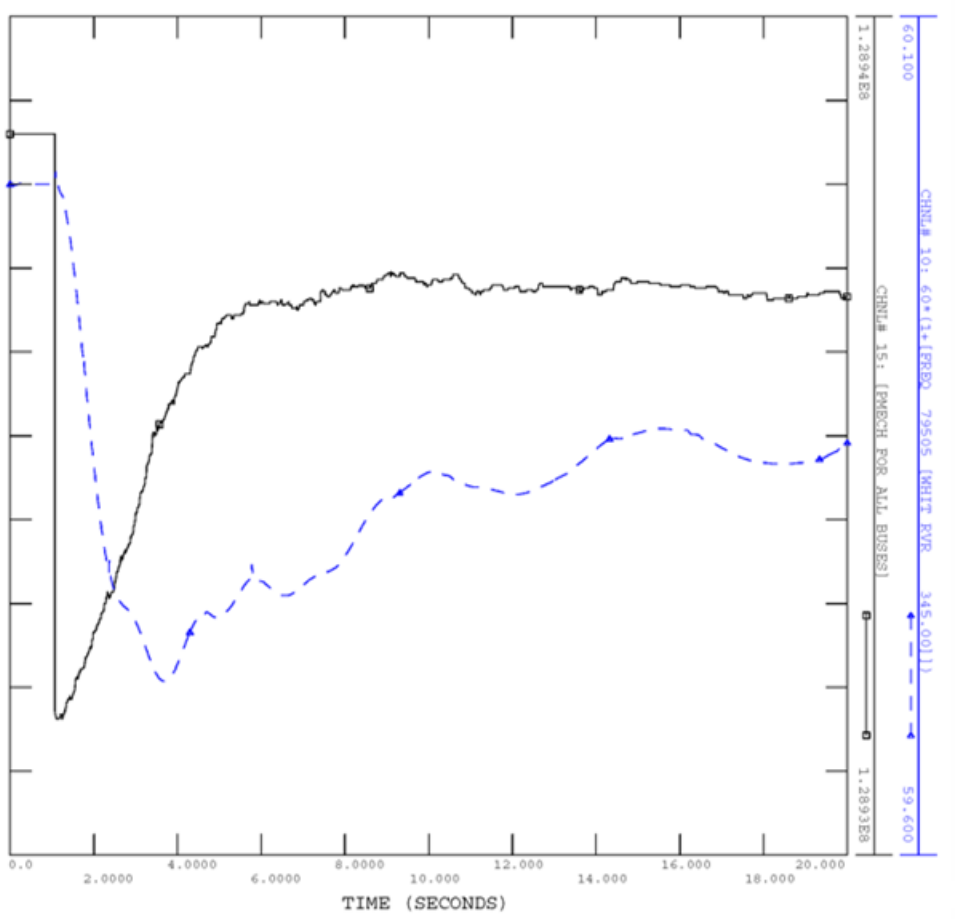


Figure 3. ERCOT simulation case 1: PSS/E

The following have been gleaned from examination of the initial condition load flow solution and the associated dynamics data file:

Total generation output	43341 MW
Total synchronous generation output	28226 MW
Total asynchronous generation output	15117 MW
Total connected synchronous generation MVA	56807 MVA
Total connected synchronous prime mover capability	52208 MW

Based on the above, the fleet makeup has been set up for the microcosm model with the generation grouped as the following fractions of the system total:

0	Coal/gas steam generation output	0.32
1	Comb. cycle generation (GT+ST) output	0.16 W
2	Hydro generation output	0.02
3	Simple cycle GT generation output	0.16
4	Nuclear generation output(post-trip)	0.04
5	Nonresponsive generation	0.00
6	Wind + solar generation output	0.30

The inertia constant used in the microcosm simulation of ERCOT is based on generator dispatch and inertia data provided by ERCOT separately from the inertia constant values contained in the PSS/E data file. The tabulation of this data is shown in Figure 4.

The data file specifying the setup of the microcosm simulation is shown in Table 2. The summary of the microcosm simulation is shown in Table 3.

	Coal fired conventional steam					Gas fired conventional steam					Gas turbine in combined cycle					Steam turbine in combined cycle					Heavy duty GT in simple cycle					Aeroderiv GT in simple cycle					Effective H
	Power produced	Sum of unit MVA	No of machines	Total MW-seconds	H	Power produced	Sum of unit MVA	No of machines	Total MW-seconds	H	Power produced	Sum of unit MVA	No of machines	Total MW-seconds	H	Power produced	Sum of unit MVA	No of machines	Total MW-seconds	H	Power produced	Sum of unit MVA	No of machines	Total MW-seconds	H	Power produced	Sum of unit MVA	No of machines	Total MW-seconds	H	Total MVA-sec divided by total MVA
07/13/2016 18:15	18826	23422	32	61513	2.63	3093	6697	23	18039	2.69	17344	27206	141	137563	5.06	8427	13309	57	57589	4.33	943	4764	53	23485	4.93	463	737	8	1668	2.26		3.939
07/14/2016 18:45	18364	23422	32	61513	2.63	3485	8421	31	24132	2.87	17605	27388	143	138616	5.06	8880	13416	58	57753	4.30	954	4683	54	22109	4.72	766	1223	15	2245	1.84		3.900
08/01/2016 18:00	16803	21896	30	57076	2.61	5558	10365	35	29275	2.82	17381	27076	144	136775	5.05	8464	13122	57	55508	4.31	1413	5318	57	26552	4.99	311	582	7	1359	2.33		3.925
08/08/2016 19:10	16404	22716	31	59333	2.61	5064	11975	40	34185	2.85	18231	28292	150	142937	5.05	9241	14074	61	60177	4.28	1102	4668	48	22813	4.89	662	1295	16	2327	1.80		3.876
08/11/2016 19:10	16245	22716	31	59333	2.61	5760	11691	39	34803	2.93	18192	28254	150	142846	5.06	9368	14218	62	60897	4.28	1270	5132	52	25060	4.88	656	1295	16	2327	1.80	3.907	3.897
07/22/2016 15:15	16503	22739	31	59600	2.62	8534	12122	46	35040	2.89	18055	27617	149	140516	5.05	9065	13811	59	56839	4.26	1442	5287	57	25720	4.87	591	1016	12	1998	1.97		3.886
08/03/2016 14:40	17764	21896	30	57076	2.61	9096	13375	48	37948	2.84	17782	27279	148	137876	5.05	8737	13412	59	57174	4.26	1696	5691	61	27032	4.75	943	1579	20	2660	1.68		3.842
08/05/2016 14:10	16893	21213	29	55164	2.60	9154	13406	47	38027	2.84	18232	28274	149	142602	5.05	9678	14210	60	60895	4.29	1851	5698	60	27877	4.89	599	1024	12	2001	1.96		3.898
08/08/2016 13:25	18222	22716	31	59333	2.61	7792	13139	45	37182	2.83	18425	28533	152	144180	5.05	9351	14368	62	61625	4.29	1186	4902	51	23686	4.83	678	1147	15	2022	1.76		3.868
09/19/2016 15:00	16865	22602	31	59256	2.62	9657	13704	47	39370	2.87	17961	27508	150	139003	5.02	8928	14107	62	60075	4.26	1660	5547	63	27504	4.96	1049	1723	22	2924	1.64	3.867	3.839
10/23/2016 02:10	7104	22232	30	58023	2.61	18	633	7	1566	2.47	3019	7632	45	38758	5.08	774	2558	15	11818	4.62	463	3563	42	17518	4.92	0	0	0	0			3.467
11/17/2016 02:50	6080	19155	26	49837	2.60	30	756	8	1882	2.48	2264	7292	41	37598	5.16	1004	3475	18	17248	4.96	538	3457	39	16004	4.80	0	0	0	0			3.607
11/22/2016 02:30	5209	16372	23	42732	2.61	152	1258	9	2982	2.37	2644	6786	46	45595	5.19	761	3167	16	14562	4.60	562	3569	41	17393	4.87	0	0	0	0			3.719
11/25/2016 03:20	5369	16644	23	43207	2.60	30	756	8	1882	2.48	3714	10473	55	54371	5.19	1368	4725	21	21735	4.60	599	3792	44	18275	4.87	0	0	0	0			3.837
11/27/2016 05:55	5613	16079	25	47409	2.62	30	756	8	1882	2.48	3008	9211	50	47127	5.12	963	3918	18	17956	4.56	606	3855	45	18914	4.91	25	142	2	350	2.46	3.673	3.717
10/09/2016 04:35	12289	21532	29	56504	2.62	265	2433	9	6156	2.53	4984	11116	63	56516	5.08	1620	4078	21	20055	4.56	558	3468	42	16998	4.90	0	0	0	0			3.639
11/06/2016 05:25	9584	18952	26	49769	2.63	30	756	8	1882	2.48	6168	13603	69	68302	5.02	2433	5309	24	25934	4.89	502	3266	38	15774	4.83	0	0	0	0			3.859
11/30/2016 02:10	7671	19907	27	52157	2.62	30	756	8	1882	2.48	7506	15097	75	74674	4.96	3496	7224	31	33646	4.66	562	3450	41	16670	4.83	0	0	0	0			3.860
11/13/2016 01:30	8659	19907	27	52157	2.62	31	756	8	1882	2.48	6236	12531	64	63683	5.08	2781	5579	25	29561	4.59	546	3450	41	16670	4.83	0	0	0	0			3.789
11/26/2016 05:10	9970	17227	24	45119	2.60	31	756	8	1882	2.48	5754	13010	64	64332	4.94	2043	5199	22	24511	4.68	637	3792	44	18275	4.87	0	0	0	0		3.798	3.844

Figure 4. ERCOT inertia data provided by ERCOT

Table 2. Fleet makeup for microcosm simulation: ERCOT

```
ChaPrefx      ercot-
I Type         FMW    Rf    Df
---- Fleet makeup
0 Steam       0.32  0.98  0.48
1 CCGT-G      0.16  0.98  0.58
2 Hydro       0.02  1.00   .95
3 SCGT        0.16  0.98   .48
4 Nuclear     0.04   .00   .00
5 Nonresp        0   .00   .00
6 Renewable   0.30   .00   .00
----  General settings
deltap    0.0625
H         5.4
kimw      0.001
lpd       1.
droop     0.04
gbasef    2.01
tbasef    1.85
---- Individual parameter settings
0  end
```

Table 3. Summary and result of microcosm simulation: ERCOT

```
Type       I    Ff     Rf    Df    Qf      Rmw      Dmw      Qmw
Steam      0  0.32   0.98  0.48  0.52   0.3136   0.1505   0.1631
CCGT-G     1  0.16   0.98  0.58  0.42   0.1568   0.0909   0.0659
Hydro      2  0.02   1.00  0.95  0.05   0.0200   0.0190   0.0010
SCGT       3  0.16   0.98  0.48  0.52   0.1568   0.0753   0.0815
Nuclear    4  0.04   0.00  0.00  1.00   0.0000   0.0000   0.0000
Nonresp    5  0.00   0.00  0.00  1.00   0.0000   0.0000   0.0000
Renewable  6  0.30   0.00  0.00  1.00   0.0000   0.0000   0.0000

Total generation                  = :    10000
Rotating synchronous generation   = :     7000
Electronic  generation            = :     3000
System regulating fraction Rfrac  = :    0.647
Sustaining frac (of Rfrac) Dfrac  = :    0.519
Non-responsive fraction    Nfrac  = :    0.053
Electronic fraction        Efrac  = :    0.300


Responsive/sustaining    MW       = :   3357.4
Responsive/nonsustaining MW       = :   3114.6
Responsive - total       MW       = :   6472.0
Non-responsive - total   MW       = :    528.0
Renewable - total        MW       = :   3000.0
Minimum frequency     (Hz)        = :   59.695

Gen loss fraction                 = :   0.0625
System inertia constant           = :   5.4000
Load control gain                 = :   0.0010
Load freq exponent                = :   1.0000
Governing droop                   = :   0.0400
Gen MVA factor                    = :   2.0100
Turbine MW factor                 = :   1.8500
```

Figure 5 shows the microcosm simulation of frequency for three variations on the fleet makeup given in Table 2 as follows:

- Red: Decrease Steam fraction of fleet by 0.05 pu/increase non-responsive fraction
- Green: Fleet fractions as given in Table 2
- Blue: Increase Steam fraction of fleet by 0.05 pu/decrease non-responsive fraction

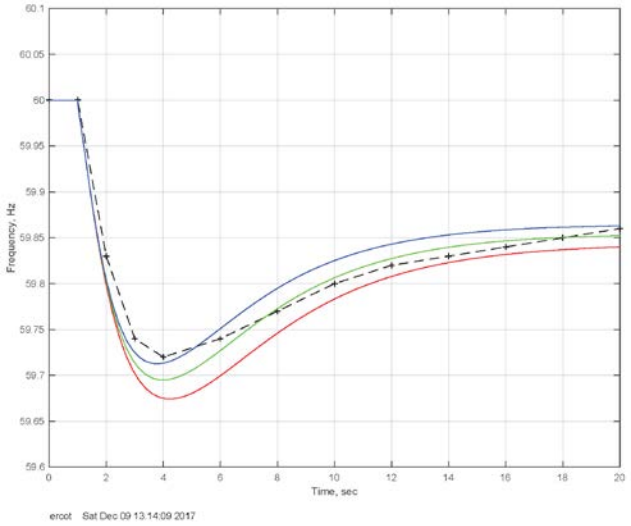
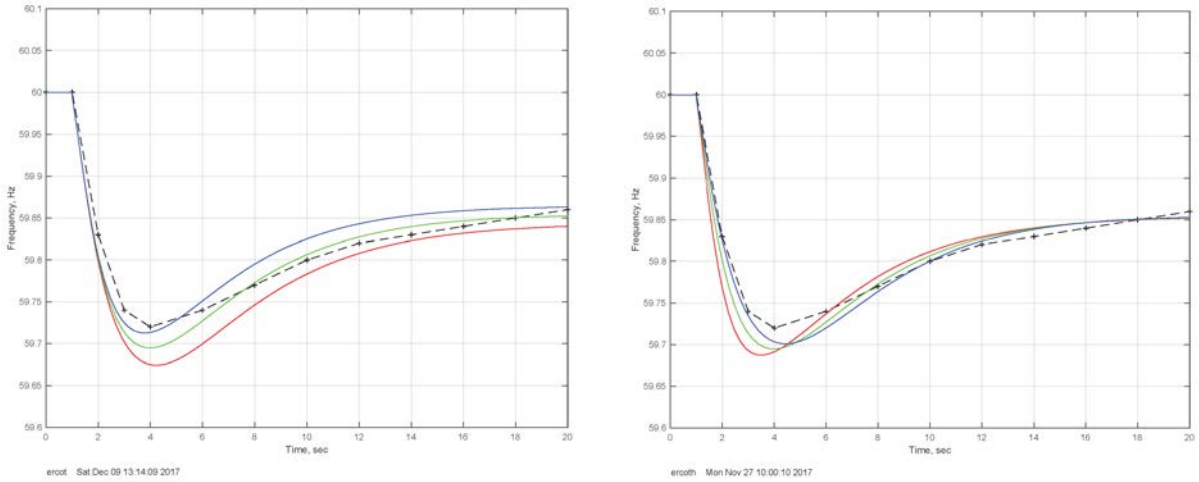


Figure 5. ERCOT simulation case 1: Microcosm

Fleet makeup shown in Table 2
Red - 25 percent steam
Green - 30 percent steam
Blue - 35 percent steam
Black - Full-scale simulation

Figure 6 illustrates the sensitivity of the frequency dip to variations of fleet makeup (Figure 6a) and fleet inertia constant (Figure 6b). For Figure 6a, the fraction of ERCOT generation in steam plants is varied -/+0.05 per unit and, for Figure 6b the overall inertia constant of the ERCOT rotating fleet is varied -/+1.0 second. (Note that Figure 6a is the same as Figure 5.)



(a) Variation of fleet fraction in steam plants

(b) Variation of overall inertia constant

Figure 6. ERCOT parameter variations

(a) ff[0] -/+0.05
(b) hg -/+1.0

3.2 Western Interconnection

Simulations of the Western Interconnection in the PSLF program considered the instantaneous loss of 2780 MW, resulting from the trip of two units of the Palo Verde Nuclear plant. The response of frequency as simulated by PSLF is shown in Figure 7. The following have been gleaned from examination of the initial condition load flow solution and the associated dynamics data file:

Total generation output	99037 MW
Total connected rotating generation MVA	168631 MVA

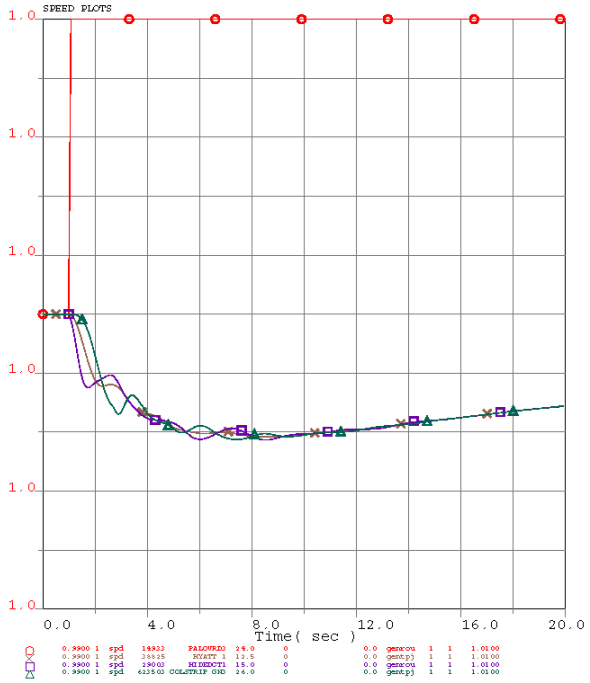


Figure 7. WECC simulation case 1: PSLF

Based on the above, the fleet makeup has been set up for the microcosm model with the generation grouped as the following fractions of the system total:

0	Coal/gas steam generation output	0.20
1	Combined cycle output (GT+ST)	0.20
2	Simple cycle GT output	0.02
3	Hydro generation output	0.40
4	Nuclear output (post-trip)	0.02
5	Nonresponsive synchronous	0.12
6	Wind + solar output	0.04

The inertia constant used in the microcosm simulation is based on the generator dispatch, MVA, and status data in the base case load flow used for the full scale simulation. The system inertia constant estimated on this basis is 3.8 seconds.

The data file specifying the setup of the microcosm simulation is shown in Table 4. The summary of the microcosm simulation is shown in Table 5.

Table 4. Fleet makeup for microcosm simulation: WECC

```
ChaPrefx        wecc-
I Type          FMW     Rf     Df
---- Fleet makeup
0 Steam       20000   0.92   0.48
1 CCGT-G      20000   0.92   0.48
2 Hydro       40000   1.00    .65
3 SCGT         2000   0.98    .48
4 Nuclear      2000    .00    .00
5 Nonresp     12000    .00    .00
6 Renewable    4000    .00    .00
----  General settings
deltap     2760
H          3.8
kimw       0.05
lpd        2.
droop      0.04
gbasef     1.78
tbasef     1.20
---- Individual parameter settings
0  end
```

Table 5. Summary and result of microcosm simulation: WECC

```
Type       I    Ff      Rf    Df    Qf      Rmw       Dmw       Qmw
Steam      0   0.20    0.92  0.48  0.52   0.1840    0.0883    0.0957
CCGT-G     1   0.20    0.92  0.48  0.52   0.1840    0.0883    0.0957
Hydro      2   0.40    1.00  0.65  0.35   0.4000    0.2600    0.1400
SCGT       3   0.02    0.98  0.48  0.52   0.0196    0.0094    0.0102
Nuclear    4   0.02    0.00  0.00  1.00   0.0000    0.0000    0.0000
Nonresp    5   0.12    0.00  0.00  1.00   0.0000    0.0000    0.0000
Renewable  6   0.04    0.00  0.00  1.00   0.0000    0.0000    0.0000

Total generation                  = :    10000
Rotating synchronous generation   = :     9600
Electronic  generation            = :      400
System regulating fraction Rfrac  = :    0.788
Sustaining frac (of Rfrac) Dfrac  = :    0.566
Non-responsive fraction    Nfrac  = :    0.172
Electronic fraction        Efrac  = :    0.040


Responsive/sustaining    MW       = :   4460.5
Responsive/nonsustaining MW       = :   3415.5
Responsive - total       MW       = :   7876.0
Non-responsive - total   MW       = :   1724.0
Renewable - total        MW       = :    400.0
Minimum frequency     (Hz)        = :   59.730

Gen loss fraction                 = :   0.0276
System inertia constant           = :   3.8000
Load control gain                 = :   0.0500
Load freq exponent                = :   2.0000
Governing droop                   = :   0.0400
Gen MVA factor                    = :   1.7800
Turbine MW factor                 = :   1.2000
```

Figure 8 shows the microcosm simulation of frequency for three variations on the fleet makeup given in Table 4 as follows:

- Red: Decrease Steam fraction of fleet by 0.05 pu/increase non-responsive fraction
- Green: Fleet fractions as given in Table 4
- Blue: Increase Steam fraction of fleet by 0.05 pu/decrease non-responsive fraction

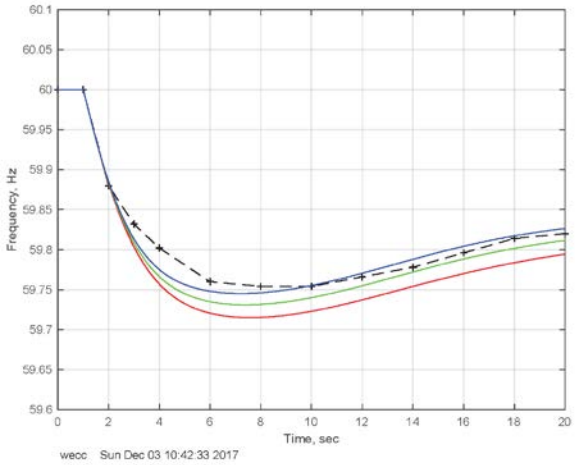
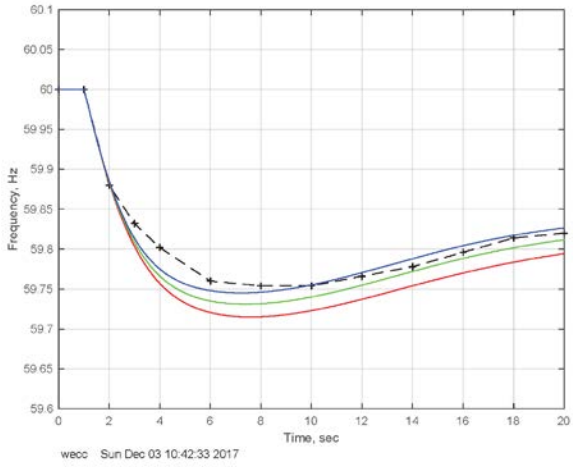


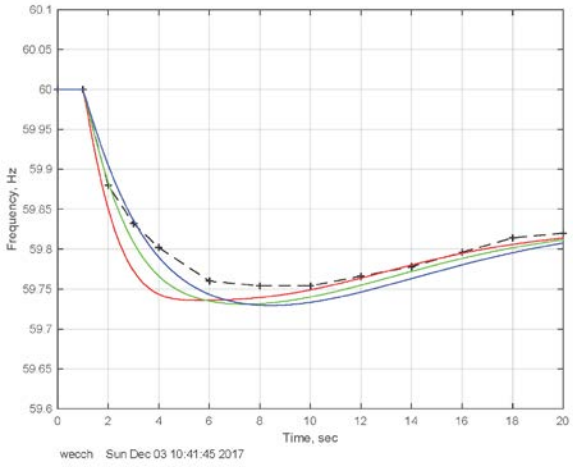
Figure 8. WECC simulation case 1: Microcosm

Red - 11 percent steam
Green - 16 percent steam
Blue - 21 percent steam
Black – Full-scale simulation

Figure 9 illustrates the sensitivity of the frequency dip to variations of fleet makeup (Figure 9a) and fleet inertia constant (Figure 9b). For Figure 9a, the fraction of WECC generation in steam plants is varied -/+0.05 per unit and, for Figure 9b the overall inertia constant of the WECC rotating fleet is varied -/+1.0 second. (Note that Figure 9a is the same as Figure 8.)



(a) Variation of fleet fraction in steam plants



(b) Variation of overall inertia constant

Figure 9. WECC parameter variations

(a) ff[0] -/+0.05
(b) hg -/+1.0

3.3 Eastern Interconnection

3.3.1 Comparison with PSS/E simulation

Simulations of the EI system in the PSS/E program considered the loss of 4600 MW, spaced over several seconds, resulting from the trip of several units in the 'Rockport' event. The response of frequency as simulated by PSS/E is shown in Figure 10.

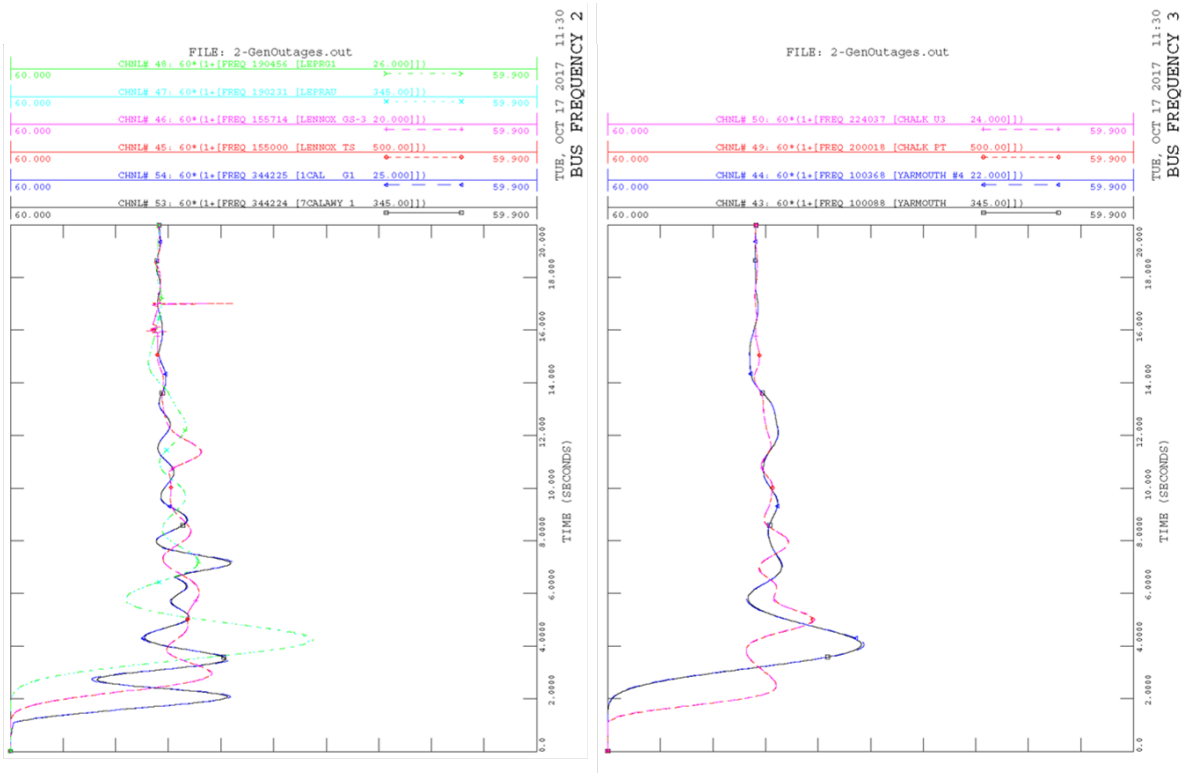


Figure 10. EI simulation case 1: PSS/E

The following have been gleaned from examination of the initial condition load flow solution and the associated dynamics data file:

Total generation output	666399 MW
Total connected rotating generation MVA	926482 MVA

Based on the above, the fleet makeup has been set up for the microcosm model with the generation grouped as the following fractions of the system total:

0	Coal/gas steam generation output	0.60
1	Comb. cycle generation (GT+ST) output	0.10
2	Hydro generation output	0.03
3	Simple cycle GT generation output	0.05
4	Nuclear generation output(post-trip)	0.10
5	Nonresponsive synchronous	0.11
6	Wind + solar generation output	0.01

The inertia constant used in the microcosm simulation is based on the generator dispatch, MVA, and status data in the base case load flow used for the full scale simulation. The system inertia constant estimated on this basis is 3.95 seconds.

The data file specifying the setup of the microcosm simulation is shown in Table 6. The summary of the microcosm simulation is shown in Table 7.

Table 6. Fleet makeup for microcosm simulation: EI

```
ChaPrefx      ei-
I Type         FMW     Rf     Df
----
0 Steam       0.60    .90    .65
1 CCGT-G      0.10    .90    .65
2 Hydro       0.03   1.00    .90
3 SCGT        0.05    .10    .60
4 Nuclear     0.10    .00    .00
5 Nonresp     0.11    .00    .00
6 Renewable   0.01    .00    .00
----
deltap     0
H          3.95
kimw       0.005
lpd        1
droop      0.04
gbasef     1.3
tbasef     1.3
----
0  end
```

Table 7. Summary and result of microcosm simulation: EI

```
Type       I    Ff      Rf    Df    Qf      Rmw      Dmw      Qmw
Steam      0  0.60    0.90  0.65  0.35   0.5400   0.3510   0.1890
CCGT-G     1  0.10    0.90  0.65  0.35   0.0900   0.0585   0.0315
Hydro      2  0.03    1.00  0.90  0.10   0.0300   0.0270   0.0030
SCGT       3  0.05    0.10  0.60  0.40   0.0050   0.0030   0.0020
Nuclear    4  0.10    0.00  0.00  1.00   0.0000   0.0000   0.0000
Nonresp    5  0.11    0.00  0.00  1.00   0.0000   0.0000   0.0000
Renewable  6  0.01    0.00  0.00  1.00   0.0000   0.0000   0.0000

Total generation                    = :    10000
Rotating synchronous generation     = :     9880
Electronic  generation              = :      120
System regulating fraction Rfrac    = :    0.665
Sustaining frac (of Rfrac) Dfrac    = :    0.661
Non-responsive fraction    Nfrac    = :    0.323
Electronic fraction        Efrac    = :    0.012


Responsive/sustaining    MW         = :   4395.0
Responsive/nonsustaining MW         = :   2255.0
Responsive - total       MW         = :   6650.0
Non-responsive - total   MW         = :   3229.9
Renewable - total        MW         = :    120.1
Minimum frequency     (Hz)          = :   59.961

Gen loss fraction                   = :   0.0000
System inertia constant             = :   3.9500
Load control gain                   = :   0.0050
Load freq exponent                  = :   1.0000
Governing droop                     = :   0.0400
Gen MVA factor                      = :   1.3000
Turbine MW factor                   = :   1.3000
```

Figure 11 shows the microcosm simulation of frequency for three variations on the fleet makeup given in Table 6 as follows:

- Red: Decrease Steam fraction of fleet by 0.05 pu/increase non-responsive fraction
- Green: Fleet fractions as given in Table 6
- Blue: Increase Steam fraction of fleet by 0.05 pu/decrease non-responsive fraction

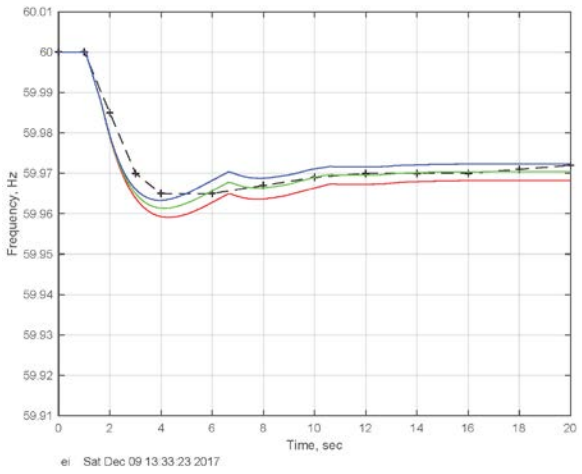
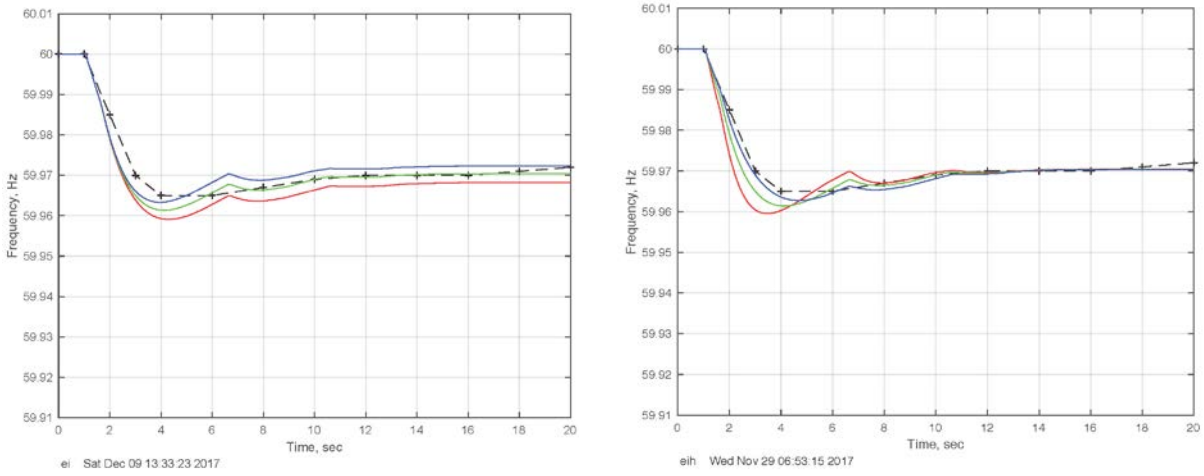


Figure 11. EI simulation case 1: Microcosm

Red - 11 percent steam
Green - 16 percent steam
Blue - 21 percent steam
Black – Full-scale simulation

Figure 12 illustrates the sensitivity of the frequency dip to variations of fleet makeup (Figure 12a) and fleet inertia constant (Figure 12b). For Figure 12a, the fraction of EI generation in steam plants is varied -/+0.05 per unit and, for Figure 12b the overall inertia constant of the EI rotating fleet is varied -/+1.0 second. (Note that Figure 12a is the same as Figure 11.)



(a) Variation of fleet fraction in steam plants

(b) Variation of overall inertia constant

Figure 12. EI parameter variations

(a) ff[0] -/+0.05
(b) hg -/+1.0

3.3.2 Comparison with reality

The fleet makeup parameters used in the previous section gave a fair match of the microcosm simulation to a full scale simulation made with PSS/E, but neither the microcosm simulations nor those made with PSS/E are in credible agreement with reality. Figure 13 compares microcosm simulations with a frequency trajectory recorded after the "Rockport event", and with the PSS/E simulation from the preceding section.

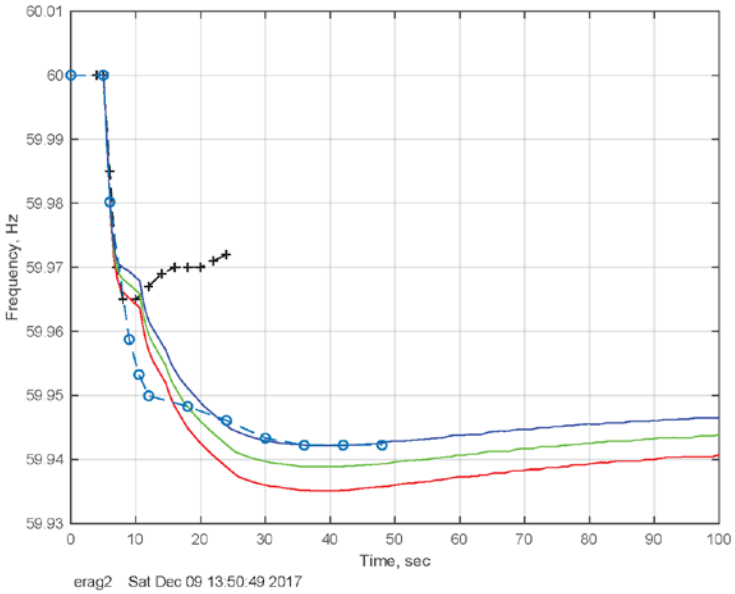


Figure 13. EI simulation of 'Rockport' event: loss of 4600MW over 9 seconds

Red - Microcosm simulation - 11 percent steam
Green - Microcosm simulation - 16 percent steam
Blue - Microcosm simulation - 21 percent steam
+ Simulation made with PSS/E and ERAG data base
o Recorded frequency

It is clear that the full scale simulation (black +) does not match the recording of reality (blue o). The three colored traces in Figure 13 are simulations made with the microcosm model using revised values of the fleet description parameters. The following changes were made to the microcosm simulation, relative to the fleet makeup parameters used to match the PSS/E simulation:

- The fractions of the steam and combined cycle generation that contribute frequency response were reduced from 0.9 to 0.7
- The sustaining fractions of the three types of responsive generation were reduced, so that the overall responsive-sustaining fraction of the fleet was reduced from 0.44 to 0.21
- Time constants representing the thermal delays in boiler reheaters and combined-cycle HRSGs were reduced to produce quicker initial response from steam and combined cycle plants

The total amounts of conventional steam, combined cycle, and simple cycle generation were not changed. The revised fleet data file is shown in Table 8.

Table 8. Adjusted fleet makeup for microcosm simulation to match the 'Rockport' event

```
ChaPrefx      erag2-
I Type        FMW    Rf    Df
----
0 Steam       0.60   .70   .35
1 CCGT-G      0.10   .70   .35
2 Hydro       0.03   1.0   .90
3 SCGT        0.05   .70   .35
4 Nuclear     0.10   .00   .00
5 Nonresp     0.11   .00   .00
6 Renewable   0.01   .00   .00
----
deltap    0
H         3.95
kimw      0.01
lpd       1.0
droop     0.04
gbasef    1.3
tbasef    1.3
----
10 ggov1 tb 5
11 ggov1 tb 5
13 ccst3 td 20
15 ccst3 td 20
0  end
```

The changed assumptions regarding the fractions of the fleet that produce initial and then sustained response results in microcosm simulation traces that:

- match the initial rate of decrease of frequency
- generally reproduce the 'elbow' where the initial rapid decline of frequency is replaced by slow 'tailing off'
- show a prolonged depression of frequency and match the amount of the depression for a substantial period after the start of the event

4. Commentary

a. The microcosm model depends on parameter values that describe the make-up of the rotating turbine-generator fleet in terms of turbine type and operating mode. The operating modes of primary importance are described by the fraction of each turbine type that is responsive to change of system frequency and the fraction of the responsive generation that sustain the initial response.

b. It has been possible, to varying degrees among the three interconnections, to glean useful data on the makeups of the fleets by turbine type. However, it has been necessary to make assumptions regarding the fractions of the fleet that are responsive and responsive-sustaining.

c. The adjustments to the microcosm model that resulted in credible correspondence to recorded reality indicate that the Eastern interconnection data base is strongly optimistic regarding both: the fractions of the thermal turbine-generator fleet that are responsive to frequency, and the fraction of the responsive generation that sustains its initial contribution.

d. The data bases used in the production grid-scale simulation programs, and the data management facilities provided by those programs, are ill suited to consideration of the frequency control issues faced by the three interconnections. This reflects the way the programs were developed with their primary focus on transmission system issues and related electrical control matters. The dynamic models used to represent power plant components and the provisions for using these models are largely based on the assumption that all plants operate with voltage controls in automatic mode, power system stabilizers in service, and with turbine governors in direct control of real power output.

e. The dynamic modeling and model management facilities of these programs do not adequately recognize that, while the electrical elements of power plants are in the same automatic operating modes for the great majority of the time, the operating modes of the thermal elements of power plants are many, are different for different types of plant, and are chosen at the discretion of the plant operators.

f. The dynamic models used to represent power plant operation in the large-scale grid simulation programs are, in many cases, overly detailed with regard to the internal operation of the equipment they represent, and naive with regard to the modes of operation that can be in effect.

5. References

Undrill, J.M. (2018a). *Microcosm Model for Simulation of Power System Frequency Dip Transients: Program Manual.* Lawrence Berkeley Laboratory. February.

Undrill, J.M. (2018b). *Primary Frequency Response and Control of Power System Frequency.* Lawrence Berkeley Laboratory. February.