Test Systems for Harmonics Modeling and Simulation

Task Force on Harmonics Modeling and Simulation*
Transmission & Distribution Committee
IEEE Power Engineering Society

Abstract - This paper presents three harmonic simulation test systems. The purpose is to demonstrate guidelines for the preparation and analysis of harmonic problems through case studies and simulation examples. The systems can also be used as benchmark systems for the development of new harmonic simulation methods and for the evaluation of existing harmonic analysis software.

11.1 Introduction

Harmonic studies have become an important aspect of power system analysis and design in recent years. Harmonic simulations are used to quantify the distortion in voltage and current waveforms in a power system and to determine the existence and mitigation of resonant conditions. Many digital computer programs are available for harmonic analysis. New analysis techniques are being developed. With a wide variety of solution methods and modeling assumptions implemented in many different programs, there is a need for benchmark test systems so that the features and results of the programs can be evaluated and compared.

This paper presents the complete data for three harmonic simulation test systems. The purpose is to demonstrate guidelines for the preparation and analysis of harmonic problems through case studies and simulation examples. Several aspects that can impact the accuracy of results such as modeling of components and solution methods are illustrated. The benchmark information provided in the paper is also useful for the development of new harmonic simulation methods and for the evaluation of existing harmonic analysis software. The test systems represent the most common harmonic study scenarios encountered in industry. Sample results are provided in the paper. More information on the test systems and results can be obtained at http://www.ee.ualberta.ca/pwrsys/harmonics.html.

11.2 Test System No.1: A 14-Bus Balanced Transmission System

This test system contains two harmonic sources. One is a twelve-pulse HVDC terminal at bus 3 and the other is a SVC at bus 8 (Figure 11.1 and Figure 11.2).

Because the system has balanced bus loads and the transmission lines are transposed, a balanced harmonic analysis is generally sufficient for determining harmonic distortion levels in this case. Main harmonic analysis issues to be demonstrated by this test system are:

1. The need to solve fundamental frequency load flows for harmonic analysis. The load flow results affect the magnitudes and phase angles of the harmonic current injected from harmonic sources. Correct representation of the phase angles are important for systems with multiple harmonic sources [1]. The harmonic filters can have a large impact on the load flow results.
2. The harmonic cancellation effects due to Y-Y and Y-Delta transformer connections (at the HVDC terminal) and the impact of other harmonic sources (the SVC). For this purpose, the HVDC terminal is modeled as two six-pulse harmonic sources.
3. The effects of using different line models such as the distributed-parameter model and the lumped pi-circuit model in harmonic resonance assessment.

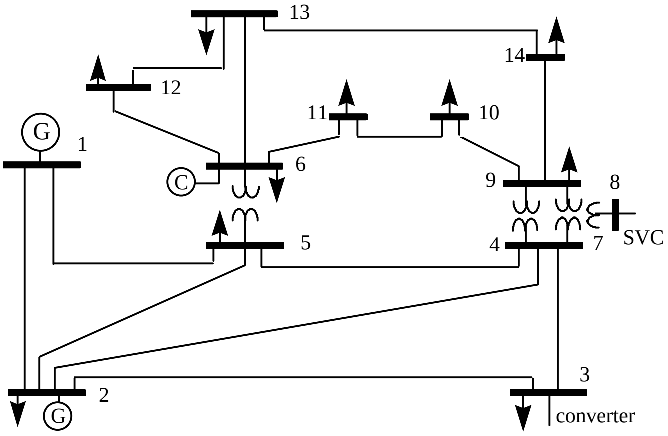

Figure 11.1. Test System 1 - 14 Bus Transmission System

Task force members and contributors are: R. Abu-hashim, R. Burch, G. Chang, M. Grady, E. Gunther, M. Halpin, C. Hatziadoniu, Y. Liu, M. Marz, T. Ortmeyer, V. Rajagopalan, S. Ranade, P. Ribeiro (vice chair), T. Sims, W. Xu (chair, editor).

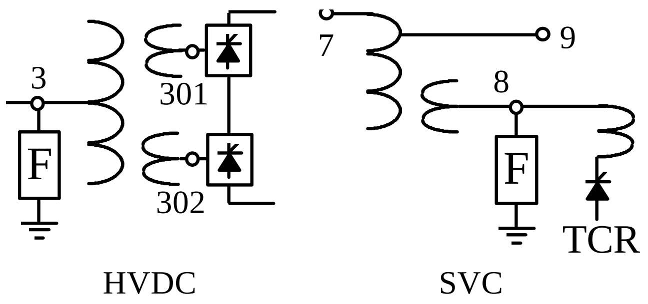

Figure 11.2. Harmonic Sources in Test System 1

Complete data for this system are shown in Tables 11.1 to 11.4. Key modeling and simulation features for this case are:

1. All transmission lines are modeled using a distributed-parameter line model. Long line effects are included in the model. Figure 11.3 shows the effects of using different line models. The curves are the frequency scan results seen at the HVDC bus (bus 3). The results suggest that the long-line effects should be included for long distance transmission lines.

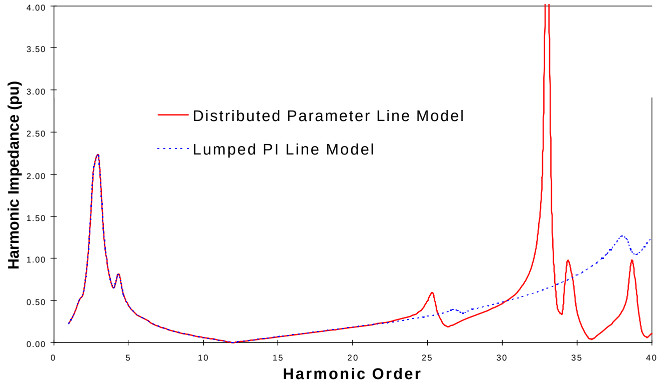

Figure 11.3. Effects of using different line models

Table 11.1. Bus Data and Results for System 1

Bus #	Nominal voltage (kV)	P Load (KW)	Q Load (KVar)	LF Voltage (pu)	LF Angle (deg)	THD (%)
1	230	0	0	1.0600	0.00	1.767
2	230	0	0	1.0450	-5.68	2.177
3	230	0	0	1.0427	-15.30	1.516
301	35.4	59,505	3,363	1.0417	-16.18	9.169
302	35.4	59,505	3,363	1.0417	-16.18	9.169
4	230	47,790	-3,900	1.0282	-11.41	0.755
5	230	7,599	1,599	1.0337	-9.82	1.462
6	230	0	0	1.0700	-15.87	0.468
7	230	0	0	1.0193	-14.47	0.423
8	13.8	0	12,900	1.0209	-14.49	0.522
9	115	29,499	16,599	1.0147	-16.09	0.482
10	115	9,000	5,799	1.0168	-16.33	0.421
11	115	3,501	1,800	1.0394	-16.21	0.394
12	115	6,099	1,599	1.0528	-16.72	0.391
13	115	13,500	5,799	1.0458	-16.73	0.376
14	115	14,901	5,001	1.0154	-17.39	0.343

1. The generators are modeled as either slack or PV buses for the fundamental frequency load flow solutions and as sub-transient reactance for the harmonic analysis. The sub-transient reactances are 0.25 per-unit.
2. Transformers are modeled using short-circuit impedances. The winding connections are represented in the model so that the phase-shifting effects on harmonic currents are included. If harmonics from transformer saturation are of interest, the magnetizing branches with saturation characteristics should be modeled. The off-nominal tap ratios of all transformers are 1.0 per-unit in this particular case.
3. The loads are modeled as constant power loads for load flow solutions and as impedances for harmonic solutions. The harmonic impedances are determined according to the 3rd model recommended in reference [2].
4. Harmonic filters are modeled as shunt harmonic impedances. All filters are the single-tuned type.
5. The HVDC terminal is modeled as two six-pulse bridge rectifiers according to the model of reference [3]. Because voltage distortion at the HVDC terminal is small, sensitivity studies showed that the terminal can be modeled as two harmonic current sources. The source spectra is provided in Table 11.4. It must be noted that the magnitudes and phase angles should be scaled and shifted according to the load flow results [1]. The HVDC terminal is modeled as a constant power load in the load flow solution.

Table 11.2: Branch Data for System 1 (Based on 100MVA)

Branch Type	Left Bus #	Right Bus #	R1 (pu)	X1 (pu)	B1 (pu)
Xfmr (Y-Y)	4	7	0.00000	0.20900	
Xfmr (Y-Y)	4	9	0.00000	0.55618	
Xfmr (Y-Y)	5	6	0.00000	0.25020	
Line	6	11	0.09495	0.19887	
Line	6	12	0.12285	0.25575	
Line	6	13	0.06613	0.13024	
Xfmr (Y-Delta)	7	8	0.00000	0.17615	
Xfmr (Y-Y)	7	9	0.00000	0.11000	
Line	9	10	0.03181	0.08448	
Line	9	14	0.01270	0.27033	
Line	10	11	0.08203	0.19202	
Line	12	13	0.22087	0.19985	
Line	13	14	0.17089	0.34795	
Capacitor@9	9	0	0.00000	0.00000	0.06330
Line	1	2	0.01937	0.05916	0.05279
Line	1	5	0.05402	0.22300	0.04920
Line	2	3	0.04697	0.19794	0.04380
Line	2	4	0.05810	0.17628	0.03740
Line	2	5	0.05693	0.17384	0.03386
Line	3	4	0.06700	0.17099	0.03460
Line	4	5	0.01335	0.04209	0.01280
Filter@8:2nd	8	0	0.52510	8.31233	0.03015
Filter@8:5th	8	0	0.52510	1.32635	0.03015
Filter@8:7th	8	0	0.52510	0.67307	0.03015
Filter@8:11th	8	0	0.52510	0.27515	0.03015
Filter@3:11th	3	0	0.00136	0.02772	0.24916
Filter@3:11th	3	0	0.00136	0.02772	0.24916
Xfmr (Y-Y)	3	301	0.00000	0.02800	0.00000
Xfmr (Y-Delta)	3	302	0.00000	0.02800	0.00000

Table 11.3: Generator Data for System 1

Bus #	Bus Type	Voltage setting (pu)	P gen. (KW)	Q gen. (KVar)	Sub-transient X (pu)
1	Slack	1.0600	261,681	-28,633	0.2500
2	PV	1.0450	18,300	5,857	0.2500
6	PV	1.0700	-11,200	44,200	0.2500

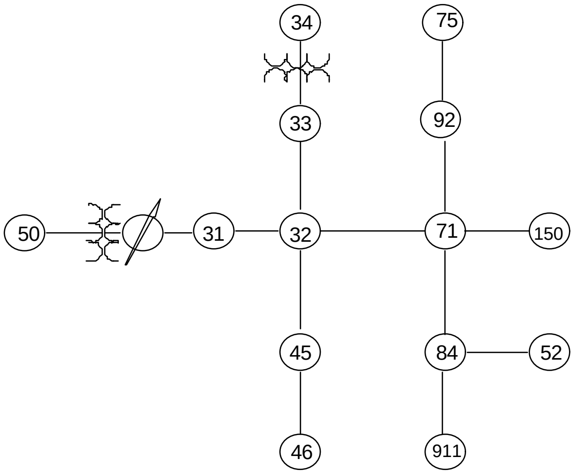

Figure 11.4. Test System 2 - Unbalanced Distribution System

Table 11.4. Harmonic Source Data for System 1

	Six-Pulse HVDC		Delta Connected TCR	
H-order	Mag(pu)	Angle(deg)	Mag(pu)	Angle(deg)
1	1.0000	-49.56	1.0000	46.92
5	0.1941	-67.77	0.0702	-124.40
7	0.1309	11.90	0.0250	-29.87
11	0.0758	-7.13	0.0136	-23.75
13	0.0586	68.57	0.0075	71.50
17	0.0379	46.53	0.0062	77.12
19	0.0329	116.46	0.0032	173.43
23	0.0226	87.47	0.0043	178.02
25	0.0241	159.32	0.0013	-83.45
29	0.0193	126.79	0.0040	-80.45

7. The SVC consists of harmonic filters and a delta-connected TCR. The TCR was modeled using the model of reference [1]. The firing angle is about 120 degrees. To facilitate the solution of the case using programs without a TCR model, the equivalent load and harmonic spectra of the TCR are listed in this paper. With this information, the TCR can be represented as a constant reactive power load in load flow solution and a harmonic current source in harmonic analysis. Because the SVC is relatively small as compared to the HVDC, its impact on overall system harmonic distortion is not significant.
8. The harmonic distortion results were obtained using the harmonic iteration method described in reference [1]. Because the results showed that the voltage distortions at the harmonic source buses are small and the equivalent harmonic current injections from the HVDC and SVC are made available in this paper, a non-iterative harmonic solution method which models harmonic sources as harmonic current injections should give the same solution results.

11.2 Test System No.2: A 13-Bus Unbalanced Utility Distribution System

This system is based on the IEEE 13 bus radial distribution test feeder [4]. The system is unbalanced and serves as a benchmark system for unbalanced harmonic propagation studies. The system was used in [1] for illustrative purposes and, with additional modifications, is proposed here as a harmonics test system.

The feeder, shown in Figure 11.4, contains voltage regulators, three and single phase line configurations, shunt capacitors, and spot and distributed loads. Phase-ground and phase-phase connected loads are included. For harmonic studies, load compositions are specified to include harmonic producing loads. Complete data are provided in the Appendix A. Current spectra for the three load types, namely fluorescent light banks, adjustable speed drives, and composite ("other") residential loads, are given for test purposes. The analysis of harmonic propagation in distribution systems must necessarily utilize a phase-domain representation. The following items must be considered in the analysis of unbalanced distribution systems:

1. It is difficult to identify or specify harmonic-producing loads. In general, several loads are served from one point and the harmonic currents represent the aggregate response of several harmonic producing devices.
2. Many distribution systems tend to contain capacitors. Frequency scan analysis can be helpful to verify if resonance conditions exist. Due to a large number of possible harmonic source locations, however, it is difficult to determine the frequency scan buses.
3. The commonly assumed properties under balanced conditions such as the zero-sequence nature of triple harmonics no longer hold. Harmonic producing devices at the distribution level can generate uncharacteristic harmonics.
4. Load and transformer connections can have large impacts on harmonic propagation. The subject of load modeling for distribution system harmonic analysis still needs considerable research [1].

As demonstrated in [1], relatively moderate variations in the models can have a significant impact on results. The test system is specified in a way that highlights all of these issues. The Alternative Transients Program was used to calculate harmonic propagation in the system [5,6]. Partial results are shown in Table 11.5 and Figure 11.5.

Table 11.5. Voltage THD (Fundamental Frequency Component)

Node #	Phase A	Phase B	Phase C
32	1.96(1.034)	1.76 (1.038)	1.69(1.007)
33	1.96(1.034)	1.76(1.038)	1.69(1.007)
34	0.96(1.018)	0.96(1.030)	1.04(1.022)
71	3.23(1.010)	2.76(1.045)	2.86(0.969)
75	3.35(1.003)	2.82(1.048)	2.95(0.967)
52	3.30(1.008)		
911			3.00(0.965)

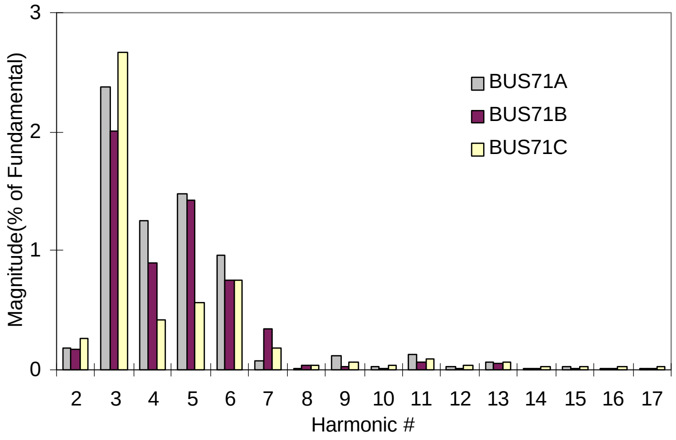

Figure 11.5. Harmonic Voltage Distortion Spectrum at Node 71

Modeling and simulation features for this case are:

1. Conventional loads were modeled as constant RL impedances obtained from the given kVA at 60Hz.
2. Harmonic producing loads were modeled as current sources with the specified spectra using the 'Models' capability of the ATP. Magnitudes were scaled based on the fundamental component of load current and phase angles were adjusted based on the phase angle of the voltage across the load obtained from the fundamental frequency solution.
3. The motor and the capacitor at node 34 were assumed out of service. For harmonic frequencies, the motor should be modeled using its sub-transient impedance (or locked rotor impedance).
4. The voltage regulator was not modeled. Rather, the substation transformer secondary taps on the three-phases were set at +15,+10 and +13, respectively.
5. Lines were modeled as mutually coupled π branches.

For the case studied, the voltage distortion levels are low. This is because several loads are connected phase-phase and harmonic phase angles are modeled. As described in reference [1], significantly different results are obtained depending on the choice of load models and harmonic current source models. It is noted that in the examples in [1], all loads were assumed to be connected phase-ground, the motor and capacitor at node 34 are in service and harmonic source spectra were different from the ones used here.

11.4 Test System No.3: A 13-Bus Balanced Industrial Distribution System

This test case consists of 13 buses and is representative of a medium-sized industrial plant. The system is extracted from a common system that is being used in many of the calculations and examples in the IEEE Color Book series [7]. The plant is fed from a utility supply at 69 kV and the local plant distribution system operates at 13.8 kV. The system is shown in Figure 11.6 and described by the data in Tables 11.6-11.9. Due to the balanced nature of this example, only positive sequence data is provided. Capacitance of the short overhead line and all cables are neglected.

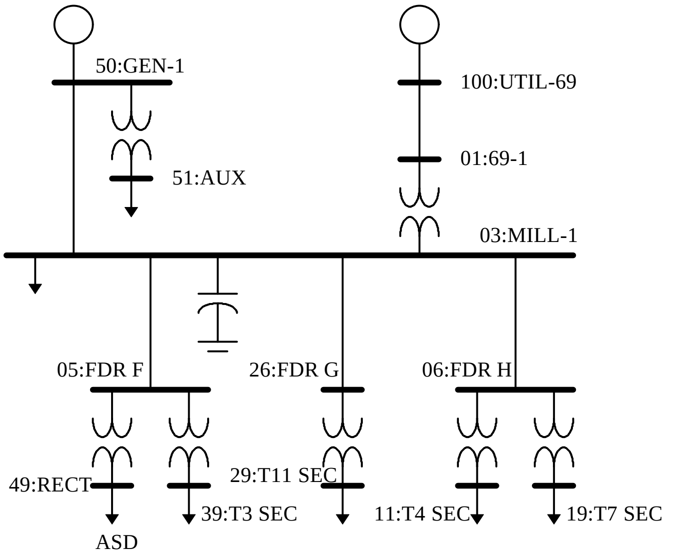

Figure 11.6. Test System 3 - A Balanced Industrial System

Additional data used to conduct a harmonic analysis of the example industrial system include the following:

1. System equivalent impedance. For this study, the system impedance was determined from the fault MVA and X/R ratio at the utility connection point. These values are 1000 MVA and 22.2, respectively. Driving point impedance (as a function of frequency) at the connection point was not available, but should be used whenever possible.
2. The local (in-plant) generator was represented as a simple Thevenin equivalent. The internal voltage, determined from the converged power flow solution, is $13.98\underline{/-1.52^\circ}$ kV. The equivalent impedance is the sub-transient impedance which is $0.0366+j1.3651\Omega$.
3. The plant power factor correction capacitors are rated at 6000 kvar. As is typically done, leakage and series resistance of the bank are neglected in this study.
4. The displacement power factor for the drive load is 0.97 lagging. This high power factor is typical of drives operated at or near full load.

Table 11.6. Per-Unit Line and Cable Impedance Data
(base values: 13.8 kV, 10,000 kVA)

From	To	R	X
100: UTIL-69	01:69-1	0.00139	0.00296
03:MILL-1	50:GEN-1	0.00122	0.00243
03:MILL-1	05:FDR F	0.00075	0.00063
03:MILL-1	26:FDR G	0.00157	0.00131
03:MILL-1	06:FDR H	0.00109	0.00091

Table 11.7. Transformer Data

From	To	Voltage	Tap	kVA	%R	%X
01:69-1	03:MILL-1	69:13.8	69	15000	0.4698	7.9862
50:GEN1	51:AUX	13.8:0.48	13.45	1500	0.9593	5.6694
05:FDR F	49:RECT	13.8:0.48	13.45	1250	0.7398	4.4388

05:FDR F	39:T3 SEC	13.8:4.16	13.11	1725	0.7442	5.9537
26:FDR G	29:T11 SEC	13.8:0.48	13.45	1500	0.8743	5.6831
06:FDR H	11:T4 SEC	13.8:0.48	13.8	1500	0.8363	5.4360
06:FDR H	19:T7 SEC	13.8:2.4	13.11	3750	0.4568	5.4810

Table 11.8. Generation, Load, and Bus Voltage Data (from power flow study results)

Bus	V_{mag} (p.u.)	δ (deg)	P_{gen} kW	Q_{gen} kvar	P_{load} kW	Q_{load} kvar
100:UTIL-69	1.000	0.00	7450	540	-	-
01:69-1	0.999	-0.13	-	-	-	-
03:MILL-1	0.994	-2.40	-	-	2240	2000
50:GEN1	0.995	-2.39	2000	1910	-	-
51:Aux	0.995	-3.53	-	-	600	530
05:FDR F	0.994	-2.40	-	-	-	-
49:RECT	0.980	-4.72	-	-	1150	290
39:T3 SEC	0.996	-4.85			1310	1130
26:FDR G	0.994	-2.40	-	-	-	-
06:FDR H	0.994	-2.40	-	-	-	-
11:T4 SEC	0.979	-3.08	-	-	370	330
19: T7 SEC	1.001	-4.69	-	-	2800	2500
29:T11 SEC	0.981	-4.16	-	-	810	800

Table 11.9. Harmonic Source Data

Harmonic #	Percent	Relative Angle
1	100.00	0.00
5	18.24	-55.68
7	11.90	-84.11
11	5.73	-143.56
13	4.01	-175.58
17	1.93	111.39
19	1.39	68.30
23	0.94	-24.61
25	0.86	-67.64
29	0.71	-145.46
31	0.62	176.83
35	0.44	97.40
37	0.38	54.36

Specific issues related to modeling for harmonic analysis must also be considered if the results presented here are to be obtained using different analysis programs. Modeling considerations applicable to this example include:

1. All loads are modeled as series RL circuits. This approach is taken instead of parallel RL modeling to more accurately represent the limited harmonic damping offered by typical induction motors without resorting to extremely detailed motor models.
2. Frequency dependence of model resistance is neglected. This is done mainly because of the significant discrepancies that exist among various programs available. In addition, neglecting frequency effects on resistance leads to over conservative results (which are often preferred).
3. Transformer magnetizing branch effects are neglected. In addition, increasing winding losses as a function of frequency are also neglected. As discussed in 2 previously, this is done to avoid problems when comparing the results presented here with those obtained using other analysis programs.

The results of a harmonic analysis of the system of Figure 11.6 are given in Table 11.10. Fundamental, fifth, and seventh voltage harmonic amplitudes and THD_V are given for each of the system buses. These results, along with those obtained from a fundamental frequency power flow study (shown in Table 11.8), give an accurate description of the voltage profiles in the plant.

11.5 Conclusions

Complete data for three harmonic test systems has been presented in this chapter. The systems can be used as benchmark systems for the development of new harmonic analysis methods and for the evaluation of existing harmonic software. Researchers, developers and users of harmonic analysis programs are encouraged to use these systems to test their programs and report their comments to the IEEE PES Harmonics Modeling and Simulation Task Force.

Table 3.5: Plant Harmonic Voltage Distortion Summary.

Bus	V_1 (V_{LN})	V_5 (V_{LN})	V_7 (V_{LN})	THD_V (%)
100:UTIL-69	39645.70	40.37	104.23	0.28
01:69-1	39538.00	52.36	135.14	0.37
03:MILL-1	7712.77	53.51	138.13	1.93
50:GEN1	7726.55	51.72	133.51	1.87
51:Aux	262.74	1.72	4.40	1.81
05:FDR F	7709.24	54.07	138.35	1.94
49:RECT	269.89	12.79	12.83	8.02
39:T3 SEC	2240.05	14.83	37.21	1.80
26:FDR G	7709.07	53.48	138.04	1.93
06:FDR H	7703.35	53.43	137.91	1.93
11:T4 SEC	260.40	1.78	4.59	1.90
19: T7 SEC	1302.74	8.58	21.78	1.81
29:T11 SEC	256.29	1.71	4.36	1.84

11.6 Acknowledgment

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11.7 References

1. IEEE Task Force on Harmonics Modeling and Simulation, "Modeling and Simulation of the Propagation of Harmonics in Electric Power Networks, Part 1 & 2", IEEE Trans. on Power Delivery, Vol. 11, No.1 January 1996, pp. 452-474.
2. CIGRE Working Group 36-05, “Harmonics, Characteristic Parameters, Methods of Study, Estimates of Existing Values in the Network”, Electra, no. 77, July 1981, pp.35-54.
3. W. Xu, J.E. Drakos, Y. Mansour, A. Chang, "A Three-Phase Converter Model for Harmonic Analysis of HVDC Systems", IEEE Trans. on Power Delivery, Vol. 9, No.3, July 1994, pp.1724-1731.
4. IEEE Distribution Planning Working Group Report," Radial Distribution Test System," IEEE Trans. on Power Systems, Vol. 6, No.3, Aug.1991, pp.975-985.
5. Canadian/American EMTP User's Group "Alternative Transients Program(ATP) Rule Book" , Portland, OR, 1995.
6. H.W. Dommel, "Electromagnetic Transients Program Reference Manual (EMTP Theory Book)", Prepared for Bonneville Power Administration, Dept. of Electrical Engineering, University of British Columbia, Aug. 1986.
7. IEEE Standard 399-1990, “IEEE Recommended Practice for Industrial and Commercial Power System Analysis”, IEEE, New York, 1990.

Appendix A: Data for Test System 2

Source System: Node 50.
Short circuit MVA 1100 at 82 degrees lagging. Balanced.

Substation: Node 50 -31
Transformer: 5 MVA, 115 kV delta -4.16 kV wye grounded
Impedance z= 1 + j 8 % at 60 Hz.

Voltage Regulators: Connected at node 31
individual phase control. Wye connected, PT Ratio=20, CT Rating=700 A, R + jX = 3+j9Ω, voltage level = 122 V

Transformers: Node 33 - Node 34
500 KVA, 4160 delta - 480, wye volts, z = 1.1 + j 2.0 %

Line phasing and 60 Hz impedance matrices
All conductors ACSR. Line geometry is available from the Internet site. Upper triangle of phase domain impedance (Z_{abc} ohms/mile) and admittance (Y_{abc} µS/mile) matrices are shown. For non-existent phases , matrices have been padded with zeros.

ID 501:
Phasing BACN, Phase conductor 556,500 26/7, Neutral 4/0 6/1.
Z_{abc} = 0.3477+j 1.0141, 0.1565+j 0.4777 0.1586+j 0.4361
0.3375+j1.0478 0.1535+j 0.3849
0.3414+j 1.0348
Y_{abc} = j6.2450 -j1.7664 -j1.3951
j5.8271 -j0.7461
j5.6985

ID 502:
Phasing CABN, phase conductor 4/0 6/1, neutral 4/0 6/1
Z_{abc} = 0.7538+j1.1775 0.1586+j 0.4361, 0 .1565+j 0.4777
0.7475+j 1.1983, 0.1535+j 0.3849
0.7436+j 1.2112
Y_{abc} = j5.6587, -j1.1943 -j1.5024
j5.2262 -j0.6626
j5.3220

ID 503:
Phasing CBN, phase conductor 1/0, neutral 1/0

Z_{abc} = 0.0000+j 0.0000 0.0000+j 0.0000 0.0000+j0.0000
1.3294+j1.3471 0.2066+j0.4591
1.3238+j1.3569
Y_{abc} = 0.0000 0.0000 0.0000
j4.7097 -j0.8999
j4.6658

ID 504: phasing A C N, conductor 1/0, neutral 1/0
Z_{abc} = 1.3238+j1.3569 0.0000+j0.0000 0.2066+j0.4591
0.0000+j0.0000 0.0000+j0.0000
1.3294+j1.3471
Y_{abc} = j4.6658 0.0000 -j0.8999
0.0000 0.0000
j4.7097

ID 505: Phasing C N, conductor 1/0, Neutral 1/0
Z_{abc} = 0.0000+j0.0000 0.0000+j0.0000 0.0000+j0.0000
0.0000+j0.0000 0.0000+j0.0000
1.3395+j1.3295
Y_{abc} = 0.0000 0.0000 0.0000
0.0000 0.0000
j4.6178

ID 508: Three-phase URD concentric netural 250 MCM AL cables, 6" apart on horizontal plane 40 " below ground . Neutral is 13 #14 Cu . OD over neutral is 1.28 "
Z_{abc} = 0.8506+j0.4037 0.3191+j0.0325 0.3191+j0.0325
0.8597+j0.4458 0.2848+j-0.0145
0.8597+j0.4458
Y_{abc} = j94.6212 0.0000 0.0000
j94.6212 0.0000
j94.6212

ID 509: Single-phase URD tape shield; 1/O copper tape shielded conductor with separate 1/o copper bare neutral on 1" spacing; 40" deep.
Z_{abc} = 0.9806+j0.5146 0.0000+j0.0000 0.0000+j0.0000
0.0000+j0.0000 0.0000+j0.0000
0.0000+j0.0000
Y_{abc} = j0.3915 0.0000 0.0000
0.0000 0.0000

0.0000

Line Connectivity Data:

Node-I	Node-J	Length (ft)	ID
32	45	500	503
33	32	500	502
45	46	300	503
31	32	2000	501
52	84	800	509
71	32	2000	501
71	84	800	504
71	150	1000	501
75	92	500	508
84	911	300	505
71	92	switch	

Shunt capacitors (kVar):

Node	Connection	Ph-A	Ph-B	Ph-C
75	Y	200	200	200
34	Y	125	125	125
911		0	0	100

Motor loads: Node 34

500 HP three-phase induction motor; running power factor 0.8, efficiency 90%; locked rotor 3000 KVA at 0.4 power factor lag.

Loads:

The following model codes are used: D-delta or phase-phase connection , Y- wye or phase-ground connection. S-constant kVA fundamental frequency model, Z-constant impedance fundamental frequency model, I-constant current fundamental frequency model.

Node No.	Model	Ph-A kW	Ph-A kvar	Ph-B kw	Ph-B kvar	Ph-C kw	Ph-C kvar
34	Y-PQ	42.63	20.18	0	0	0	0
	Harmonic load: None						
45	Y-PQ	0	0	170.53	125.09	0	0
	Harmonic load: 60% other (composite) types						
46	D-Z	0	0	230.22	131.97	0	0
	20% fluorescent, 20% ASD, 20% others. Note: this load is connected between phase B&C.						
52	Y-Z	127.90	85.79	0	0	0	0
	10% fluorescent, 10% ASD, 20% others						
71	D-PQ	383.70	219.95	383.70	219.95	383.70	213.95
	30% fluorescent, 60% others.						
75	Y-PQ	486.02	189.07	68.21	60.55	289.91	212.65
	15% fluorescent, 20% ASD, 15% others.						
92	D-I	0	0	0	0	170.53	151.38
	15% fluorescent, 20% ASD, 15% others. Note: the load is connected between phases C&A.						
911	Y-I	0	0	0	0	170.53	80.74
	15% fluorescent, 20% ASD, 15% others.						
32	Y-PQ	16.48	9.45	66.40	38.06	116.97	97.05
71	Note: this is a distributed load between nodes 32 & 71						

Current spectra of harmonic loads:

Phase angles are with respect to the fundamental frequency voltage in degrees.

H	Fluorescent		ASD		Other	
order	Mag.	Phase	Mag.	Phase	Mag.	Phase
1	1	-41.2	1	-1.5	1	-35.0
2	0	0	0	0	0	0
3	0.2	273.4	0.542	0.7	0.007	-105.8
4	0	0	0	0	0.095	-167.4
5	0.107	339.0	0.152	110.8	0.002	-275.5
6	0	0	0	0	0.083	-42.6
7	0.021	137.7	0.069	151.9	0	0
8	0	0	0	0	0.005	-247.8
9	0.014	263.2	0.043	-95.0	0	0
10	0	0	0	0	0	0
11	0.009	39.8	0.036	-13.9	0	0
12	0	0	0	0	0	0
13	0.006	182.4	0.029	95.2	0	0
14	0	0	0	0	0	0
15	0.005	287.0	0.025	-182.7	0	0