MODELING AND SIMULATION OF THE PROPAGATION OF HARMONICS IN ELECTRIC POWER NETWORKS

PART II : SAMPLE SYSTEMS AND EXAMPLES

Task Force on Harmonics Modeling and Simulation*

Abstract: *This report is the second part of a review on the nature and modeling of harmonic sources in electrical power systems and the analysis of harmonics propagation. Existing IEEE standard test systems are used to develop sample systems for harmonic studies. Examples of model development and study results are provided. Research needs in the area are identified.*

Keywords: *Power System Harmonics, Harmonics Simulation, Harmonics Modeling.*

I. INTRODUCTION

Conventional ac electric power systems are designed to operate with sinusoidal voltages and currents. However, nonlinear loads, electronically switched loads and converters cause distortion in the steady–state ac voltage and current waveforms. Periodic steady–state distortion can be very effectively studied by examining the components of a Fourier series representation of the waveforms. A Harmonic Analysis (Harmonic Study) numerical tool is applied to study the generation and propagation of harmonics in an arbitrary topology network.

The companion paper [1] has explored the theoretical aspects of harmonic modeling and simulation. The purpose of the present report is to illustrate harmonic studies using two test systems. Issues of basic modeling assumptions, representation of harmonic sources, typical studies, and the question of extent of network modeling are explored. It is not always possible to provide *rules of thumb*; standard industry practice is highlighted wherever possible.

The goal of any harmonic study is to determine the state and performance of the system at harmonic frequencies and to analyze the consequences of waveform pollution. Standards such as the IEEE–519 [2] are referred to for guidelines of operation under harmonic conditions, and for developing and evaluating mitigation measures.

The scope of this paper is limited to describing the process of setting up a study for distribution and transmission systems. Procedures for the classical industrial plant type of situations are well documented in [2].

Two test systems derived from existing IEEE test systems for power flow studies are analyzed in Sections III and IV to illustrate the basic harmonic steady–state studies. Section V explores different types of representations for harmonic sources and explores network modeling and truncation.

Conclusions and recommendations for additional research are provided in the last section.

II. TEST SYSTEMS

For illustration purposes, two standard IEEE tests systems have been adapted for use with harmonic analysis. These systems are described in Appendices A and B respectively. The first system (System 1, Fig. A1) is a balanced EHV network corresponding to the IEEE 14–bus test system for power flow studies [3]. This standard system is modified by replacing a synchronous condenser with a Static Var Compensator (SVC), and adding the sending end of an HVDC system in place of a load. All other data remain the same.

The second system (System 2, Fig. B1) is an unbalanced distribution system corresponding to the IEEE 13–bus distribution test system [4]. This system consists of a three–phase primary feeder with three–, two– and single–phase laterals. It includes both overhead open–wire lines and underground cables. Loads consist of three–phase motor loads and single–phase loads. A load composition that includes passive–linear, fluorescent, and electronic load is specified. The distribution test system is extremely unbalanced.

III. BALANCED SYSTEM STUDY: SYSTEM 1

This system is a balanced three–phase system (see Appendix A for data). The general goals of a harmonic study of such a system are to determine possible frequencies at which resonance conditions might exist, to determine distortion levels and component loadings at various operating conditions, to examine possible HVDC–SVC harmonic interactions, and to examine the need for additional filters.

Modeling Considerations

Under perfectly balanced conditions it is only necessary to model the system at characteristic harmonic frequencies. Because of the presence of the SVC it is necessary to model all odd harmonics except triplens. It is necessary to model both positive and negative sequence networks since a number of synchronous machines are present. Further, if transformer saturation is modeled, triplen harmonics can exist. In this case

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the zero sequence conditions must be modeled at triplen frequencies. The presence of two harmonic sources necessitates the modeling of the phase shifts in transformers. The present illustration considers a balanced case only.

It may initially be convenient to use current source models, adjusted for the bus voltage phase angles. As discussed in Part I [1], such data can be obtained from the references cited therein. If the calculated THD levels are high (approaching 5–10 %) then a detailed model of the converter and SVC needs to be used. The models used for the SVC and HVDC are given in reference [5]. The generators, including synchronous condensers, were modeled at harmonic frequencies by their negative sequence reactance. The Type B load model described in the companion paper [1] was used.

Frequency Scan Study

The development of a frequency scan is usually the first step in a study. A frequency or impedance scan refers to a plot showing the magnitude and phase of the driving point impedance (of the linear network) at a bus of interest versus frequency. The frequency scan can provide some useful, if sometimes qualitative, insight into the system response at harmonic frequencies. The following general observations can be made regarding frequency scans:

- In balanced systems each harmonic is associated with a particular sequence, e.g., third harmonics appear as zero sequence, fifth as negative, etc. The scan for the appropriate sequence model must be used to interpret the potential impact of a harmonic. Conversely sequence models are appropriate only when dealing with harmonics of power frequency.
- Sharply tuned peaks (minimums) in impedance magnitude at harmonic frequencies or distortion frequencies that are expected are indicative of parallel or series resonances that might cause equipment damage. This is the major application of the scan.
- A resonance close to a harmonic frequency is a cause for concern as is a broad impedance peak with a phase crossover. In these cases the harmonic current in the components involved in the resonance can be substantially larger than the source harmonic current itself.
- When a source produces distortion at non–harmonic frequencies the balanced interpretations do not apply and in fact the overall waveforms may be aperiodic. The sequence impedance scan can nonetheless indicate if resonance related problems might occur since overall response to a single sinusoidal source at the frequency of interest will be governed by the three sequence impedances.
- Suppose a resonance is observed at third harmonic frequency in the positive sequence network. Under ideal conditions this is not a problem since the third harmonic is of zero sequence. However it is appropriate to investigate this resonance since minor unbalances always exist in which case pure zero sequence third harmonic cannot be assumed.
- Frequency scans are also useful in qualitatively and visually assessing the impact of filters.

Frequency scans are not, however, a substitute for formal Harmonic Power Flow studies. The latter models the actual harmonic generation from sources in the presence of distortion. Further, in a frequency scan study one usually looks at driving point impedances and not at transfer impedances. In the circuit of Figure 1 it may be verified that the driving point impedance at bus 1 is zero at the fifth harmonic frequency while the transfer impedance from bus 1 to bus 2 is $-j\,0.5$ pu ohms. Thus, a fifth harmonic current source can create substantial harmonic distortion at bus 2 with negligible distortion at bus 1. It is of course possible to develop transfer impedance scans but this detracts from the use of scans as a simple screening tool.

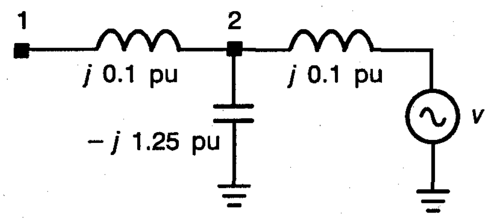

Figure 1 An illustration circuit for driving point and transfer impedances. The impedances shown are given at fundamental frequency

Frequency scan results for the HVDC bus are shown in Figure 2 for the cases of the SVC being an open circuit and in full conduction, respectively. Note that all filters are modeled. The scan is performed using the positive sequence network model and indicates a resonant condition around the third harmonic and a minor resonance around the fifth. Subsequently the impedance diminishes because of the filters. As a general rule filters look capacitive at frequencies below their tuned frequency and thus the impedance at lower frequencies increases. If transformer magnetization current is expected to be significant, it would be necessary to investigate resonance problems in this region.

Harmonic Power Flow study

Figure 3 summarizes bus voltage THDs calculated from the detailed–model study for three cases, namely, both HVDC and SVC operational, HVDC only and SVC only. The SVC has little impact on voltage THD, while the HVDC system contributes significantly to distortion. The effect of various HVDC operating conditions, in terms of firing angle, is illustrated in Figure 4. The dc side current was maintained constant. It is seen that the distortion increases as the firing angle is increased and can exceed the IEEE–519 recommended limit. Figure 5 illustrates the effect of additional filters at the HVDC bus. It is seen that there is little to be gained past the addition of the third filter.

This example serves to illustrate a typical harmonic screening study. The actual design of filters for high power harmonic producing equipment such as HVDC and SVC requires a much more detailed accounting of variations in harmonic current generation, ac system harmonic impedance

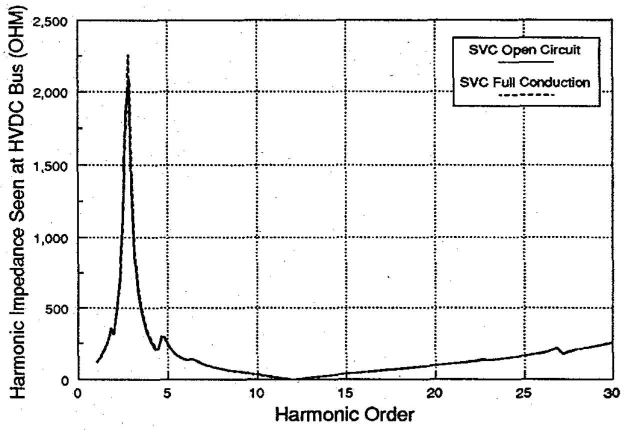

Figure 2 **Frequency scan at the HVDC bus 3 (System 1)**

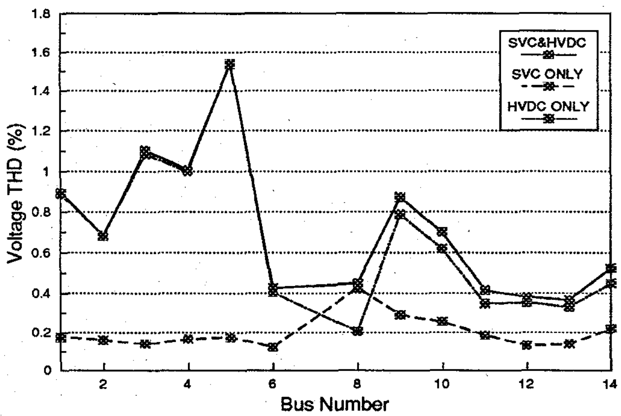

Figure 3 **Voltage THDs for the 14–bus test system (System 1)**

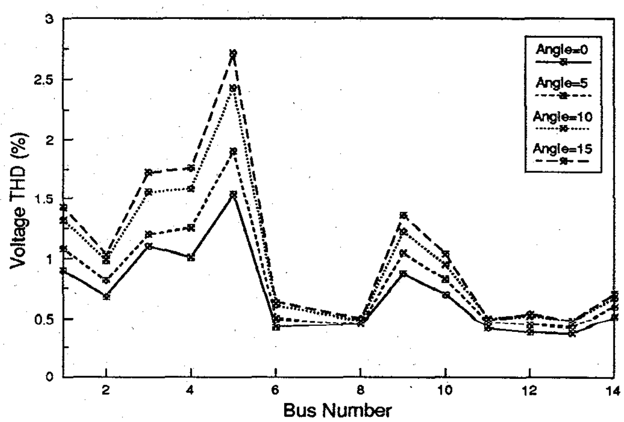

Figure 4 **Effect of converter firing angle on voltage THD (System 1)**

changes with topology, and filter detuning effects.

IV. UNBALANCED SYSTEM STUDY: SYSTEM 2

This unbalanced test system is described in Appendix B. The fundamental frequency current unbalance (ratio of negative

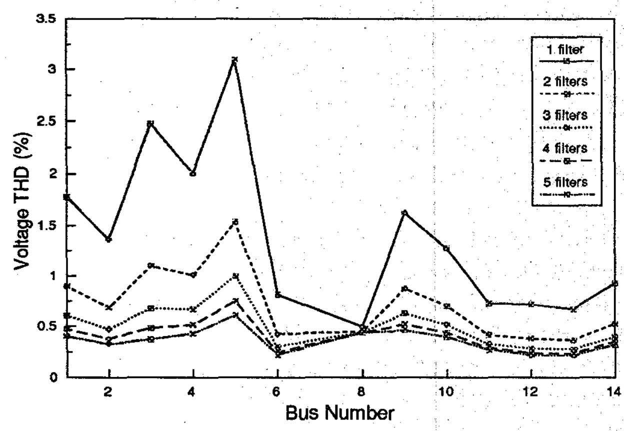

Figure 5 **Effect of filtering on voltage THD (System 1)**

sequence current to positive sequence current) as measured at the substation source can be as high as 20%. The harmonic producing loads include fluorescent lighting, Adjustable Speed Drives (ASD) for heat pumps, and *non–specific* sources such as PCs, TVs, etc.

Modeling Considerations: A system such as this must be analyzed using a detailed three–phase model in order to correctly account for transmission line and load unbalance and the variety of possible transformer connections. The methodology of reference [5] was adopted for this study.

As in the balanced case, a frequency scan study can be utilized for assessing resonance conditions. In a typical distribution system a large number of capacitors at different buses as well as a large number of harmonic producing loads are present. Thus, there can be significant variation in impedance seen at each bus and even in different phases at each bus.

Harmonic Power Flow study

For the harmonic power flow study various components were modeled as described below. Distribution lines were modeled using a distributed parameter (long–line) model with frequency dependent earth return effects included. Although the actual feeders are multigrounded, the assumption of continuous grounding was found to yield acceptable results. Transformer connections were modeled using the coupled coil approach but saturation was ignored. In practice, saturation should be modeled if high voltages, e.g., 1.1pu exist. Motors were modeled as constant power loads at fundamental frequency and a transient impedance corresponding to 0.2 pu at 60 Hz on machine base. Note that, realistically, this implies that the motor actually draws the specified fundamental frequency power and an additional component corresponding to harmonics. The motor connection was also modeled.

Passive loads were modeled as constant power loads at fundamental frequency. The composition of the load is specified in the given data. At harmonic frequencies the *linear* or *static* (see [1]) part of load was modeled as a constant impedance at appropriate frequency. The harmonic producing loads were modeled as current sources with spectra as specified in

Appendix B. The magnitudes of current harmonics were scaled according to the value of fundamental current. Three different approaches were taken to define harmonic current phase angles, as summarized below:

▪S1: The phase angles were adjusted according to the phase angle of the fundamental current with respect to reference.

▪S2: All harmonic sources were assumed to have the same phase angles.

▪S3: Only the non–specific sources were modeled as having the same phase angle.

Finally, the source system was modeled as a purely sinusoidal source with impedance derived from the given three–phase and single–line–ground fault data.

Table 1 lists the THD calculated at each bus by phase, for each of the three scenarios regarding phase angle assumptions described previously. In scenario S1 only 12 of 34 buses have a THD in excess of the 5% limit recommended by IEEE–519. In scenarios S2 and S3 several buses are out of compliance and in some cases THD exceeds 10 %. Thus modeling assumptions must be carefully scrutinized particularly when comparing against guidelines. A more detailed study of Table 1 shows that it is not possible to draw a general conclusion as to which type of modeling is most conservative. Section V explores this issue further. Figure 6 shows the voltage spectra at bus 32 for the three phases.

Table 1 also shows the THD calculated when only one type of harmonic producing element is modeled at one time.

Even a rather simple example such as this indicates the difficulties encountered in assessing distribution system harmonic levels. There are several other aspects that cannot be illustrated due to space limitations. The most important one relates to practical observations that very often distribution level voltage THDs are much lower than what might be expected from a harmonic power flow study. Some obvious reasons can be cited. Manufacturing tolerances and diversity of usage in devices may create enough difference in spectra such that harmonic cancellation occurs within an aggregate load. In many commercial installations devices such as fluorescent lighting banks are distributed amongst the three–phases. If identical banks were served from a delta–wye transformer in a balanced manner triplen harmonics would be completely eliminated at the feeder level. We expect that until substantial additional experience is gained, distribution system harmonic analysis will retain some subjectivity.

BUS–		Scenario S1	S2	S3	Harmonic source type Fluo.	ASD	Non–spec
45	B	2.701	4.502	4.859	2.400	0.221	0.887
45	C	3.311	6.882	5.831	2.845	0.278	1.346
33	A	2.921	4.557	5.022	2.516	0.305	1.166
33	B	2.670	4.525	4.823	2.361	0.222	0.908
33	C	3.258	6.894	5.756	2.773	0.278	1.364
46	B	2.702	4.495	4.855	2.402	0.221	0.882
46	C	3.348	6.897	5.895	2.887	0.278	1.348
32	A	2.914	4.548	5.010	2.511	0.304	1.163
32	B	2.663	4.515	4.810	2.355	0.221	0.906
32	C	3.251	6.878	5.741	2.767	0.277	1.361
52	A	5.549	9.326	9.156	4.794	0.669	2.127
71	A	5.386	8.945	9.046	4.687	0.546	2.104
71	B	4.700	8.370	8.369	4.111	0.384	1.677
71	C	6.153	3.362	10.51	5.172	0.523	2.690
84	A	5.512	9.288	9.098	4.769	0.629	2.121
84	C	6.588	4.516	11.57	5.507	0.576	2.908
150	A	5.386	8.945	9.046	4.687	0.546	2.104
150	B	4.700	8.370	8.369	4.111	0.384	1.677
150	C	6.153	3.362	10.51	5.172	0.523	2.690
92	A	5.386	8.945	9.046	4.687	0.546	2.104
92	B	4.700	8.370	8.369	4.111	0.384	1.677
92	C	6.153	3.362	10.51	5.172	0.523	2.690
911	C	6.746	4.952	11.98	5.631	0.598	2.991
75	A	5.603	9.290	9.516	4.865	0.567	2.227
75	B	4.861	8.679	8.745	4.244	0.404	1.754
75	C	6.342	3.862	10.94	5.310	0.545	2.809
34	A	1.506	1.064	2.569	1.201	0.208	0.789
34	B	1.203	1.323	3.761	1.054	0.152	0.527
34	C	1.522	1.499	4.174	1.253	0.217	0.822

Table 1 Distribution system (System 2) voltage THD according to phase angle definition scenarios and harmonic source types

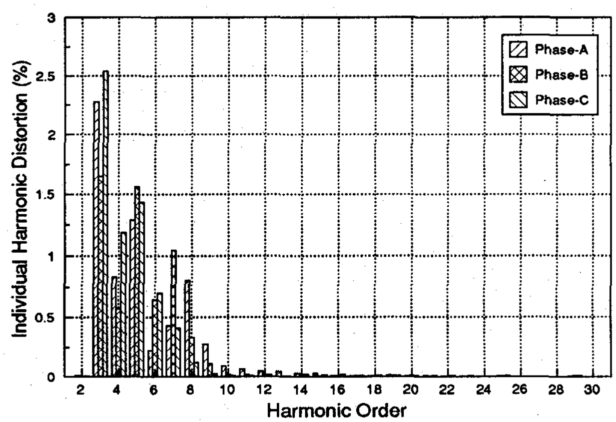

Figure 6 Bus 32 voltage spectra (System 2)

V. DISCUSSION OF MODELING CONSIDERATIONS

Harmonic Source Phase Angles

For systems with only one harmonic–producing element, the phase angles of the harmonic current sources are not a concern since the harmonic distortion in the system is determined completely by the magnitudes of the injected currents. However, if there are multiple harmonic sources in a system, the harmonics from each source will add vectorialy. As a result, the combined harmonic distortion levels are highly dependent on the phase angles assumed.

Assuming that all current sources have the same phase angle (*Equal*) is one of the methods to address the phase angle problem. In most cases, this approach yields conservative estimates of the harmonic distortion level. However, the results are not necessarily the worst case distortion that may be experienced by the system.

For the multiple source harmonic assessment, it is worthwhile to estimate the worst case combination of the phase angles. The results can be obtained by performing harmonic studies with one harmonic–producing element being modeled at a time. The *Worst case* harmonic level, voltage or current, is the arithmetic summation of the harmonic magnitudes calculated in each study.

To perform a more accurate analysis (better *Estimated* phase angle), the phase relationship between the fundamental frequency current and the harmonic currents produced by a nonlinear element must be used. For example, the phase angle of a six–pulse bridge rectifier harmonic h current is given by [7]: $\theta_h = h\theta_1 + \theta_h^{offset}$ where θ_1 is the phase angle of fundamental frequency current and θ_h^{offset} is the predicted theoretical offset for harmonic h also related to transformer connection.

In the sample case shown in Figure 7, two DC–drives are installed at different buses. The total harmonic voltage and current distortions at two locations of the plant were calculated by using the above three phase–angle assumptions and compared with an *Exact* solution obtained with a multiphase harmonic power flow program [5]. The results are shown in Table 2.

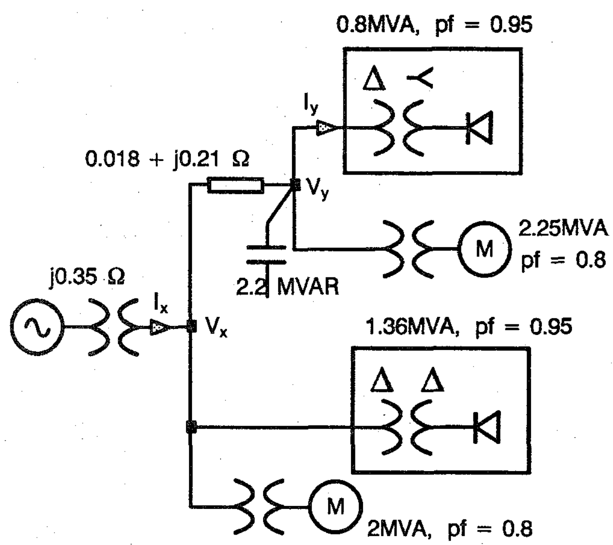

Figure 7 System used to illustrate effects of phase angle assumptions

Table 2 THD (%) as a function of phase angle assumption

Current Voltage	Phase angle: Equal	Worst case	Esti-mated	Exact solution
I_x	9.64	9.75	3.63	3.28
I_y	37.67	37.67	15.45	15.26
V_x	6.48	6.74	3.44	2.56
V_y	12.10	12.10	3.88	3.84

Voltage distortion and the current source model

When a current source model is used instead of an *Exact* solution, the typical harmonic current spectra are determined by assuming that the terminal voltage has little harmonic distortion. Therefore, the current values may not be correct for buses where the voltage distortion is significant. The most common causes of significant voltage distortion are harmonic voltage resonance, excessive harmonic injections from other sources, and non–ideal conditions.

To determine if the current source model is adequate, a preliminary analysis can be performed by using the current source model. If the results indicate significant harmonic voltage distortion (much more than IEEE–519 voltage distortion limits) at the buses where the harmonic current sources are connected, the current source models must be used very carefully. For power convertor devices, a 5–10% total harmonic voltage distortion can be considered high and, as a result, detailed modeling and formal harmonic power flow studies are warranted.

Typical non–ideal conditions are unbalance and/or harmonic distortion in the supply system and parameter deviations of the harmonic–producing element. If the effects of these non–ideal conditions are of concern, the current source model is no longer useful. In such cases, a three–phase harmonic analysis with iterative improvement of the current source model is necessary. Detailed time–domain analysis is applied in the ultimate case.

Extent of Network Modeling

The size of the system equivalent has to be determined when modeling harmonic propagation in large scale networks. As in any other equivalencing process two questions must be asked: which system elements should be retained and how is the remainder of the network to be represented. These questions can only be addressed properly through a sensitivity study.

In an industrial facility it is common to represent the utility source by its short–circuit impedance. If two systems are coupled at a single point a representation of the *external* network can be developed rather easily from a knowledge of the short–circuit capacity or from a frequency scan of this network. More generally it appears common to represent the *external* network at least five buses and two transformations back from the point of interest. In particular, buses with significant levels of capacitive compensation should be modeled. On the other hand, a logical place to truncate or equivalence the model is in the vicinity of large generating plants which serve as sinks due to their relatively low subtransient impedance. The balance of the system can be represented at boundary buses by a short–circuit equivalent. This equivalent ignores the potentially beneficial effects of damping due to load in the equivalenced system as well as the detrimental effects of resonances in the equivalenced system. While the ideas above will often yield a useful model, such equivalents should always be examined through a sensitivity study. The frequency scan technique can be used for this purpose as illustrated in the following case studies.

The limitations of the frequency scan technique should be kept in mind.

Case 1 : This case involves the modeling of a network external to the NYPP system with respect to a bus called Fraser. The study was performed before an SVC was specified for this bus. Two different size equivalents of the NYPP system were studied. The first model includes the NYPP system up to 3 buses away from the Fraser 345 kV bus with equivalents beyond. The main network parameters for this model are: 56 transmission lines, 66 single phase transformers, 9 three–phase capacitor banks, 25 three–phase source equivalents, 3 current sources. The harmonic model consists of 222 buses and 192 nodes. The second model is an extended version of the first. It includes the NYPP system up to 5 buses away from the Fraser 345 kV bus and consists of 68 transmission lines, 81 single phase transformers, 9 three–phase capacitor banks, 44 three–phase source equivalents, 3 current sources. Overall, the second equivalent consists of 294 buses and 238 nodes.

Impedance versus frequency plots at Fraser for phases a, b and c are shown in Figures 8a and 8b, for configurations 3 and 5 buses away from Fraser, respectively. Frequency scans were performed with a 10 Hz frequency step. Comparing these figures, it is seen that the reduced model is sufficient for determining qualitatively system resonant frequencies, e.g., 4th, 5th, etc. The resonant frequencies around 4th and 5th harmonics and corresponding impedance magnitudes are shown in Table 3. These values are somewhat different from the values shown in Figure 8, because they were obtained using a frequency step of 1 Hz. A considerable difference in impedance magnitudes is noticed between the two models, the reduced model giving 25–60% larger impedances in general. It can be concluded that a reduced system model may be used to make a frequency scan over a wide frequency range to determine resonant frequencies. An extended system model, as seen from the bus of interest, is needed for studying in detail harmonic impedances and voltages around the resonant frequencies.

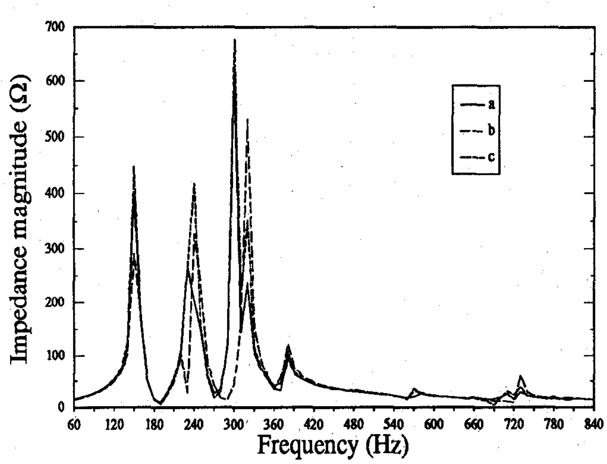

Figure 8a Driving point impedance at Fraser, NYPP system modeled 3 buses away from Fraser

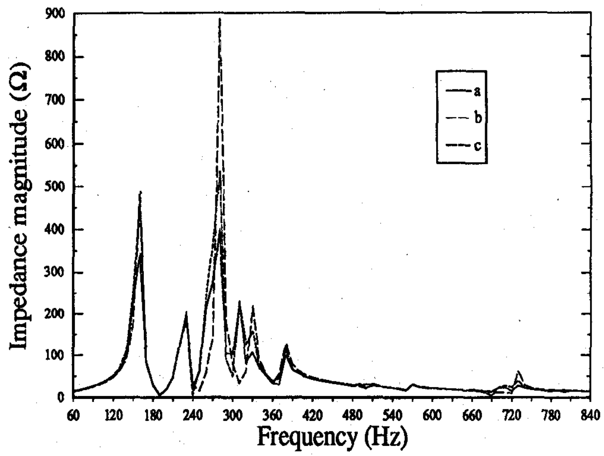

Figure 8b Driving point impedance at Fraser, NYPP system modeled 5 buses away from Fraser

Table 3 Positive sequence driving point impedances at Fraser

Harm Order		3 bus external system Ph. a	Ph. b	Ph. c	5 bus external system Ph. a	Ph. b	Ph. c
4	Z (Ω)	804	864	1018	649	550	475
	f (Hz)	235	244	235	227	226	227
5	Z (Ω)	665	688	729	405	885	536
	f (Hz)	299	318	299	281	280	280

Case 2 : This case involves a study of the effects of a 200 MW HVDC Tie in a 230 kV network. The network consists of 200 buses ranging in voltage from 69 to 230 kV, 170 transmission lines, 120 load buses and 24 generators. Figure 9 shows the positive sequence driving point impedance at the HVDC bus as a function of model size. Each successively larger system representation is terminated at the boundary with approximate short–circuit impedances. As the bus count increases these boundary equivalents are further and further away form the HVDC station. At 110 buses a very large generation site, with multiple machines, is explicitly represented in the system. Additional detail beyond this point does not significantly alter the driving point impedance. In this case the 110 bus model is found to be acceptable.

This case study illustrates the risk of an inadequate extent of network modeling. Had the 20–bus representation been used the analysis would have incorrectly shown resonances at the fifth and twelfth, rather than the sixth and the thirteenth. This is significant since the thirteenth and some fifth harmonic injection is expected from the HVDC system.

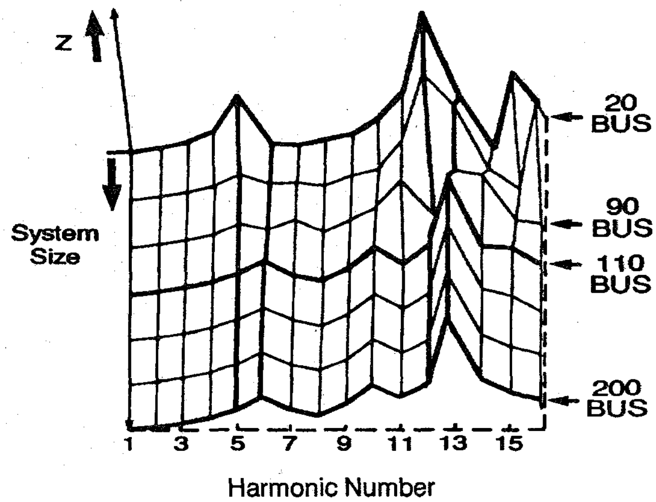

Figure 9 Sensitivity study of a 200 bus system : Driving point positive sequence impedance vs harmonic order and system size

VI. CONCLUSION AND FUTURE RESEARCH NEEDS

Engineering analysis often follows a trend in which initially isolated problems are analyzed using simplified and empirical methods. As the appreciation of problems increases, rapid development of theoretical ideas occurs and quickly outpaces the availability of data that is necessary for their use. The area of harmonic modeling and simulation appears to be at such a stage.

The domain of harmonic propagation studies used to be in HVDC and SVC systems, and power factor correction in industrial plants in the presence of converter based motor drives. It is now anticipated that harmonic injection into conventional power systems will increase significantly. Therefore, the scope of harmonic studies has broadened to include transmission, subtransmission, distribution and industrial systems.

It is expected that algorithmic and modeling improvements in computer programs will result in even more efficient, comprehensive, and easy–to–use tools. Research in these areas is always important. However, in many respects harmonic modeling and simulation still remains an art.

The first problem area deals with modeling of aggregate harmonic sources such as found on distribution systems. There is evidence that actual harmonic levels are substantially lower than what one would project based on equipment inventory. Secondly there is much more variation in such sources as compared to the very well defined nature of HVDC systems or converter based drives. An associated problem is the time variation of these sources.

The second area of research needs deals with modelling of the loads and their effect on system frequency response. Loads are largely isolated from EHV transmission due to several intervening levels of voltage transformation. Further, harmonic sources at the transmission level or at the plant level involve equipment that is critical and warrants *Worst case* analysis. At subtransmission and, particularly, distribution levels, neither observation is applicable. The modeling of loads is therefore suggested as an important area of research.

Finally, as the proliferation of distorting sources increases it is to be realized that a number of sources exist that cannot be described by the techniques discussed herein. Additional research and typical data cases are needed for distortion sources at *non–harmonic* frequencies.

There is an increasing overlap between harmonic propagation studies and studies that fall under the umbrella of power quality. The research needs for power quality are identified in [6].

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APPENDIX A
TEST SYSTEM: MODIFIED IEEE 14–BUS SYSTEM

The standard IEEE 14–bus system is modified by replacing the 91 MW load at bus 3 (Figure A1) with a 100 MW dc terminal and by replacing the condenser at bus 8 by an SVS.

Data for the HVDC terminal :

- the converter configuration is shown in Fig. A2
- transformer : 135 MVA,
  230 kV – 35.42 kV – 35.42 kV wye–wye–delta,
  X = 2.8%

- the filter $\mathcal{F}$ is an assembly of two identical damped filters with $C = 1.25\,\mu F$, $L = 39\,mH$ and $R = 300\,\Omega$
- the converter delivers 100 MW at 83.3 kV on dc side
- the dc side is modelled as a fixed current source according to the controlled angle α

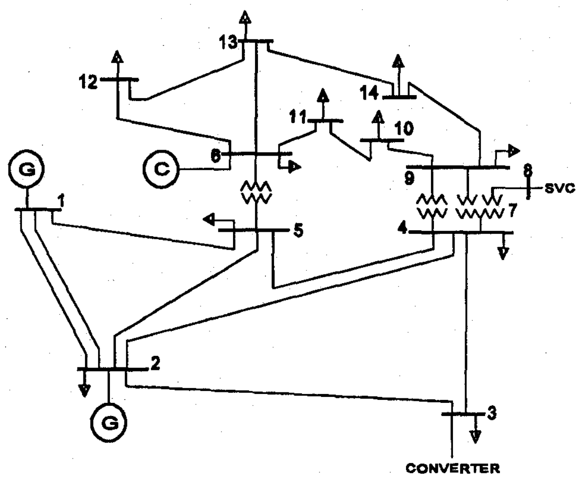

Figure A1 Single–line diagram of IEEE 14–bus balanced system

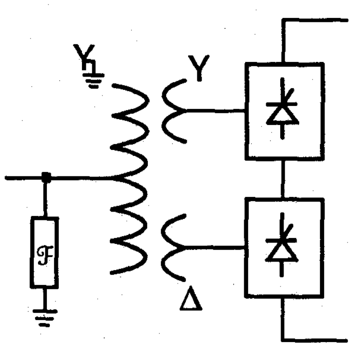

Figure A2 HVDC converter at Bus 3 of Fig. A1

Data for the SVS :

- the SVS configuration is shown in Fig. A3
- transformer : 230 kV – 115 kV – 13.8 kV auto delta–tertiary; SVC and filters on tertiary
- delta TCR with L = 48 mH
- the SVC provides 10 MVAR
- the filters are listed in Table A1

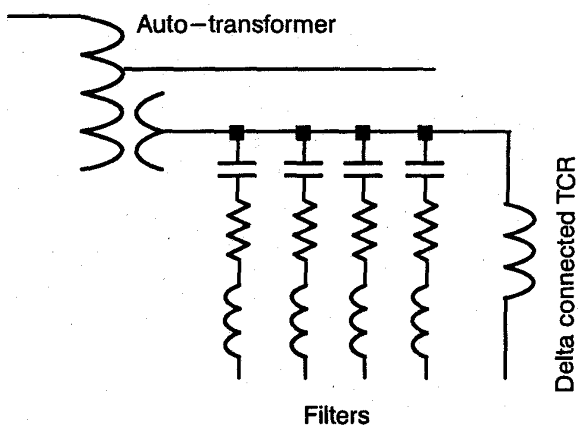

Figure A3 The Static Var System at bus 8 of FIg. A1

Table A1 SVS Filters

Harmonic	R (Ω)	L (mH)	C (μF)
2	1	42	42
5	1	6.7	42
7	1	3.4	42
11	1	1.39	42

APPENDIX B
TEST SYSTEM: MODIFIED 13–BUS DISTRIBUTION SYSTEM

The basic topology of the IEEE 13–bus test system [4] is shown in Fig. B1. The node numbers are shown within circles representing buses. The injected harmonic current source spectra is shown in Table B1. Load data is given in Table B2 and is linked to the node numbers in Fig. B1. The only modification is the specification of load composition in terms of harmonic producing loads. All loads are taken to be spot loads. The motor at bus 34 is a 500 HP three–phase induction motor with running power factor 0.8, efficiency 90%; locked rotor 3000 kVA at 0.4 lag power factor.

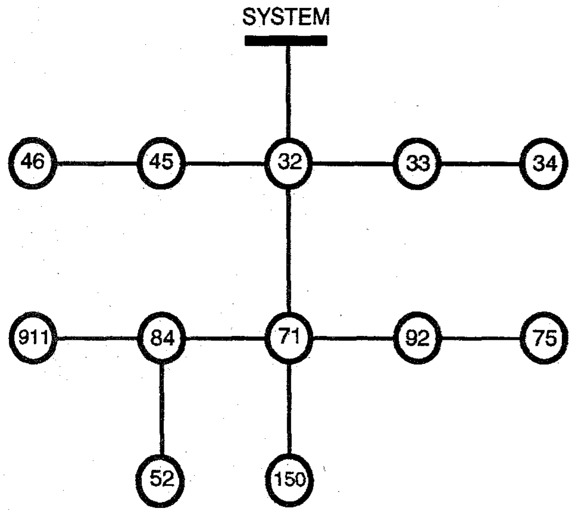

Figure B1 Single–line diagram of the IEEE 13–bus distribution system

Table B1 Harmonic current magnitude as % of fundamental and Phase angles with respect to voltage

	Harmonic source type					
	ASD		Fluorescent		Non–specific	
Harm Order	Mag (%)	Phase (°)	Mag (%)	Phase (°)	Mag (%)	Phase (°)
1	100	−1.45	100	−107	100	105.5
3	84.6	−8.34	19.2	76	3.6	−44.4
5	68.3	−14.23	10.7	10	3.2	139.4
7	47.8	−20.13	2.1	37		
9	27.7	−29.02	1.4	31		
11	0.2	−27.91	0.9	36		
13	6.1	158.2	0.6	47		
15	4.2	122.3	0.5	20		

Table B2 Load Data

node	kW A	kVAR A	kW B	kVAR B	kW C	kVAR C
34	42.63 Motors Passive	15 60% 40%				
45			170.53 Motors Fluo. Passive Other	54 20% 20% 40% 20%		
46					230 Motors Fluo. Passive Other	73 20% 20% 40% 20%
52	127.9 Motors Passive Fluo. ASD	55.79 20% 60% 10% 10%				
71	383.7 Motors Fluo. Passive	140.95 60% 30% 10%	383.7	140.95 60% 30% 10%	383.7	140.95 60% 30% 10%
75	486.02 Motors Fluo. Passive Other	189.07 15% 15% 50% 20%	68.21	60.55 15% 15% 50% 20%	289.91	212.65 15% 15% 50% 20%
92					170.53 Motors Fluo. Passive Other	51.38 15% 15% 50% 20%
911					170 Motors Fluo. Passive Other	45 15% 15% 50% 20%

Discussion

[For a discussion of this paper and the companion paper "Modeling and Simulation of the Propagation of Harmonics in Electric Power Networks, Part I: Concepts, Models, and Simulation Techniques" (95 WM 264-2 PWRD) see pp. 461-465.]