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

PART I : CONCEPTS, MODELS, AND SIMULATION TECHNIQUES

Task Force on Harmonics Modeling and Simulation*

Abstract: *This two-part report presents a review of the modeling and analysis of harmonic propagation in electric power systems, along with practical considerations and sample case studies. Part I of the report concentrates on the theoretical aspects of harmonics modeling and simulation. Concepts and characteristics of power system harmonics, modeling of harmonic sources and network components, and techniques for network-wide harmonic analysis are discussed.*

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 and electronically switched loads will distort steady state ac voltage and current waveforms. Periodically distorted waveforms can be studied by examining the harmonic components of the waveforms. Power system harmonic analysis investigates the generation and propagation of these components throughout the system.

Harmonic studies have become an important component of power system analysis and design [1,2]. They are used to quantify the distortion in voltage and current waveforms at various points in a power system and to determine whether dangerous resonant conditions exist and how they might be mitigated. Such studies are important because the presence of harmonic producing equipment is increasing. As harmonics propagate through the system they result in increased losses and possible equipment loss-of-life. Equipment can be damaged by overcurrents or overvoltages resulting from resonances. Additionally, harmonics can interfere with control, communication, and protective equipment [3]. The current emphasis on power quality [4] has reinforced the need for harmonic studies as a standard component of power system analysis and design activities.

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Interest in the analysis of harmonics and their effects dates back to the early 1900s. Subsequent harmonic modeling and analysis techniques were specialized to meet the requirements of High Voltage Direct Current (HVDC) systems and Static Var Compensators (SVC). Since the early seventies, the subject of power system harmonics has gained increasing attention due to the wide-spread use of static power converters [5]. Research in this area began to focus on the assessment of network-wide harmonic power flow. This led to the availability of fairly general techniques and software for the formulations and solutions of harmonic propagation problems. An example is the work of reference [6]. The work also spurred advances in the modeling of network components and in the collection of field experience.

The purpose of this as well as the companion report is to provide a concise review of the modeling and analysis of harmonic propagation in ac power networks, along with practical considerations and sample case studies. The first part of the report concentrates on the theoretical aspects of harmonics modeling and simulation. Section II provides a brief review of some fundamental concepts. Section III presents general goals, formulation and solution of the harmonic propagation problem. The modeling of harmonics sources and network components is discussed in Sections IV and V, respectively. It is hoped that readers, through the discussion process, will bring to light any references or techniques that may have been omitted.

II. CONCEPT OF POWER SYSTEM HARMONICS

Nonlinear and switched loads and sources can cause distortion of the normal sinusoidal current and voltage waveform in an ac power system. In this section, basic definitions and concepts associated with the analysis of *periodic steady state waveform distortion* are discussed.

Fourier Series and Harmonics: Under periodic steady state conditions, distorted voltage and current waveforms can be expressed in the form of a Fourier Series. The Fourier series for a periodic function f(t) with fundamental frequency ω can be presented as:

$$f(t) = C_0 + \sum_{n=1}^{\infty} C_n \cos(n\omega t+\theta_n) \tag{1}$$

The coefficients C_n and phase angles θ_n for n-th harmonic are given by:

$$C_n=\sqrt{A_n^2+B_n^2} \qquad \theta_n=\tan^{-1}(-B_n/A_n) \tag{2}$$

where $T=2\pi/\omega$ and C_0 is the dc component of the function. The rms value of f(t) is defined as:

$$A_n = \frac{2}{T}\int_0^T f(t)\cos(n\omega t)dt \qquad B_n = \frac{2}{T}\int_0^T f(t)\sin(n\omega t)dt \quad (3)$$

$$C_0 = \frac{1}{T}\int_0^T f(t)dt \quad (4)$$

$$RMS = \sqrt{C_0^2 + \sum_{n=1}^{\infty}\left(\frac{C_n}{\sqrt{2}}\right)^2} \quad (5)$$

In general, one can think of devices that produce distortion as exhibiting a nonlinear relationship between voltage and current. Such nonlinear relationships can lead to several forms of distortion as summarized below:

- A periodic steady state exists and the distorted waveform can be expressed as a Fourier series with a fundamental frequency equal to the power frequency.

- A periodic steady state exists and the distorted waveform can be expressed as a Fourier series with fundamental frequency that is a submultiple of power frequency.

- The waveform is aperiodic but perhaps almost periodic. A trigonometric series expansion may still exist (as an exact representation or as an approximation) [7].

The first case is commonly encountered in harmonic studies. There are several advantages to decomposing waveforms in terms of harmonics. Harmonics have a physical interpretation and an intuitive appeal. As discussed later, the transmission network is usually modeled as a *linear* system. Thus the propagation of each harmonic can be studied independent of others in the frequency domain. Generally, the number of harmonics to be considered is small which simplifies computation. Consequences such as losses can be related to harmonic components and measures of waveform quality can be developed in terms of harmonic amplitudes.

Certain types of pulsed or modulated loads and integral cycle controllers can create waveforms corresponding to the second category. The Fourier representation, when applicable, can be advantageous for the reasons cited above and measures of waveform quality can be adapted to such systems, although standards do not yet exist.

Some practical situations correspond to the third case. For example, dc arc furnaces consist of a conventional rectifier input but the underlying process of melting is not a periodic process. When reference is made to harmonics in this instance it corresponds to the periodic waveform that would be obtained if furnace conditions were to be maintained constant over a period of time. While such modeling obviously does not predict the exact response, it can, to a certain extent, lend insight into some of the potential problems caused by the distortion producing devices.

Origin of Harmonics: There are two main sources of harmonics in conventional power systems:

1. Devices involving electronic switching: Static power converters are a typical example of such devices. The switching process is generally synchronized to 60 Hz and causes distortion on the switched waveforms. The distortion can be studied by the Fourier Series method.

2. Devices with nonlinear voltage and current relationships: Iron-core reactors are a typical example of such devices. When excited with a periodic voltage input, the nonlinear v-i relationship leads to the production of harmonic currents. Devices such as arc-furnaces also fall into this category.

Distortion Indices: The most commonly used measure of deviation of a periodic waveform from a sinewave is called total harmonic distortion (THD) or distortion factor.

$$THD = \frac{1}{C_1}\sqrt{\sum_{n=2}^{\infty} C_n^2} \quad (6)$$

The term distortion factor is more appropriate when the summation in the equation above is taken over a selected number of harmonics. IEEE Std. 519 [1], specifies limits on voltage and current THD for 'Low Voltage, General Distribution, General Subtransmission, and High Voltage systems and Dispersed Generation and Cogeneration'.

Several other distortion indices are defined [1], each intended to capture a specific impact of harmonics. Telephone Influence Factor (TIF), the C-message weighted indices, and the V•T and I•T products are used to measure telephone interference. These indices have been revised by some utilities to reflect modern telephone cable design, changes in the coupling mechanism, and the response of modern receiving sets. The K-factor index is used to describe the impact of harmonics on losses and is useful in derating equipment such as transformers [8]. Most harmonic analysis programs calculate and report these indices.

Power Definitions[9]: Consider a two terminal device with voltage v(t) and current i(t), both of which are assumed periodic and given by the Fourier series

$$i(t) = \sum_{n=1}^{\infty}\sqrt{2}I_n\cos(n\omega t+\theta_{in}) \qquad v(t) = \sum_{n=1}^{\infty}\sqrt{2}V_n\cos(n\omega t+\theta_{vn}) \quad (7)$$

The dc terms have been omitted for convenience. The instantaneous power p(t) delivered to the device is then given by:

$$p(t) = v(t)\,i(t) \quad (8)$$

and contains oscillatory components at frequencies that are the sum and differences of the harmonic frequencies in v(t) and i(t). The real or active power represents the average power delivered to the device in the steady state and can be shown to be

$$P = \frac{1}{T}\int_0^T p\,(t)dt = \sum_{n=1}^{\infty} V_n I_n \cos(\theta_{vn}-\theta_{in}) \tag{9}$$

In analogy with linear circuits with purely sinusoidal excitation it is common to define the reactive power as:

$$Q=\sum_{n=1}^{\infty} V_n I_n \sin(\theta_{vn}-\theta_{in}) \tag{10}$$

The volt-amperes in the device can be defined as:

$$S = \sqrt{\sum_{n=1}^{\infty} V_n^2 I_n^2} \tag{11}$$

Furthermore, we have an additional term, D, distortion volt-amperes, in the power triangle:

$$S^2 = P^2 + Q^2 + D^2 \tag{12}$$

D accounts for the cross-frequency terms inherent in (11).

These definitions are used in power calculations and also in the formulation of some harmonic analysis methods. Various alternative definitions and interpretations have been forwarded and the reader is referred to [10] for more detailed discussions.

Characteristics of Harmonics in Power Systems: Most devices operate in an identical manner in the positive and negative half cycle, thus eliminating even order harmonics.

In balanced three-phase systems, under balanced operating conditions, harmonics in each phase have specific phase relationships. For example, in the case of the third harmonic, phase b currents would lag those in phase a by 3x120° or 360°, and those in phase c would lead by the same amount. Thus, the third harmonics are in phase and appear as zero-sequence components. As such, in a grounded wye system these harmonics flow in the lines and neutral/ground circuits, while in delta or ungrounded systems they cannot exist in line current at all. Similar analysis shows that fifth harmonics appear to be of negative sequence, seventh are of positive sequence, etc. Therefore, the impedances and manner of connection of rotating machines, transmission lines, and transformers must be modeled carefully for each harmonic. The harmonics produced by many devices, particularly solid-state power converters are well-defined 'characteristic harmonics'. An ideal, p-pulse, line-commutated, converter, for example, produces ac side harmonic currents of order $np \pm 1$, n=1,2,3....

The interpretations discussed above do not apply to the unbalanced cases. When supplied with unbalanced voltage, most three-phase power electronic converters can generate noncharacteristic harmonics. In many cases, the three-phase harmonics do not follow the sequence order of the balanced cases. Furthermore, the nature of some harmonic problems requires the assessment of unbalanced harmonics. For example, zero sequence harmonic currents generally cause much more interference with telephone circuits than positive or negative sequence harmonics. Systems with unbalanced loads and components need to be studied using a three-phase model with proper representation of neutral and ground circuits.

III. TECHNIQUES FOR HARMONIC ANALYSIS

This section reviews the techniques presently being used for power system harmonic analysis. These techniques vary in terms of data requirements, modeling complexity, problem formulation and solution algorithms. New methods are being developed and published.

Frequency scan is the simplest and most commonly used technique for harmonic analysis [11]. The input data requirements are minimized. It calculates the frequency response of a network seen at a particular bus or node. Typically, a 1 per unit sinusoidal current (or voltage) is injected into the bus of interest and the voltage (or current) response is calculated. This calculation is repeated using discrete frequency steps throughout the range of interest. Mathematically, the process is to solve the following network equation at frequency $n \cdot f_o$:

$$[Y_n][V_n]=[I_n] \tag{13}$$

where $[I_n]$ is the known current vector (for current injection scan) and $[V_n]$ is the nodal voltage vector to be solved. In a typical frequency scan analysis, only one entry of $[I_n]$ is nonzero. In other analysis, a set of positive or zero sequence currents may be injected into three phases of a bus respectively. The results are the positive or zero sequence driving-point impedance of the network. Frequency scan analysis is the most effective tool to detect harmonic resonance conditions in a system. It has also been widely used for filter design.

If more data are available on the harmonic source characteristics, the frequency scan analysis can be expanded to determine additional harmonic distortion information. For example, the 1 per unit injection current can be replaced by a specific harmonic current. The current has a magnitude determined from the typical harmonic spectrum and rated load current of the harmonic-producing equipment under study:

$$I_n = I_{rated}\frac{I_{n-spectrum}}{I_{1-spectrum}} \tag{14}$$

where n is the harmonic order and the subscript 'spectrum' indicates the typical harmonic spectrum of the element. Typical spectrums of some harmonic sources can be found in a number references such as reference [1]. Eq.(13) is then solved only at harmonic frequencies. The results are the harmonic voltages created by the harmonic-producing equipment. To compute the distortion indices such as THD, the nominal bus voltage at fundamental frequency is used. This approach has been extended to cases with multiple harmonic sources in some harmonic analysis programs. The extension, however, is approximate if the phase angles of the injection currents are set arbitrarily. Depending on the phase angles used, the effects of two harmonic sources seen at a particular bus can either add or cancel. The results can be either pessimistic or optimistic.

A fundamental frequency load flow solution is needed to extend the above approach to accurately model multiple harmonic sources. Typical phase relationships between the fundamental frequency current and the harmonic currents of the nonlinear element must be available as well. The load flow, modeling the harmonic-producing devices as constant power loads, calculates the fundamental frequency current injected from the load to the system. Assuming that the current has a phase angle of θ_1, the phase angle of harmonic current θ_n corresponding to that nonlinear element can be determined by:

$$\theta_n = \theta_{n-spectrum} + n\ (\theta_1 - \theta_{1-spectrum}) \tag{15}$$

where $\theta_{n\text{-spectrum}}$ is the typical phase angle of the harmonic source current spectrum. This approach is very effective for analyzing power systems with power electronic devices. The fundamental frequency load flow solution is also beneficial for providing more accurate information such as base voltages that can be used for distortion index calculations. The magnitudes of harmonic current sources tend to be more accurate as well since the load flow dependent base current, not the rated current, is used to determine the harmonic current magnitudes. Data requirements for this type of analysis can normally be met.

The main disadvantage of these methods is the use of typical harmonic spectra to represent harmonic-producing devices. This prevents an adequate assessment of cases involving non-typical operating conditions. Such conditions include, for example, partial loading of harmonic-producing devices, excessive harmonic voltage distortions and unbalanced network conditions. Even under typical conditions, the voltage-dependent harmonic-producing nature of nonlinear devices may make the accuracy of typical spectrum based methods unacceptable. For some devices with nonlinear v-i relationships, the voltage-dependency is so strong that no typical spectra exist. These considerations promoted the development of a number of advanced harmonic analysis methods.

One of the well-known methods is the so-called 'harmonic iteration' method [12,13,14]. In this method, a harmonic-producing device is modeled as a supply voltage-dependent current source:

$$I_n = F(V_1,\ V_2,\ \ldots\ V_H,\ c) \qquad n=1...H \tag{16}$$

where (V_1 ... V_H) are the harmonic phasors of the supply voltage, and c is a set of control variables such as converter firing angle or output power. This equation is first solved using an estimated supply voltage. The results are used as the current sources in Eq.(13) from which bus harmonic voltages are then solved (for the fundamental frequency, load flow equations can be used). The voltages are in turn used to calculate more accurate harmonic current sources from Eq.(16). This iterative process is repeated until convergence is achieved. One of the main advantages of this 'decoupled' approach is that the device model can be in a closed form, a time-domain simulation process, or any other form. Reliable convergence has been reported in many case studies, although difficulties occur near sharply tuned resonances. Convergence can be improved by including the equivalent admittance of nonlinear devices into the admittance matrix Eq.(13) [13].

Another method that takes into account the voltage-dependent nature of nonlinear devices is to solve system Eq.(13) and device Eq.(16) *simultaneously* using Newton type algorithms [6,15,16]. This method generally requires that the device models be available in a closed form or in a form wherein derivatives can be efficiently computed. In theory, convergence of this method is better than that of the harmonic iteration scheme if the iteration starting point is close to the solution point. A variation of this method is the formulation of the system equation. In reference [6], Eq.(13) is formulated as a power flow equation and the control variables (firing angles) are solved based on the converter power specifications.

The various methods above have been extended to the case of unbalanced three-phase systems by recasting the system equation and the device equations in the multi-phase domain [13,17,18]. A multiphase (or three-phase) approach to harmonic analysis has some advantages. First is the modeling of zero-sequence harmonic flows. Even under balanced conditions, some harmonic-producing equipment such as three-phase transformers can generate zero sequence harmonics. Second is the capability of assessing the generation of non-characteristic harmonics. These harmonics, generated under unbalanced conditions, can be harmful since mitigation measures are normally not designed for them. Furthermore, three-phase modelling can easily represent the phase-shifting effects of transformers on harmonics.

Besides the frequency-domain methods described above, techniques have also been developed for harmonic analysis in the time-domain [19]. The simplest approach is to run a time simulation until a steady state is reached. Electromagnetic transient programs such as EMTP [20] have been used as such a tool. Complex techniques, such as the shooting method [21], have been proposed to accelerate the convergence to steady state. One of the main disadvantages of time-domain based methods is the lack of load flow constraints (such as constant power specification at load buses) at the fundamental frequency.

In summary, the problem of harmonic analysis can be cast mathematically as the solution of a network equation and a set of device equations at fundamental and harmonic frequencies. The network equation can be formulated in an admittance matrix form or in a power flow equation form. The device equations can be as simple as known current sources or as complex as control-variable dependent circuits. Which technique to use for a particular harmonic problem is, to a large extent, determined by the available data. An important consideration in harmonic analysis is to use a method commensurate with input data accuracy.

It is appropriate to note that a large number of harmonics related problems encountered in practice need to be analyzed by a combination of the various methods. Measurements may also be an essential component in the analysis. For example, a frequency scan is often used to determine the resonance frequencies and desirable filter responses, while harmonic power flow solutions are applied to determine distortion levels and to check compliance with harmonic limits. For cases with only one harmonic source, inclusion of phase angle information is not critical. On the other hand, for the studies of HVDC/SVC systems or saturation of large power transformers with direct current offset, three-phase harmonic power flow analysis may be used.

IV. NATURE AND MODELING OF HARMONIC SOURCES

Nonlinear Voltage-Current Sources: The most common sources in this category are transformers (due to their nonlinear magnetization characteristics), fluorescent and other gas discharge lighting, and devices such as arc-furnaces. In all cases there exists a *nonlinear* relationship between the voltage and current. For devices such as core-and-coil ballasted fluorescent lights, the relationship can be relatively constant over a reasonable range of excitation. In the case of transformers, on the other hand, it can be very complex if hysteresis characteristics of the magnetic materials are considered. In the case of arc-furnaces the voltage-current relationship has both a time-dependent variation depending on the stage of melt as well as a random variation.

The harmonic currents generated by these devices are more affected by the waveforms and peak values of supply voltages than electronic switching devices. It is desirable to represent the devices with their actual nonlinear v-i characteristics in harmonic studies, instead of as voltage independent harmonic current sources. Both harmonic iteration and Newton methods have been proposed to more accurately model these devices [22].

Line-Commutated Solid State Converters: By line-commutated solid-state converters we mean electronic power converters supplied from the ac system in which the switching of devices is synchronized to zero-crossings of the ac voltage or its fundamental component. Generally a periodic steady state exists. Under ideal conditions devices switch in an identical manner in the positive and negative half-cycles and thus only odd-harmonic components exist. Compared to the nonlinear v-i devices, harmonic currents generated from converters are less sensitive to supply voltage distortion. Harmonic current source models are therefore commonly used to represent these devices. As discussed before, the phase angles of the current sources are functions of the supply voltage phase angle. They must be modeled adequately for harmonic analysis involving more than one source. Typical devices utilizing line-commutated solid state converters include static var compensator, HVDC link and dc drives.

Static Var Compensators (SVC): These devices normally have large MVar ratings and are connected to high voltage transmission systems. Harmonic currents generated from SVCs may therefore affect a large number of customers and equipment [23]. Common SVC-related harmonic studies tend to represent the device in detail. Factors such as firing-angle dependent harmonic generation and supply voltage unbalance are taken into account. These studies normally scan through various possible SVC operating conditions and filter performance under each condition is evaluated.

Three-Phase Static Power Converters: The most common form of static power converters is the six-pulse bridge rectifier type. It is widely used as the front end for HVDC terminals, dc drives and adjustable speed drives. The nature of the bridge connection precludes the generation of zero sequence harmonics from the converter, even when the supply voltage is unbalanced or distorted. Several six-pulse converters may be connected in a multipulse form which allows elimination of several harmonics. The harmonic current spectrum is moderately sensitive to the converter firing angle.

Although equipped with a similar bridge converter front-end, harmonic currents generated by HVDC terminals, dc drives and adjustable speed drives differ significantly. This is due to the different dc link designs. In the case of HVDC [24], sufficient dc link filters are available to filter out the dc link current ripples. Therefore, the waveforms of HVDC ac side current are very close to the well-known rectangular shape. In the case of dc drives, however, dc link filters are normally not present and the dc motor inductance is used for current smoothing [25]. Thus the dc drive current contains higher harmonic components. Most adjustable speed drives (the voltage-source inverter and pulse-width modulated types in particular) have a large capacitor in the dc link [26]. This capacitor amplifies the dc link (converter side) current ripple. As a result, the ac side current has higher harmonic levels (Figure 1).

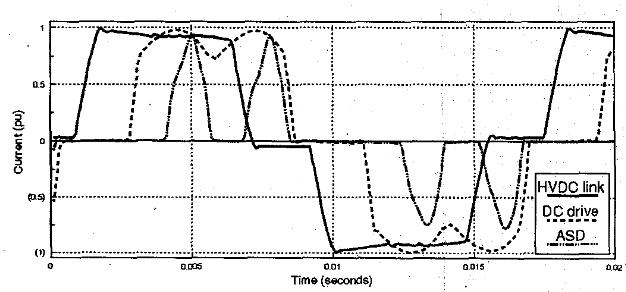

Figure 1: Typical current waveforms of 6-pulse HVDC links, dc drives and adjustable speed drives.

Single-Phase Static Power Converters: These converters are commonly found in electronic equipment (computers and TVs), small adjustable speed drives and others. The most common single phase power supply consists of a capacitively filtered rectifier followed by different types of regulating stages. Such a supply draws pulses of current corresponding to periods of time in each half-cycle where the line voltage exceeds the capacitor voltage. The spectrum consists of all odd harmonics with magnitudes depending on the shape of the pulse [1].

Theoretically speaking, these devices can be represented individually in network-wide harmonic studies as harmonic current sources. The problem is that there exist a number of such devices in a typical system and detailed studies using harmonic power flow programs becomes impractical. What really is of concern in distribution system harmonic analysis is the collective effects of such devices [27].

High Frequency Sources: Advances in power electronic devices have created the potential for a wide range of new power conversion techniques. The electronic ballast for fluorescent lighting is included in this category [28]. Other possibilities include techniques for improving current waveshape and power factor, minimizing filter requirements, and minimizing switching losses. In general, these systems employ high frequency switching to achieve greater flexibility in the power conversion. With proper design, these techniques can be used to reduce the low frequency harmonics. Distortion is created at the switching frequency which is generally above 20 kHz. Due to its high frequency, the distortion generally cannot penetrate far into the system.

Non-Harmonic Sources: There exist several power electronic systems which produce distortion at frequencies that are not integer multiples of the fundamental frequency. There are also devices whose (aperiodic) waveforms do not have a Fourier series representation. Lacking standard terminology, we will call these non-harmonic sources. These sources are discussed here for completeness.

Cycloconverters: Cycloconverters use static switches to convert a constant frequency fixed voltage source of ac power to a variable, lower frequency, controlled voltage output. Typical current drawn by the devices consists of a few periodic components whose frequencies are lower than the source frequency. Reference [29] describes a three-phase 60 Hz to single-phase 25 Hz cycloconverter for a traction system. The distortion frequencies for this converter include:

$$f_c = | f_i \pm 2nf_0 | , n= 1,2,3,... \tag{17}$$

where f_i is the input frequency, f_0 is the output frequency, and f_c is the distortion frequency. This converter, having a fixed output frequency, produces distortion at fixed frequencies.

Doubly Fed Machine Drives: Doubly fed machines are a class of wound rotor induction machines in which, typically, the stator is fed from the utility supply, while the rotor is fed by a variable voltage, lower power, variable frequency electronic source. In these machines, the rotor currents will be of the slip frequency. With electronic converters supplying the rotor windings, the winding currents will carry harmonics of the slip frequency. These will be coupled through the air gap to the stator, causing currents in the stator winding at frequencies which are not harmonics of the stator frequency. This application is more difficult to study due to the fact that the frequency of these currents resulting from slip frequency harmonics will vary with the rotor speed. Therefore a system resonance at any frequency will be excited for some particular operating speed [30].

Adjustable Speed Drives: Adjustable speed drives may also inject non-harmonic currents back into the power system. The magnitude of these currents will depend on the design of the ASD. Reference [33] reports harmonic currents of low magnitude at the frequencies $f=6f_i \pm f_o$, where f_i is the inverter frequency and f_o is the AC system frequency. This reference cites a case study where an ASD excited a resonance at a non-harmonic frequency.

V. MODELS FOR NETWORK COMPONENTS

This section summarizes the typical representations of common network components for harmonic analysis.

Overhead Lines: The modeling of transmission lines and transformers over a wide range of frequencies is relatively well documented in the literature [5]. Typical overhead lines can be modeled by a multiphase coupled equivalent-pi circuit as shown in Figure 2. For balanced harmonic analysis, the model can be further simplified into a single-phase pi-circuit determined from the positive sequence impedance data of the line. The main concerns for modeling overhead lines are:

- The frequency-dependency of the unit-length series impedance. Major causes of the frequency-dependency are the earth return effect and the conductor skin effect.
- The distributed-parameter nature (long-line effects) of the unit-length series impedance and shunt capacitance.

To construct a line model as shown in Figure 2, the unit-length series impedance and shunt admittance parameters are first computed according to the physical arrangement of the line conductors. The series impedance is composed of external and internal impedance. The external impedance is a function of earth return condition and the frequency of interest. This impedance is determined from Carson's formula [32]. The conductor skin effect is important in the calculation of the internal resistance because its increase with frequency can be considerable. Sophisticated skin effects equations [34] are based on Bessel functions and a separate formula [32] must be used for stranded (compared to tubular) conductors for improved accuracy at higher frequencies. Approximate expressions are applied in several programs [34,35]:

$$\frac{R(\omega)}{R_{dc}} = \begin{cases} 0.035M^2+0.938 & M<2.4 \\ 0.35M+0.3 & M\geq 2.4 \end{cases}$$

$$M=0.05012\sqrt{\frac{f\mu_r}{R_{dc}}}$$

where μ_r is the relative permeability of the cylindrical wire, f is the frequency in Hz and R_{dc} is the dc resistance in Ω/km.

After obtaining the unit-length parameters, matrices [Z] and [Y] can be calculated by including or not including the long-line effects. If long-line effects are ignored, which is only applicable to short lines or low order harmonics cases, the [Z] and [Y] matrices are the unit-length parameters multiplied by the line length. If long-line effects are to be included, the [Z] and [Y] matrices should be computed using the well-known hyperbolic long-line equations [20]. For multiphase lines, the equations are in matrix form and are solved using modal transformation [20]. This feature has been built into some harmonic analysis programs. With the same input data, users only need to specify which line model (lumped or distributed parameter models) is to be used.

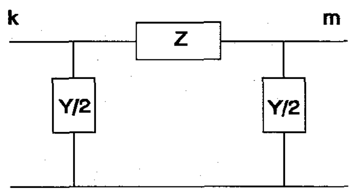

Figure 2: Overhead Line Model.

Some guidelines can be given as to the use of the line models discussed. Inclusion of the frequency-dependent effects requires the calculation of unit-length line constants for each harmonic frequency. This requires much input data for harmonic analysis programs. The earth return effects mainly affect the zero-sequence harmonic components. The conductor skin effects mainly affect the line resistance which in turn affects the damping level at resonance frequencies. Therefore, if zero sequence harmonic penetration and damping at resonance frequencies are not of significant concern, the frequency-dependency effects may be neglected. In this case, a single unit-length [Z] matrix computed at the dominant resonance frequency is adequate.

Whether or not to include the long-line effects depends on the length of the line being modelled and the harmonics of interest. An estimate of critical line lengths where the long-line effects should be represented is 150/n miles, where n is the harmonic number. Finally, reference [31] suggests that for line lengths of 250 km for the third harmonic and 150 km for the fifth, transpositions are ineffective and can aggravate unbalance. Thus three-phase line model should be considered.

Underground cables: Underground cable models are very similar to overhead line models. The long-line effects of underground cables can be represented in the same way as that used for overhead lines. The difficulty for cable modeling is the determination of unit-length parameters for a cable. Reference [20] provides detailed descriptions on the calculation of cable parameters. Cables have more shunt capacitance than overhead lines. Therefore, long-line effects are more significant. An estimate of critical cable lengths where the long-line effects should be represented is 90/n miles.

Transformers: Figure 3 shows one relatively general model for a multi-winding transformer that is adequate for harmonic analysis. The resistance R_m is a constant resistance that accounts for core loss. R_i and L_i represent the winding resistance and leakage inductance, respectively, of winding i. Resistance R_{pi} is used to represent the frequency-dependent characteristics of short-circuit resistance and inductance.

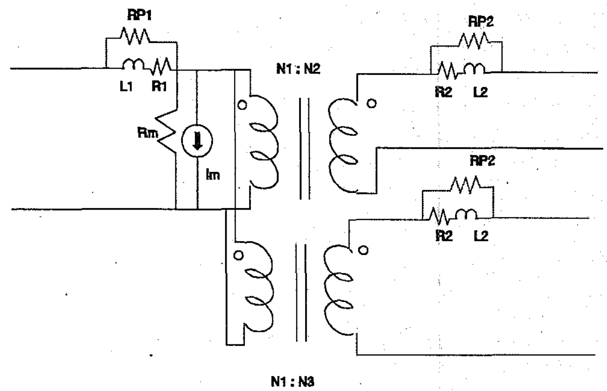

Figure 3: Transformer Model.

The characteristics of a transformer that affect harmonic flows are the short circuit impedance, magnetizing characteristics and winding connections. Although the resistance and inductance components of the transformer short circuit impedance are frequency-dependent, modeling them as constant R and L is generally acceptable for typical harmonic studies. This is because the frequency-dependent effects are not significant for the harmonic frequencies of common interest. The current source in Figure 3 is used to represent the harmonic-generating effects of the magnetizing branch. The value of the current source should be determined from the flux-current curve and the supply voltage. Inclusion of the saturation characteristics are important only when the harmonics generated by the transformer are of primary concern. Exact replication of saturation is virtually impossible due to the complexities of local phenomena in the magnetic core and minor loop hysteresis. If a transformer is subject to a dc current injection, harmonics generated from the magnetizing branch can be significant.

Transformers can give a ±30 degree phase shift to harmonic voltages and currents, depending on the harmonic order, the sequence, and transformer connections. Modeling phase shifting effects is essential if there is more than one harmonic source in the system. Three-phase representations automatically include phase-shifting effects. Single-phase approaches should use a phase-shifter model to represent the effects.

Other factors such as the nonlinear resistance characteristics of the magnetizing branch and winding stray capacitance may also affect the harmonic performance of a transformer. For most transformers, however, the effects of stray capacitance become noticeable only for frequencies higher than 4kHz. Harmonics due to nonlinear resistance is small compared to the nonlinear inductance. Therefore, these effects may need to be considered *only for extreme* conditions or specially-designed transformers.

Rotating Machines: In synchronous and induction machines the rotating magnetic field created by stator harmonics rotates at a speed significantly higher than that of the rotor. Therefore at harmonic frequencies the impedance approaches the negative sequence impedance. In the case of synchronous machines the inductance is usually taken to be either the negative sequence impedance or the average of direct and quadrature subtransient impedances. For induction machines the inductance is taken to be the locked rotor inductance. In each case the frequency-dependency of the resistance can be significant due to skin effects and eddy current losses. The resistance normally increases with frequency in the form of h^a, where h is the harmonic order and a is in the range of 0.5 to 1.5. Figure 4 shows the negative sequence impedance of a 1100 hp synchronous motor as a function of frequency. Most motors are connected in delta or ungrounded star form. These motors do not provide a path for zero sequence harmonic currents.

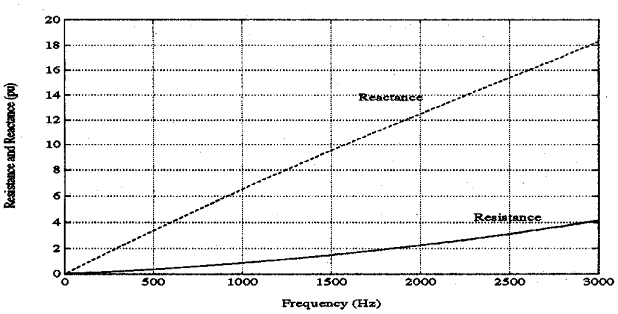

Figure 4: Measured impedance of a synchronous motor.

For salient pole synchronous machines, a negative sequence fundamental frequency current in the stator winding induces a second harmonic current in the field winding. The harmonic current can in turn induce a third harmonic current in the stator. A similar situation arises for the unbalanced harmonic currents in the stator winding. This harmonic conversion mechanism causes a salient pole synchronous machine to generate harmonic currents. A more accurate machine model has been proposed to take such effects into account [16].

Passive Loads: Linear passive loads that do not produce harmonics have a significant effect on system frequency response primarily near resonant frequencies. As in other power system studies it is only practical to model an *aggregate load* for which reasonably good estimates (MW and MVAR) are usually readily available. Such an aggregate must include the distribution or service transformer. At fundamental frequency the effect of distribution transformer impedance is not of concern in the analysis of the high voltage network. At harmonic frequencies the impedance of the transformer can be comparable to that of motor loads, since induction motors appear as locked-rotor impedances.

A general model for passive loads is given in Figure 5. To properly characterize this model it is necessary to know the typical composition of the load. Such data are usually not easily available. The following models have been suggested in literature (n represents the harmonic order):

Model A: Parallel R,L with $R=V^2/P$; $L=V^2/(2\pi f_o Q)$.

Model B: Parallel R,L with $R=V^2/(k\cdot P)$; $L=V^2/(k\cdot 2\pi f_o Q)$, $k=0.1n+0.9$.

Model C: Parallel R,L in series with transformer inductance L_s, where $R=V^2/P$; $L=nR/(6.7\cdot 2\pi f_o(Q/P)-0.74)$; $L_s=0.073nR/2\pi f_o$.

Model A assumes that the total reactive load is assigned to an inductor L. Since a majority of reactive power comes from induction motors, this model is not recommended. Model C is derived from measurements on medium voltage loads using audio frequency ripple generators. The coefficients cited above correspond to one set of studies [28], and may not be appropriate for all loads.

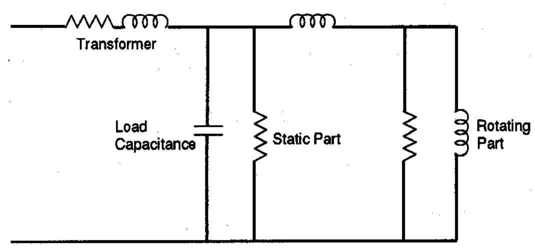

Figure 5: Basic Load Model.

VI. SUMMARY

Propagation of harmonic components in power systems depends on the characteristics of harmonic sources as well as the frequency responses of linear network components.

Characteristics of various harmonic sources and their modeling features are discussed. Some non-harmonic sources are also described. Representation of linear network components such as overhead lines and transformers is summarized.

Different approaches and methods for the system harmonic analysis are examined. In general, a harmonic analysis method is a function of the problem to be solved. The analysis method should represent a compromise between the required accuracy of the solution and the availability of system data.

ACKNOWLEDGEMENTS

We would like to acknowledge the support of the IEEE PES Harmonics Working Group chaired by Dr. W.M. Grady for initiating and supporting this effort.

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Discussion

A.E. Hammad, Consultant, N.E. Swiss Power Co., Baden, Switzerland: The task force members are commended for their work that produced a concise and clear paper with useful information.

Under "Techniques for Harmonic Analysis", frequency scan and harmonic iteration (multiphase/harmonic load flow) are cited besides time domain simulations (EMTP). For investigating the harmonic interaction of HVDC and SVC schemes and their controls and filtering equipment in large ac networks, the transfer function approach can also be used [A]. In this method, all system components are represented by their respective non-linear differential (state) equations. Current and voltage time derivatives of circuit elements are taken into consideration besides the detailed dynamics of controllers, e.g., HVDC and SVC controls and triggering circuits. Common load flow and transient stability input data are utilized. Effective (or apparent) system impedance is treated as a complex transfer function between an injected current signal with frequency ω at a certain bus and the resulting voltage vector. Eigenvalue (frequency-domain) analysis can also be performed using the state-matrix after linearizing the state equations around a particular operating point.

Under the section on "Models for Network Components", three models are cited for passive loads. In large network studies, aggregate load models should also include the effect of feeders, e.g., underground cables and overhead distribution lines [B]. The aggregate load model shown in Fig. 5, however, with minor modifications, can accommodate such effects.

[A] A. Hammad, "Analysis of Second Harmonic Instability for the Chateauguay HVDC/SVC Scheme," *IEEE Trans. on Power Delivery*, Vol. 7, No. 1, Jan. 1992, pp. 410-415.

[B] A. Morched, P. Kundur, "Identification and Modelling of Load Characteristics at High Frequencies", *IEEE Trans. on Power Systems*, Vol. 2, No. 1, Feb. 1987, pp. 153-160.

Manuscript received February 14, 1995.

I. Kamwa *(Hydro-Québec, IREQ, Varennes, Québec, Canada J3X 1S1)*, **P. Viarouge, H. Le-Huy** *(Electrical Engineering, Laval University, Québec, Canada G1K 7P4)* and **E.J. Dickinson** *(Mechanical Engineering, Laval University, Québec, Canada G1K 7P4).* The task force should be encouraged in their timely effort to collect, organize and disseminate information crucial to harmonic studies.

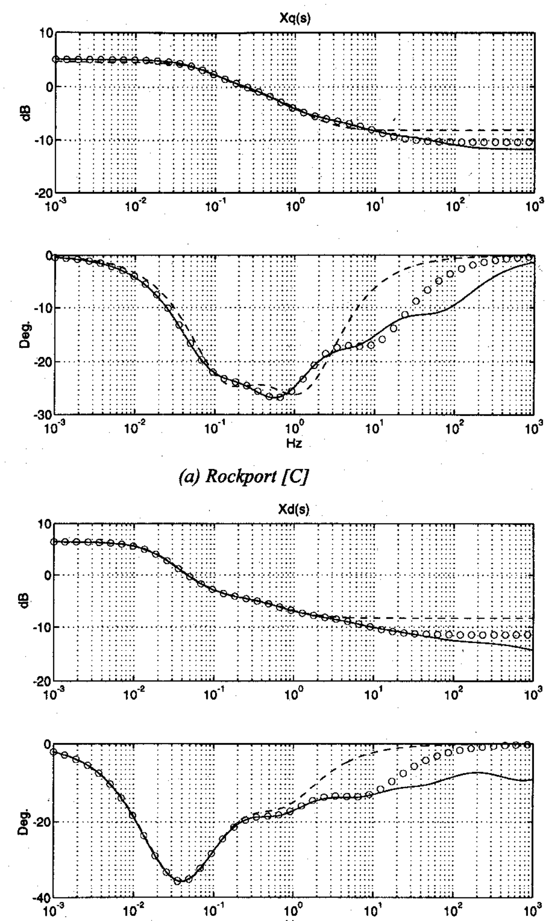
However, having been involved in synchronous-machine problems for some time, we feel we should warn the task force that their comments about this device are misleading and tend to translate into the harmonic domain various simplifying assumptions which in many cases do not even hold for lower frequencies, i.e. in the stability and sub-synchronous domains.

1) To reproduce the behavior of a synchronous machine in an extended-frequency range, second-order operational impedances are insufficient, especially for turbine-generators [A]. In fact, it has been known since the mid eighties that only third-order impedances and above are able to achieve adequate modeling of synchronous machines at frequencies above 10 Hz. This has led to the so-called sub-sub-transient quantities, physically explained by Canay [B].

2) If relevant information (e.g., in the form of standstill frequency responses) is lacking, we agree to assume a constant d-axis impedance at harmonic frequencies. However, we suggest that this value is better approximated by the half sum of x'''d and x'''q, rather than x"d and x"q as stated in the paper.

3) We argue that, where high-order SSFR-based models of turbine-generators are available [C-E], incorporating them into harmonic studies is not sufficiently complicated to justify in itself a simplification as drastic as that evoked in 2). Actually, the analysis method proposed by Xu et al. [F] is sufficiently general to allow for the inclusion of machine models of order higher than two, expressed either in the form of equivalent circuits or admittance matrices, with only minor modifications.

To further illustrate how serious our concerns for improved harmonic models of turbine generators are, few sample comparisons between a second- and higher-order models are shown in Fig. A. In each case, the highest-order model is the result of an optimal adjustment to real data; the values are borrowed from [C] and [D] for the Rockport and Nanticoke turbines, respectively. The second- and third-order models are obtained as optimal reduced-order approximations of the full model using a Hankel norm-based reduction scheme available in the Matlab robust control Toolbox. It is clear from this figure that the best models of the Rockport and Nanticoke generators cannot be easily approximated up to harmonic frequencies by resorting to a second-order model. At least three rotor windings should be used, even if we



(a) Rockport [C]

(b) Nanticoke Turbine [D]

Fig. A: comparison of reduced-order models with a full high-order model optimally adjusted to SSFR test data. ____ 3rd-order approximation; -----2nd-order approximation; o Full model: of order 4 in (a) and 5 in (b).

restrict our interest to sub-synchronous resonance studies [A]. We can provide numerous other real-world cases where second-order models dramatically fail to predict dynamic phenomena between 10 Hz and 100 Hz, not to mention harmonics [A, E].

The fact is that second-order models are well suited for the stability studies for which they were originally designed and on which they have been successfully tested by a generation of engineers. However, available evidence on actual turbine generators strongly suggests that they should be used with caution when dealing with harmonic phenomena, especially if information about the phase of the harmonic phasors is of interest. To a large extent, this comment also applies to large induction motors with deep bars or solid rotor.

We thank the task force in advance for taking our comments into consideration.

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Manuscript received February 17, 1995.

A. Medina (University of Toronto): The authors are to be commended for their comprehensive and well written paper. It presents an overview of the state of the art of the modeling and simulation techniques for harmonic analysis of electric power networks. I would like to raise the following comments:

As accurately pointed out by the authors, frequency domain is most appropriate for the modeling of the transmission network. This is because of its intrinsic accuracy and efficiency for the calculation of frequency dependent phenomena. Since the network is linear, there is no coupling between harmonics and therefore they can be treated independently. A small number of harmonics can be explicitly represented as long as it can be established that higher order harmonics in the network will be negligible. Higher order harmonics can however be excited depending on the characteristics of the transmission system and the harmonic contribution of the nonlinear and time-varying network components. In these elements, an input of a certain harmonic order will result in the same output harmonic order and other harmonics, which in addition are coupled. Harmonics of different orders can thus interact in the system.

The effect of the explicit representation of harmonic coupling and harmonic truncation was analyzed in [A] using detailed three-phase models in the frequency domain for the generator, transformer and transmission system for the study of their harmonic interaction. An iterative process based on a Newton type formulation was used.

A rather simple transformer model is presented by the authors for harmonic analysis. Harmonics produced by transformer saturation can well exceed permissible harmonic levels, as demonstrated for a practical system in a previous contribution [B]. In a more recent work [C] a detailed model of multilimb power transformers is described where harmonic coupling, saturation at different core regions, core losses and mutual effects of windings are represented and analyzed.

Modeling of nonlinear and time-varying components in the frequency domain is based on a linearization process around an operation point. Only in its vicinity is valid a linear relationship between harmonic voltages and currents. This implies the evaluation of a harmonic Norton equivalent which represents the effect of harmonic coupling. An accurate and rigorous solution would require this equivalent to be iteratively updated. The imposed computational burden can be considerable as it increases fast with the size of the network to be solved and the number of harmonics and nonlinear components represented.

A new technique for the efficient and accurate calculation of power systems with nonlinear and time-varying components has recently been developed [D]. It uses a hybrid time and frequency domain methodology. The network components are solved in their natural frame of reference, e.g. frequency domain for the linear network and time domain for the nonlinear network. In this approach to power system modeling, the iterative process based on a Newton type formulation is decoupled for the individual harmonics, yet it leads to an accurate solution. The efficiency of the hybrid process is enhanced with the use of Newton type algorithms for fast convergence to the periodic steady state in the time domain simulations. The solution of a power network with the hybrid technique yields very accurately the base frequency load flow solution, plus the harmonics.

In our experience [D], Newton techniques for acceleration of convergence of time domain simulations are neither "complex" as the authors claim nor difficult to implement. It might be that until recently they have not been sufficiently understood or their potential fully exploited for efficient time domain computations.

Once more I would like to congratulate the authors for their informative contribution.

[A] A. Medina and J. Arrillaga, "Analysis of Generator-Transformer Interaction in the Harmonic Domain", Proceedings IEE, Part C, Vol. 141, No. 1, January 1994, pp. 38-46.

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[C] A. Medina and J. Arrillaga, "Simulation of Multilimb Power Transformers in the Harmonic Domain", Proceedings IEE, Part C, Vol. 139, No. 3, May 1992, pp. 269-276.

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Manuscript received February 27, 1995.

G. Carpinelli (Università di Cassino, Italy), A. Testa (Università di Trieste, Italy): The Authors are to be commended for their contribution in the area of power system harmonics. They presented a concise but comprehensive and useful review of the modelling of sources, network components and systems.

Comments on the item that follows will be greatly appreciated.

The Authors evidence as the results accuracy obtainable by Direct Injection Method (DIM) is improved when: i) data are available on the harmonic source characteristics and ii) a fundamental frequency load flow is utilised to estimate the phase angles of harmonic currents of multiple sources. They add that the accuracy of DIM is, however, unacceptable in presence of excessive harmonic voltage distortion as occurring, for instance, in case of resonances.

In our experience, a good improvement to the DIM accuracy consists in:
i) determining frequency dependent equivalent circuits fitting the AC system impedance at the nonlinear device points of coupling;
ii) evaluating the harmonic currents of the nonlinear devices by solving models that are able to take into account the equivalent circuits determined in i).
The equivalent circuits in step i) can be determined by simple procedures as those reported in [R-1, R-2] while the harmonic currents in step ii) can be evaluated by a classical time domain simulation process or analytically [R-3]. The described procedure introduces a growth of complexity and of computational efforts but also very interesting advantages in the result accuracy; it can be particularly useful when harmonic iteration and Newton type methods are expected to present convergence difficulties.

To give an idea of the benefits, Table A compare the results obtainable by a conventional DIM with those of the improved DIM, in terms of harmonic voltages errors evaluated assuming as reference the results of a whole system time domain simulation. The case study considered is reported in [R-4] and it refers to a DC motor drive supplied by a node of an AC system characterised by a strong resonance closed to the 11-th harmonic.

Finally, it should be noted that the improved DIM is also able to take into account the ambient harmonics when the effects of adding a single nonlinear device are dealt with.

Table A

Percentage errors of Conventional and Improved DIM assuming the time simulation results as reference

Harmonic order	Conventional DIM error [%]	Improved DIM error [%]
5	+12	- 1
7	+20	+2
11	+55	+4
13	- 14	- 4

[R-1] G. Carpinelli, R. Lamedica, A. Piccolo, A. Prudenzi: " Equivalent Circuits for Network Harmonic Impedance Representation", Int. Symposium on Electric Energy Conversion in Power Systems, paper n. W-H.8, Capri (Italy), May 1989.

[R-2] R. Carbone, M. Fantauzzi, F. Gagliardi, A.Testa: " Some Considerations on the Iterative Harmonic Analysis Convergence", IEEE Trans. on Power Delivery, Vol. PD-8, n.2, April 1993.

[R-3] G. Carpinelli, F. Gagliardi, M. Russo, D. Villacci: "Generalised Convertor Models for Iterative Harmonic Analysis in Power Systems", IEE Proc. Gener. Transm. Distr., Vol. 141, n. 5, September 1994.

[R-4] U. De Martinis, M. Fantauzzi, A. Testa: "An Improvement of the Iterative Harmonic Analysis Method", European Trans. on Electrical Power Engineering, Vol. 3, n. 2, March 1993.

Manuscript received March 7, 1995.

A.S. MORCHED (Ontario Hydro, Grid System Strategies and Plans): The author is to be congratulated on a well thought out, well written paper on a timely and important subject. The increased importance of this subject is mainly due to the increasing use of solid state devices in power applications with the accompanying generated harmonics and their effects on power quality.

I would like, in this discussion, to express my agreement with most of the concepts brought forward by the author and to add the following remarks.

1. Steady-state power frequency solution including harmonics can be achieved through time domain transient solution carried out long enough for the transients to damp out and a "distorted wave" steady-state is reached. This can be time-consuming if the attenuation of the involved frequency components is low, as is the case for harmonic frequencies in power systems.

A better approach is the iterative application of the nonlinear characteristic to the stimulating voltages, the Fourier Analysis of the resulting current waves, the solution of the network for each of the harmonics and the reconstruction of the voltage wave out of these harmonics.[A] This results in a much more efficient process for reaching steady state. This approach has been implemented in the EMTP as the multi-frequency initialization feature.

Another EMTP feature which is useful in harmonic analysis studies is the frequency scan option which can provide the frequency dependent driving point impedance (admittance) of a network as seen from one bus. It can also provide the frequency dependent voltage (current) transfer function between any two points in the system. This allows for an easy identification of network series and parallel resource frequencies as well as degree of and frequencies at which voltage magnification between different points in the network occurs.

2. The author has rightly pointed out the lack of load models suitable for use in harmonic studies. However, I would like to attract his attention to previous work conducted in Ontario Hydro to identify the frequency characteristics of loads and feeders and provided a technique to fit simple RLC circuits to these characteristics.[B]

The method used is based on applying signal processing techniques to the transient bus voltage and feeder current produced by a capacitor bank switching operation. The method was applied to the identification of the high frequency characteristics of 27.6 kV feeders in Ontario Hydro's distribution system. Models reproducing the identified frequency characteristics were developed and their frequency behaviour was compared to those of the conventional models. Obtained models were accurate for a frequency range of up to 5 khz.

Capacitor bank switching is conducted daily in many substations, which makes the application of this method extremely simple.

3. The need for modelling large portions of the system for harmonic analysis studies cannot be emphasized enough. Frequency components in the harmonic range can travel very far without being attenuated (especially aerial mode components), be reflected from far away discontinuities and can come back to influence the characteristics of the area under study. These are techniques to assess the adequacy of the network size such as changing the network termination (SC&OC) and testing its effect on the frequency characteristics of driving point impedances. In the absence of a reliable measure one should model as a large network as possible.

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Manuscript received March 13, 1995.

[The following closure covers the 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) and the companion paper "Modeling and Simulation of the Propagation of Harmonics in Electric Power Networks, Part II: Sample Systems and Examples" (95 WM 265-9 PWRD) which follows in this issue.]

Task Force on Harmonics Modeling and Simulation: The task force thanks the discussers for providing important commentary and a valuable extension to the list of references.

Drs. Hammad, Morched, Carpinelli and Medina have pointed out several significant extensions to simulation techniques. We agree with Dr. Hammad that transfer function techniques are very useful in incorporating the effect of control systems. The other discussions point out recent advances in the use of hybrid methods. In these techniques the network solution is interfaced with a time or frequency domain solution of the nonlinear device. Dr. Morched has summarized the ideas used in the multi-frequency initialization in the EMTP which basically addresses the harmonic simulation problem. Reference [A] of this discussion describe additional contrbutions including the ability to find multiple solutions.. The motiviation for these approaches is, of course, to develop algorithms that are substantial faster than a time domain simulation carried to staeady-state Dr. Carpinelli and Testa explain the advantages frequency-dependent network equivalents in the interfacing process . Dr. Medina and his colleagues have made substantial contributions to the efficient solution of the hybrid problem wherein the nonlinear component is modeled in the time domain. The task force agrees that the techniques are not necessarily 'complex' and welcomes the references provided by the authors. The techniques that are becoming available are important in cases of complicated interaction and severe distortion.

Drs. Hammad and Morched have reemphasized the need for load models. While the model given in the paper is an adequate baseline, attention must be paid to the effect of feeders and compensation that may exist at the lower voltage levels. Ambient harmonics are a related issue. Dr. Morched's work in identifying the frequency characteristics of loads should prove to be a useful tool in this area. We look forward to papers that extend load modeling capabilities in the harmonic simulation area.

Dr. Medina correctly points out that, under appropriate conditions, transformers can become a significant source of harmonics and we appreciate his providing references to advanced models. Where available data permits their use these models can help make analyses more precise.

Drs. Kamwa Viarouge, Le-Huy and Dickinson's warning regarding simplified synchronous machine models is well founded. The use of X_d" and Xq" is warranted when data are unavailable and using the average of the two is indeed a better approximation. The impedance shown in Figure 4 of the paper is from actual measurements made by Dr. W. Xu on a 1100 HP motor and is consistent with the above approximation. The recommendation to use higher order models qualified by SSFR tests is of course appropriate in principle. However these data are not widely available for machines. Further, *current* procedures for SSFR tests do not really address the range of harmonic frequencies. Reader's interested in this area are encouraged to consult discusser's reference [D] and the associated discussion and closure. Further research in this area is necessary.

In preparing these papers the objective of the task force was to summarizing the current tools, techniques and practice in the harmonics simulation area. The discussions demonstrate that this is an area where advances are continually being made. The discussers have provided references to these contributions. While many advances have been made, present day harmonic analysis does involve some subjective evaluation of the scope of the problem and the availability of data.

Finally, we would like to note a typographical error in the next-to-last paragraph in Section 3 which is missing a citation to reference [4].

[A] Lombard, X., Mahseredjian, J., Lefebvre, S., Kieny, C.," Implementation of a new Harmonic Initialization Method in EMTP, " Paper 94 SM 438-2 PWRD, presented at the 1994 IEEE Summer Power Meeting, San Francisco, Ca, July 24, 1994.

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