PQSoft Case Study

General Reference
Modeling for Harmonic Analysis

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References			

Abstract:

Harmonics have existed on electric power systems for many years. Recently, however, much more attention has been given to monitoring and analyzing the presence and effects of harmonics on utility and customer devices than in the past. This new concern is the result of significant increases in harmonic distortion on many electric power systems in recent years.

Harmonic distortion problems range in severity from nuisance tripping of customer equipment to failure of very expensive utility and customer equipment.

This case provides an overview of harmonic modeling for system studies.

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RELATED STANDARDS

IEEE Standard 519-1992
IEEE Standard 1036-1992

GLOSSARY AND ACRONYMS

ASD	Adjustable-Speed Drive
PWM	Pulse Width Modulation
THD	Total Harmonic Distortion

INTRODUCTION

A fundamental objective of electric utility operations is to supply each electric customer with a constant sinusoidal voltage. The voltage signal at any point within the power system is ideally a constant sinusoidal signal that repeats at a rate of precisely 60 times per second, or 60 Hz. Although not perfect, the voltage signal produced by power system generators approximates a perfect sinusoid with a rather high degree of accuracy. Almost all load equipment connected to the electric power system has been designed to operate from a sinusoidal voltage source.

Some load equipment, however, does not draw a sinusoidal current from a perfectly sinusoidal voltage source. This equipment is said to be "nonlinear"; that is, the relationship between voltage and current at every instant of time is not constant. Because power systems are voltage-regulated, current drawn by any load does not affect neighboring devices since it is voltage, not current, that they share. Non-sinusoidal currents are generally not a problem for parallel connected loads. Present trends in the electric power industry have placed an increased emphasis on the impact of nonlinear equipment. These include:

- The increasing size and application of nonlinear equipment. The most important nonlinear equipment classification is power electronic equipment. The percentage of electric power that passes through power electronic equipment is increasing dramatically because of the increased energy efficiency and flexible control that power electronic devices provide.
- Increased application of capacitors to maximize the utilization of existing power system equipment. Utilities encourage their customers to make better use of transformer capacity with power factor penalty clauses in rate structures; the utilities themselves may rely on capacitor application at both transmission and distribution levels to provide necessary voltage control as system load fluctuates over the course of a day or season.
- Modern architectural/construction practices. The use of single-phase harmonic loads (lighting and office PC's) requires that reduced size neutral wiring no longer be employed. Unfortunately, under-floor wiring with daisy-chained neutrals makes modification to these circuits difficult.

MODELING FOR HARMONIC ANALYSIS

Harmonic simulation programs are used for a wide variety of studies. Some of the most important applications include:

- Application of capacitors / harmonic resonance
  - Utility transmission and distribution banks
  - Industrial customer power factor correction
- Impact of harmonics on equipment / derating
- Design of harmonic filters
- Analysis of equipment failure
- Evaluation of harmonic standards (IEEE 519-1992 Compliance)

Harmonic studies have become an important part of power system analysis and design. They are used to determine distortion levels and identify dangerous resonance conditions. Such studies are important because of the amount of harmonic producing load is increasing significantly. As harmonics propagate throughout the system they increase losses and equipment loss-of-life. Equipment can be damaged by overcurrents or overvoltages resulting from resonance conditions. Additionally, harmonics can interfere with communication and control circuits. Studies involving harmonic analysis generally fall into two categories. One is design, such as the placement and sizing of capacitor banks and the specification of harmonic filters. The other is solving operating problems, such as equipment failure or misoperation.

Program Inputs

Harmonic simulation programs require input data to describe the electrical network, nonlinear load characteristics, and the output requirements. The electrical network data is based on individual elements (lines, transformers, capacitors, etc.). Detailed descriptions of the data requirements for each element supported and the other data case requirements are provided in the software user's manual. The basic elements of a data case are listed below.

- Special request information (i.e. frequency scan simulation)
- Lumped branch data - resistance, inductance, capacitance
- Coupled R-L elements (represented by positive and zero sequence data)
- Transmission lines and cables
- Transformers (including exciting current)
- Nonlinear load elements (harmonic current injection)
- Linear load elements
- Synchronous and induction machine models
- Desired outputs

Program Outputs

The main output of a harmonic simulation consists of the frequency domain information describing node voltages, differential voltages (node-node), and branch currents. The programs often perform a full steady state solution to develop initial operating conditions for the harmonic solution. The initial conditions used for nonlinear elements depend on the specific model involved. The output from the steady state solution is very useful for debugging the harmonic model. The various output quantities available include:

- Steady-state phasor solution - branch voltages and currents (illustrated in Figure 1), bus voltages, power loss, and power flows.
- Spectral data - voltage and current magnitudes and angles as a function of frequency (frequency scan option, illustrated in Figure 2.
- Frequency scan - the system impedance versus frequency at the selected bus of interested illustrated in Figure 3.

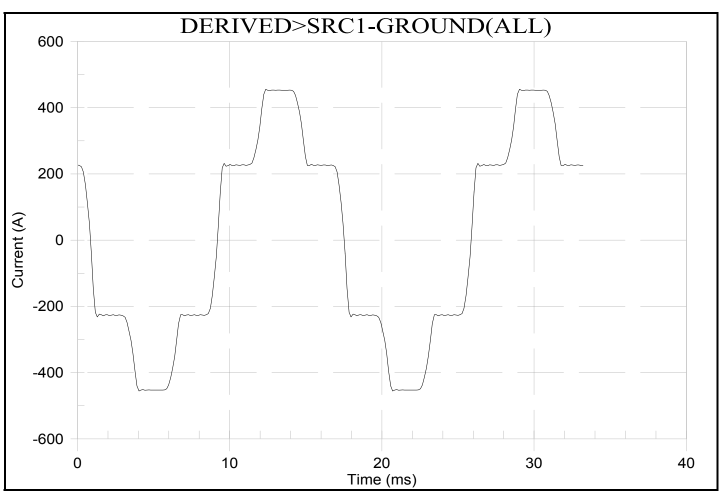

Figure 1 - Example Output: Branch Current Waveform

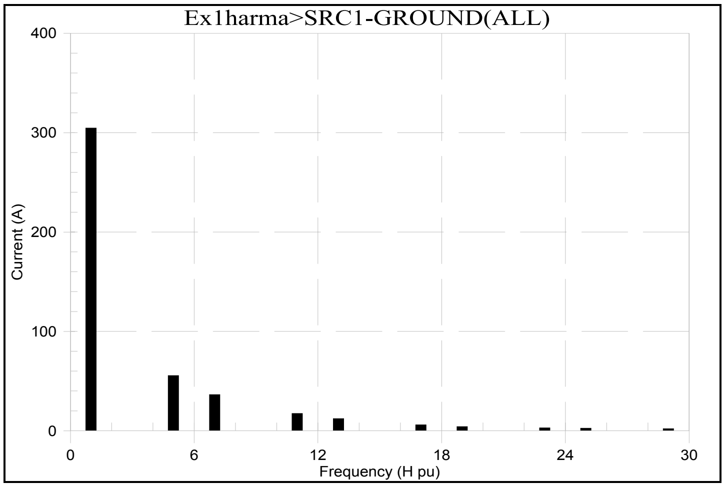

Figure 2 - Example Output: Branch Current Spectrum

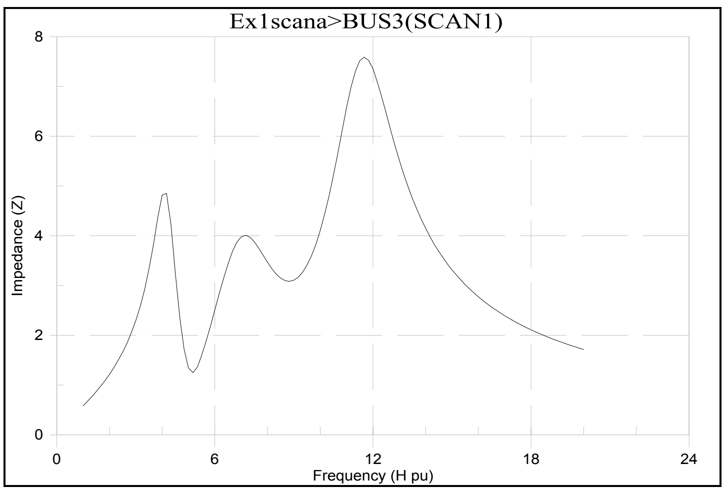

Figure 3 - Example Output: Frequency Response

Study Procedure

The following is a suggested procedure for using a harmonic simulation program to perform harmonic studies:

- Identify the study objectives. The objectives will dictate the frequency range of interest, the modeling requirements, the variables to be investigated, and the types of output that are needed from the simulation.

- Develop the system model. The extent of the system model depends on the capacitors and/or lines to be switched and the frequency range of interest. Obviously, it would be desirable if the model could include the entire system and you could just switch the device(s) of interest.

- Draw a connection diagram and assign bus names. The bus labels will be used in the harmonic data file for identification.

- Develop component models. Each component model (transmission line, transformer, breaker, etc.) will depend on the frequency range of interest and the specific harmonic event being evaluated.

- Run a steady-state solution case. This case will verify system connectivity and provides a sanity check on many of the system components. This is a very important step that must not be skipped, or gross errors could result.

- Estimate the expected results. This can be done from previous studies, from the literature, or from hand calculations. It is important to know what to expect from the simulation so that major problems can be identified quickly.

- Use a sensitivity analysis for unknown or important quantities. Important variables from the simulation should be evaluated to determine their impact on results. These could include capacitor bank size, transformer size, line length, source strength, etc.

- Develop solutions. Possible solutions (i.e. filters) are evaluated and design specifications are developed.

Simulation Process

The process for completing a harmonic simulation consists of first collecting and developing the necessary data to represent the circuit to be modeled. Often this system representation is completed by “describing” the interconnection and component values in a simple ASCII text file. For example, the following SuperHarm datafile excerpt represents a 1500kVA, three-phase step-down transformer.

```
//
//      Step down transformer #1 (@ service entrance)
//      1500 kVA, 12.5kV / 480 Volt, (connection - delta / wye-ground)
//      Z = 6% @ 1.5 MVA, X/R = 10
//      Ie = 1% @ 100% V
//

TRANSFORMER   NAME = STEP1   H = DELTA   X = WYE
   MVA = 1.50     %IMAG = 1.0    KV.H = 12.5     KV.X = 0.480
   H.A = PCC_A    H.B = PCC_B    H.C = PCC_C
   X.A = 4801A    X.B = 4801B    X.C = 4801C     X.N = GROUND
   MVAB.HX = 1.5  %R.HX = 0.6    %X.HX = 6.0
```

After the data file has been created, it is submitted to the harmonic solution engine (solver). The solver reads the data file, line-by-line, and reports any significant errors. Satisfied that the case will solve, the solver generates a matrix representation of the interconnected system.

In general, there are two types of harmonic simulations:

- Frequency Scans: The frequency scan is the simplest and most commonly used technique for harmonic analysis. A scan calculates the frequency response characteristic at a particular bus or node. Usually, this is accomplished by injecting one amp into the bus over a range of frequencies and then observing the resultant voltage. The resultant voltage is directly related to the system impedance in ohms. Frequency scan analysis is the best method for identifying resonance conditions. It has also been used a great deal in filter design.

- Distortion Simulations: Harmonic distortion simulations use harmonic source characteristics of nonlinear loads to determine current and voltage distortion levels at various points in the system. Harmonic source characteristics (current source) are obtained from field measurements, other simulation programs (Electromagnetic Transients Program - EMTP), or a library of typical waveforms. Distortion simulations are useful for evaluating component duty and determining harmonic limit compliance (i.e. IEEE 519-1992).

Developing a System Model

One of the most important problems associated with developing a system model is "How much of the system do I need to model?" Unfortunately, there are no hard-and-fast rules to guide a user; it is often more of a feel that is developed over time. A good starting point for harmonic studies is to model one or two buses back from the bus of interest (connection of nonlinear load). However, even this simple guideline fails from time-to-time. Perhaps the best method for determining the appropriate system model is to start with a small simple circuit that accurately represents the phenomena, and then add more of the system details to determine their impact on the solution result.

In addition to the need to accurately select the appropriate portion of the system to model, the user must determine if a single-phase model will correctly represent the system and phenomena of concern. Many harmonic studies are completed using a single-phase (positive sequence) representation.

However, there are several cases when the user must extend the model to a full three-phase representation.

- Single-phase of unbalanced harmonic sources - the imbalance can only be represented with a three-phase model.

- Harmonic current cancellation - when there are multiple harmonic current sources, a certain amount of cancellation will occur. Determining the level of cancellation requires modeling the current sources with both magnitude and phase angle information, and modeling the system using a three-phase representation.

- Single-phase capacitor banks - balanced positive sequence models are not sufficient when there are single-phase capacitor banks on the system.

- Telephone interference - the influence of residual harmonic current is the critical factor, therefore, the system and harmonic source imbalance must be fully modeled in order to accurately determine the residual currents.

- Triplen harmonic voltage sources - a three-phase model is required to accurately represent the high zero sequence impedance.

Fortunately, most harmonic analysis programs provide the capability to easily extend the model to a full three-phase representation. Therefore, developing a three-phase model would seem to provide the highest level of flexibility.

Model Verification

The single most important tool that the user has for verifying the simulation results is a basic knowledge of power system harmonics. Field test results, technical papers, basic textbooks, and more experienced engineers can all help. Learning by doing can be very frustrating and applying the simulation results can be risky, when the user does not feel comfortable with the results of the study.

When verifying the results of a harmonic case, the user should always check the input parameter interpretation and network connectivity. The steady-state solution should be checked to verify known quantities, such as bus voltage, branch currents, etc.

Presentation of Results

Upon completion of the harmonic simulation case, an evaluation of the accuracy of the results is required. As previously mentioned, it is desirable that the user have a basic understanding of the phenomena of interest. In essence, the user should know what the result should be (or at least have a good idea of what the waveform should look like) before completing the case. In reality, however, this is not always the case, so it becomes even more important that the user have confidence in the accuracy of the data file.

Simulation results are generally presented in the form of impedance vs. frequency plots and voltage and current distortion levels (waveforms). Presentation of simulation results may take a number of different forms (i.e. graphical, tabular, etc.). It may be just as important to present the result in a way easily understood by the audience, as it is to complete the simulation correctly. Failure of either results in no action taken.

In addition, study results may take the form of summary tables and/or graphs that illustrate the results for multiple simulations. For example, one common method for presentation of results is in the form of a distortion (THD) vs. variable graph. The “variable” may be quantities like transformer size, capacitor size, choke size, etc. It is much easier for the audience to understand the impact of a specific variable on the distortion range using this method.

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