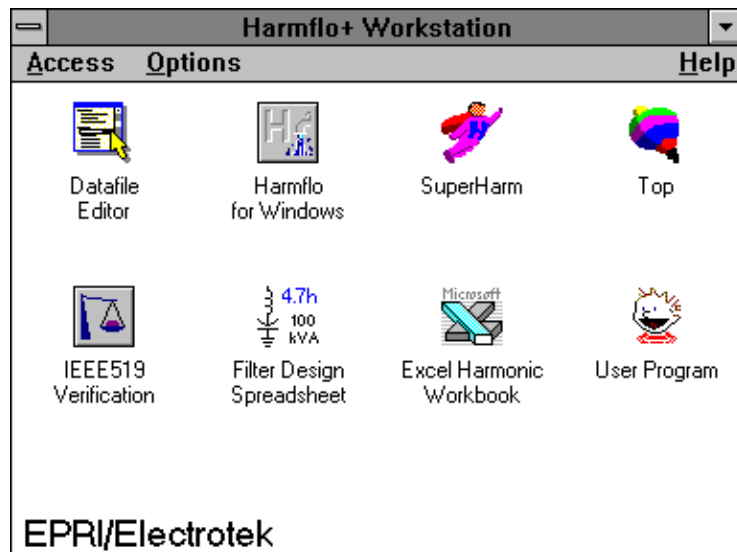# HarmFlo+
Tech Notes

for users of the EPRI/Electrotek HarmFlo+ Workstation

Issue # 93-1   *June, 1993*   *Editor: Thomas Grebe*

in this issue:

Letter from the Editor:

This is the initial issue of *HarmFlo+ Tech Notes*. The technical newsletter provided to members of the HarmFlo User's Group. The initial plan for the newsletter is a quarterly technical publication highlighting contributions from members of the User's Group.

Contributions in the following areas are welcome:

Technical articles
Modifications / enhancements to the code
Case studies / unique simulations
Research projects
SuperHarm / HARMFLO data preparation / model development
Include / library files developed for distribution on the BBS
Letters to the editor / User's Group
Technical paper abstracts
Questions for members of the User's Group

I believe that the exchange of technical information is one of the most important functions of the HarmFlo User's Group and this newsletter, in conjunction with The Resonant, will help to serve the needs of the members. As always, I'm open for suggestions regarding this publication and the User's Group in general.

Thanks for your support

For more information concerning the newsletter or to submit a contribution please contact:

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SuperHarm Include Files

Background

SuperHarm has many useful features which make repetitive tasks much easier. These features include:

- Include files. Include files can be used if the same data is going to be represented over and over again in the SuperHarm model.

- Define Files. Define files can be used to define files that will be used within the model. This is a useful feature if you want to define several load conditions for the model.

- Library Files. Library files are used to combine several include files. This is useful to store all PWM drives.

- Inline math. Inline math is useful for calculating a parameter within the CDL rather than entering a precalculated value.

This article discusses the SuperHarm include file and how to use it. Include files are a great benefit when constructing data files that use the same type of device over and over again. This is the case when modeling a plant that has a large quantity of ASDs. Most ASDs have similar current spectrums. Therefore, one include file can be used for all ASDs modeled. The only differences will be the NAME, BUS, KVA, DF, and maybe KV parameters. These parameters can be passed to the include file each time it is called.

SuperHarm Include Files - (*.SHI):

The syntax for the include is relatively simple. First, the include file will be constructed and second, the calling convention within the main data file (.SHA) will be shown. The example that follows shows how to construct an include file for a single phase PWM drive.

```
// SINGLE PHASE MODEL
//
// %1 = NAME OF DEVICE PASSED FROM SHA FILE
// %2 = BUS WHERE DEVICE IS CONNECTED PASSED FROM SHA FILE
// %3 = KVA OF DEVICE (1PH).  PASSED FROM SHA FILE
// %4 = KV RATING OF DEVICE (L-N) PASSED FROM SHA FILE
// %5 = DISPLACEMENT FACTOR OF DEVICE PASSED FROM SHA FILE
//
// TABLE OF CURRENTS TAKEN FROM ACTUAL MEASUREMENTS OF PWM
// DRIVE WITHOUT INPUT CHOKE.
//

NONLINEARLOAD  NAME = %1
     BUS = %2 KVA = %3
     KV = %4          DF = %5
     TABLE =  {
              { 1,      100.0,      -8},
              { 5,       45.1,     116},
              { 7,       21.2,    -116},
              {11,        8.2,     -50},
              {13,        4.1,       9},
              {17,        4.1,     101},
              {19,        2.2,     136},
              {23,        2.5,    -108},
              {25,        1.5,     -89}
              }
```

It is always good to document the include file as much as possible. This will make it easier for another person to use. The following example shows how you would make this a three phase device.

```
// THREE PHASE MODEL
//
// %1 = NAME OF DEVICE PASSED FROM SHA FILE
// %2 = BUS WHERE DEVICE IS CONNECTED. PASSED FROM SHA FILE
// %3 = KVA OF DEVICE (1PH).  PASSED FROM SHA FILE
// %4 = KV RATING OF DEVICE (L-N).  PASSED FROM SHA FILE
// %5 = DISPLACEMENT FACTOR OF DEVICE. PASSED FROM SHI FILE
//
// TABLE OF CURRENTS TAKEN FROM ACTUAL MEASUREMENTS OF PWM
// DRIVE WITHOUT INPUT CHOKE.
//
//     PHASE A
NONLINEARLOAD  NAME = %1^A
     BUS = %2^A       KVA = %3
     KV = %4          DF = %5
     TABLE =  {
              { 1,      100.0,      -8},
              { 5,       45.1,     116},
              { 7,       21.2,    -116},
              {11,        8.2,     -50},
              {13,        4.1,       9},
              {17,        4.1,     101},
              {19,        2.2,     136},
              {23,        2.5,    -108},
              {25,        1.5,     -89}
              }
```

```
//      PHASE B

NONLINEARLOAD  NAME = %1^B
        BUS = %2^B         KVA = %3
        KV = %4            DF = %5
        TABLE =   {
                  { 1,        100.0,      -8},
                  { 5,         45.1,     116},
                  { 7,         21.2,    -116},
                  {11,          8.2,     -50},
                  {13,          4.1,       9},
                  {17,          4.1,     101},
                  {19,          2.2,     136},
                  {23,          2.5,    -108},
                  {25,          1.5,     -89}
                  }

//      PHASE C

NONLINEARLOAD  NAME = %1^C
        BUS = %2^C         KVA = %3
        KV = %4            DF = %5
        TABLE =   {
                  { 1,        100.0,      -8},
                  { 5,         45.1,     116},
                  { 7,         21.2,    -116},
                  {11,          8.2,     -50},
                  {13,          4.1,       9},
                  {17,          4.1,     101},
                  {19,          2.2,     136},
                  {23,          2.5,    -108},
                  {25,          1.5,     -89}
                  }
```

The "^" symbol is used to concatenate the phase designator on the NAME and the BUS parameters within the include file. By using this method, a separate parameter for each phase name and each phase bus does not need to be passed.

Notice how the spectrums for all phase are identical. SuperHarm can use the same spectrum for each phase. The SuperHarm solution engine calculates a fundamental voltage for each phase at the bus where the device is connected. Using this calculated voltage and given DF, it calculates a current (magnitude and phase) based on the KVA parameter and the ratio between the fundamental value to the harmonic value. This calculation is performed for each value in the table. This method, alleviates the need for three separate spectrums (in some cases only a single phase spectrum is available).

The values for KV and KVA must be consistent. In other words, if Line-to-Line voltage is entered, then three phase kVA must be entered. By the same token if Line-to-Neutral voltage is entered, then single phase kVA must be entered.

To call the include file from the main data file is a relatively simple procedure. This procedure follows.

```
//
//      CALL INCLUDE FILE FOR PWM ASD
//      USE SINGLE PHASE MODEL
//
//      NAME = ASD1
//      BUS = 480BUS
//      KVA = 100
//      DF = 0.98
//      KV = 0.277
//
//      CALLING CONVENTION
//
//      #INCLUDE PATH OF SHI FILE (NAME, BUS, KVA, DF, KV)

#INCLUDE C:\SHFILES\1PH_ASD.SHI (ASD1, 480BUS, 100, -
0.98, 0.277)
```

Hopefully, these examples have provided some useful information regarding SuperHarm include files. Include files, that have been developed at Electrotek and by members of the HarmFlo User's Group, will be available on the HarmFlo bulletin board.

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Investigating Harmonic Problems

The increasing application of power electronic equipment, at the customer level, has led to a growing awareness of harmonic related problems for electric utilities. Problems previously encountered include excessive distortion levels resulting in transformer overheating, motor failures, capacitor fuse blowing / can failure, and misoperation of electronic controls. In addition, the continued application of power factor correction capacitors (utility distribution and industrial systems) compounds the concern for harmonic distortion levels. Capacitors and the system short circuit reactance combine to create resonances which can magnify harmonic currents from nonlinear loads resulting in unacceptable voltage distortion levels. This article summarizes the important sources of harmonics and methods to analyze their impact on system performance. The most common solution to harmonic problems involves the application of harmonic filters. Filter design procedures are described. In addition, the impact of IEEE Standard 519-1992 is illustrated using a utility / industrial customer interface case study.

Background

A fundamental objective of electric utilities is to supply each customer with a fairly constant sinusoidal voltage. The voltage signal at any point within the power system is ideally a constant sinusoidal signal which 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 by themselves are not a concern to parallel connected loads.

A commonly used indicator of the impact of nonlinear load is total harmonic distortion (THD). THD is measurement waveform distortion with respect to the fundamental value. Voltage or current THD can be determined using the following relationship:

$$V_{THD} = \frac{\sqrt{V_2^{2+} + V_3^2 + V_4^2 + \ldots + V_n^2}}{V_1}$$

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 which 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 modular office construction with reduced size neutral wires in three phase circuits has created a major concern for supplying single phase nonlinear loads, such as PC's, terminals, printers, etc. Although the 1990 National Electric Code requires neutral conductors to be sized the same as phase conductors for circuits supplying electronic equipment or fluorescent lighting, design engineers often still use the old Article 220 permitting undersized neutrals.

Origin of Power System Harmonics

Harmonic currents are created by devices and loads that have a nonlinear voltage/current characteristic. Nearly all of these devices are shunt connected, the bulk of which are loads. These devices fall into three major categories:

1. Power Electronics

Examples of equipment in this category include: rectifiers, adjustable-speed drives (ASDs - refer to Figure 1), uninterruptible power supply (UPS) systems, and inverters. Besides being the most significant source of harmonic currents on the system, this equipment can also be the most sensitive to distortion in the voltage waveform.

2. Ferromagnetic Devices

Transformers are the most important device in this category. The level of harmonic generation increases as the applied voltage increases above the transformer rating (increased magnetizing current due to saturation). Transformers are numerous, but produce distortions of only about 1% of the rated load current.

3. Arcing Devices

Arcing devices generate harmonics due to the nonlinear characteristics of the arc. Arc furnaces are large harmonic sources in this category. However, fluorescent lighting has basically the same characteristic and is much more prevalent.
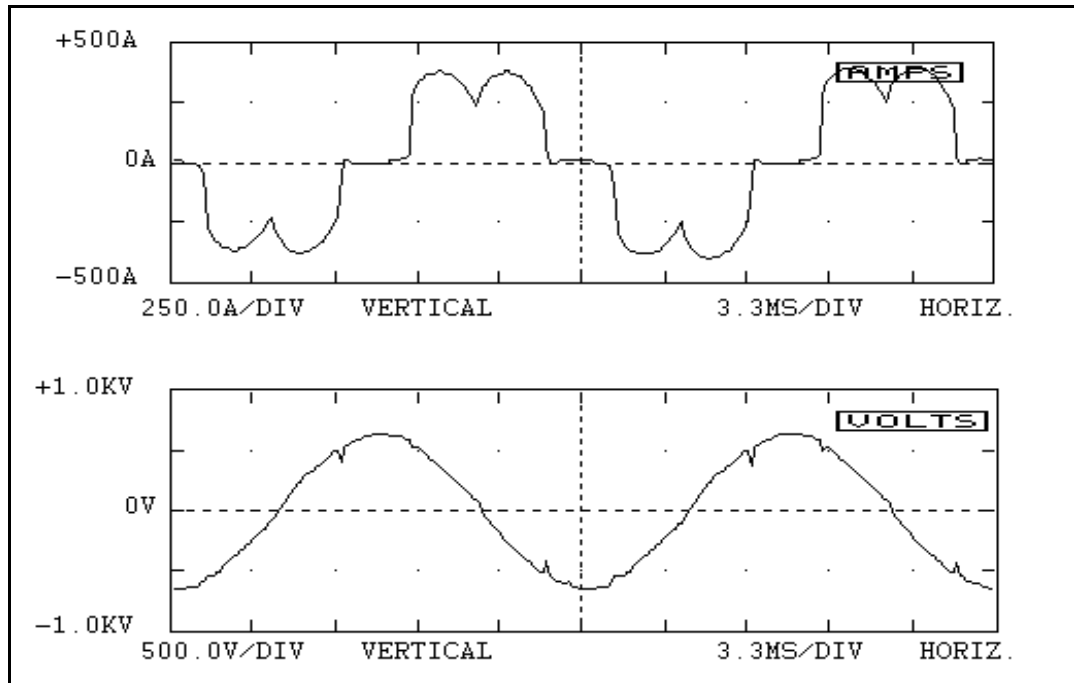
*Figure 1 - Example Measured Input Current and Voltage
Waveforms for an Adjustable-Speed Drive.*

For the most part, the previously described devices inject harmonic current components into the distribution system (constant current source assumption valid when $Z_{source} << Z_{load}$). The level of harmonic voltage distortion developed is a function of both the system impedance and the amount of current injected. In general, power systems can absorb a great deal of harmonic current without noticeable problems. However, changes to the power system, such as the addition of power factor correction capacitors, can cause voltage distortion levels to exceed recommended limits.

Analysis of harmonic concerns involves determining the amount of harmonic current which can be injected by nonlinear loads and then determining the system response to these harmonic currents.

System Analysis

The utility / industrial harmonic interface problem can be solved using a comprehensive approach including site surveys, harmonic measurements, and computer simulations. One general procedure used for a harmonic analysis study consists of the following steps:

1. Preliminary Analysis / Model Development

Simple calculations are used to determine the system resonant frequencies and then the preliminary model development is completed. Frequency response characteristics, as illustrated in the impedance versus frequency diagram (Figure 2), indicate the reaction of the system to injected harmonic currents. Initial estimates of voltage distortion levels are made based on the level of harmonic current injection and the frequency response characteristic.

Often problems associated with capacitor installation are a result of parallel resonance with the source impedance. Parallel resonance (large impedance as compared to Z_{source}) occurs at the frequency where the shunt capacitive reactance is equal to the inductive source reactance and can be expressed in terms of the 60 Hz values as follows:

$$h = \sqrt{\frac{MVA_{SC}}{MVAr_{cap}}} = \sqrt{\frac{I_{SC}}{I_{cap}}} = \sqrt{\frac{X_C}{X_S}} \approx \sqrt{\frac{100*kVA_{tx}}{kVAr_{cap}*Z_{tx}(\%)}}$$

where:

h = parallel resonance frequency (x 60 Hz)
MVA_{SC} = short circuit duty in MVA
$MVAr_{cap}$ = capacitor bank rating in MVAr
I_{SC} = three-phase short circuit current in amps
I_{cap} = capacitor bank load current in amps
X_C = shunt capacitive reactance (C - capacitance)
X_{SC} = short circuit reactance (L_S - inductance)
kVA_{tx} = step-down transformer rating
Z_{tx} = step-down transformer impedance
$kVAr_{cap}$ = capacitor bank rating

This simple relationship provides an excellent first check to see whether or not harmonics are likely to be a problem. Almost all harmonic distortion problems occur when this parallel resonance moves close to the fifth or seventh harmonic, since these are the largest harmonic current components in loads like ASDs. However, the eleventh and thirteenth harmonics can also be a problem when ASDs (PWM type) are a large percentage of the total load. If the addition of a capacitor results in a significant increase in harmonics problems, parallel resonance phenomena is the most likely cause.

Series resonance can also be a concern. The series combination of an inductor and capacitor appears as a very small impedance at its resonant frequency. There are certain instances where a shunt capacitor and the inductance of a transformer or distribution line may appear as a series LC circuit to source of harmonic currents. If the resonant frequency (same calculation as above) corresponds to a characteristic harmonic frequency of the nonlinear load, the series LC circuit will attract a large portion of the harmonic current that is generated. A customer having no nonlinear load, but utilizing power factor correction capacitors, may in this way experience high voltage distortion due to neighboring harmonic sources.
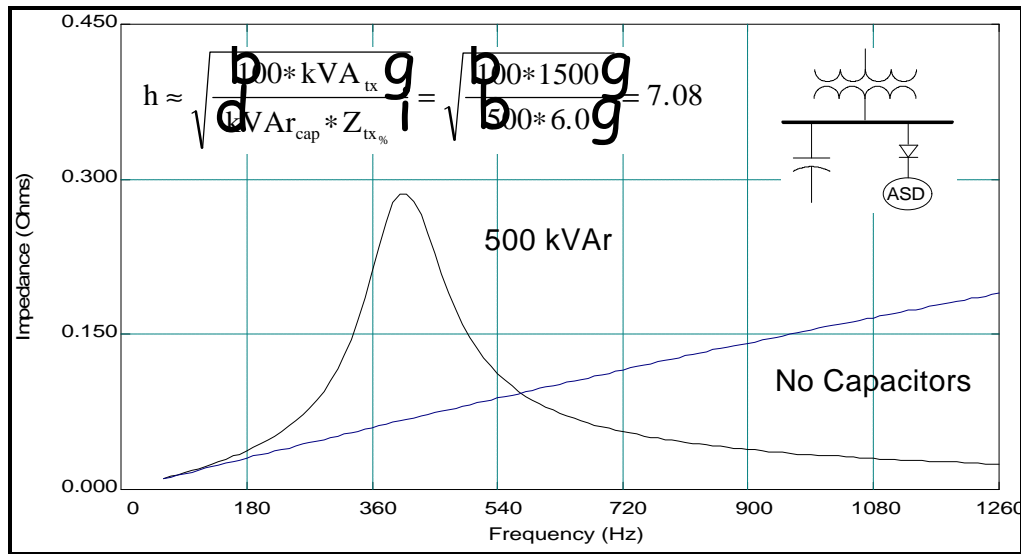
$$h \approx \sqrt{\left(\frac{100*kVA_{tx}}{kVAr_{cap}*Z_{tx_\%}}\right)} = \sqrt{\left(\frac{100*1500}{500*6.0}\right)} = 7.08$$

500 kVAr

No Capacitors

Figure 2 - Frequency Response Characteristic for a
1500 kVA, 6% Transformer and a 500 kVAr Capacitor Bank

2. Harmonic Measurements

Measurements are performed to characterize harmonic generating equipment and to verify the preliminary calculations. In conjunction with a computer simulation tool, harmonic measurements can be a very powerful method for evaluating harmonic distortion levels. Harmonic current and voltage measurements should be completed at individual loads to characterize nonlinear elements. The current measurement defines the harmonic generating characteristic of the load and the voltage measurement indicates the system response. Measurements on power systems can be quite costly due to manpower and equipment requirements. It is therefore wise to develop a measurement plan, with clear objectives, before beginning the effort. Modern

spectrum analyzers have greatly enhanced the ability to perform measurements inexpensively.

3. Performing Simulations

The initial model, as developed in step 1, is modified based on the measurement results. Detailed simulations are performed to estimate harmonic distortion levels for a variety of conditions (an example of simulated voltage distortion is illustrated in Figure 3). "Frequency scan" simulations identify system configurations that can cause harmonic problems due to resonance conditions and harmonic distortion simulations are completed to evaluate the effectiveness of harmonic filters.
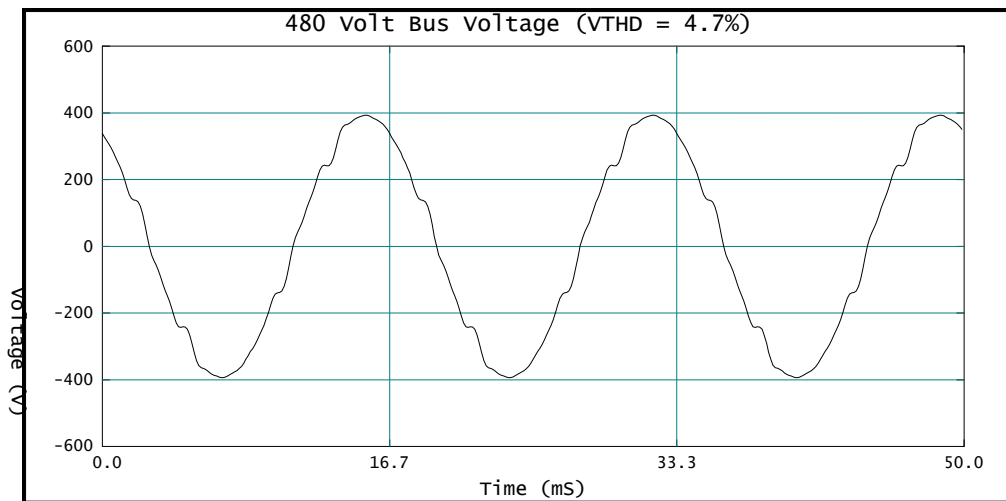

Figure 3 - Example of Simulated Voltage Waveform

4. Evaluating the Impact of Harmonics

A principal effect of harmonic distortion is to increase losses and heating in almost every component in the electric power system. While contributing almost no useful work, harmonic components of voltage and current increase the RMS value of voltages and currents. Interaction of harmonic quantities and resistive loss mechanisms in power system components generates excess heat. Some losses are actually sensitive to frequency, so that the power loss per ampere of harmonic current is actually greater than that for fundamental frequency currents.

Problems with harmonics often show up at capacitor banks first. The main reason for this is that capacitors form the resonant circuit that magnifies

harmonic current levels causing high voltage distortion levels. The highest voltage distortion in the resonant circuit occurs at the capacitor bank. This results in high capacitor currents at harmonic frequencies and overheating due to excessive RMS current is one common failure mode. Fuse blowing can also occur due to the high harmonic currents in the capacitor bank. The RMS current through a capacitor can be increased substantially by harmonics even when little voltage distortion exists because of the low capacitor impedance at harmonic frequencies. If voltage distortion is significant, insulation failure due to excessive peak voltage values can occur, since the peak value of the voltage can be as high as the arithmetic sum of all the individual harmonic voltages.

Resistive loads will actually absorb slightly more power from a distorted voltage since harmonic components will increase the RMS value of the waveform. The increase in power consumption is small for typical values of voltage distortion.

Line connected motor loads can be significantly impacted by harmonic voltage levels. Harmonic voltage distortion at the motor terminals is translated into harmonic fluxes within the motor. Harmonic fluxes do not contribute significantly to motor torque, and may act in a direction opposite to motor rotation. The effect on motors is similar to that of negative sequence currents. Decreased efficiency and torque, along with increased losses, heating, and vibration are symptoms of harmonic voltage distortion.

Power transformers are also affected by harmonic distortion. Distortion of transformer load current is the most significant impact, leading to higher than normal temperatures at "hot spots" within the windings. If harmonic distortion of the load current is high, transformers must be derated to account for the increased heating effect of the distorted current. Guidelines for transformer derating are detailed in ANSI/IEEE Standard C57.11O.

5. Determining IEEE 519 Compliance

It may be necessary to evaluate harmonic current production with respect to utility requirements. IEEE Standard 519-1992 presents a methodology for evaluating the harmonic current a customer injects onto the utility system. It also protects the customer by specifying maximum harmonic voltage distortion levels that utilities can supply. The standard should be used for guidance in the design of power systems with nonlinear loads. Table 1 illustrates example current requirements.

Table 1 - Harmonic Current Injection Limits for
Individual Customers (120V-69kV)

Individual Frequency Limits (% of I_L)

SCR	h<11	11-17	18-23	24-35	h>34	TDD
SCR<20	4.0	2.0	1.5	0.6	0.3	5.0
20<SCR<50	7.0	3.5	2.5	1.0	0.5	8.0
50<SCR<100	10.0	4.5	4.0	1.5	0.7	12.0
100<SRC<1000	12.0	5.5	5.0	2.0	1.0	15.0
SCR>1000	15.0	7.0	6.0	2.5	1.4	20.0

Note:

SCR = ratio of the short circuit current at the point of common coupling* to the maximum average demand load current

TDD = Total Demand Distortion, current distortion in percent of the maximum average demand load current (I_L)

* IEEE 519-1992 defines the point of common coupling (PCC) as: "A point of metering or any point as long as both the utility and the customer can either access the point for direct measurement of the harmonic indices meaningful to both or estimate the harmonic indices at a point of interference (POI) through mutually agreeable methods"

6. Developing Solutions to Harmonic Concerns

In the event that distortion levels are not within acceptable limits, the frequency response characteristics of the system can be altered by changing capacitor sizes or locations, by changing source characteristics, or by designing harmonic filters.

Shunt filters are the most common solution because they can provide reactive power support at the fundamental frequency and a low impedance path for one or more harmonic current components to flow. The filter components must be specifically designed to withstand the harmonic components along with the

fundamental frequency voltages and currents. In general, it is desirable to use capacitors with a higher voltage rating than the system.

The harmonic filter provides a low impedance path for harmonic currents, thereby minimizing harmonic voltage distortion problems. The filter is tuned slightly below the harmonic frequency of concern. This method allows for tolerances in the filter components and prevents the filter from acting as a short circuit for the offending harmonic current. This allows the filter to perform its function of providing a low impedance at the harmonic frequency while helping to reduce the duty on the filter components.

The general method for applying filters is as follows:

- Apply one single-tuned shunt filter first. and design it for the lowest generated frequency.

- Determine the filters effectiveness by determining the voltage distortion (THD) and the harmonic currents injected into the system. Compare values with specified limits (i.e. IEEE Std 18-1992 for capacitors).

- Vary the filter elements according to the specified tolerances and recheck its effectiveness.

- Check the frequency response characteristic to verify that the newly created parallel resonance is not close to a harmonic frequency.

- If necessary, investigate the need for several parallel filters, such as 5th and 7th.

Example Utility / Industrial Interface Case Study

The application of power factor correction capacitors in a nonlinear environment (ASDs) can create harmonic problems if resonance concerns are not evaluated. The following case study illustrates one possible method for evaluating power correction and harmonic concerns together. In addition, the impact of harmonic current limits, such as those outlined in IEEE 519-1992, are illustrated.

System Description:

Figure 4 summarizes the oneline diagram and harmonic current waveforms for the system to be analyzed. The system illustrated consist of a utility distribution feeder supplying an industrial plant. Source strength, feeder impedance, step-down transformer impedance, and loading can be considered typical. The harmonic current characteristics were determined from previous field measurements.

System Parameters:

12.5kV Source Strength:	200 MVA (0.78Ω)
12.5kV Capacitor Size:	3 MVAr
12.5kV Feeder Load:	5 MW
Distribution Feeder Impedance:	0.2Ω

Plant Load Summary:

480 Volt Bus #1:

Fluorescent Lighting (THD = 21.7%):	200 kVA
Miscellaneous Load (pf = 85%):	500 kVA

480 Volt Bus #2:

Induction Motor (pf = 85%):	200 HP
dc Drive (THD = 35.2%):	250 HP
PWM ASD - no choke (THD = 130.7%):	25 HP
PWM ASD - 3% choke (THD = 45.1%):	100 HP

120 Volt Bus #1:

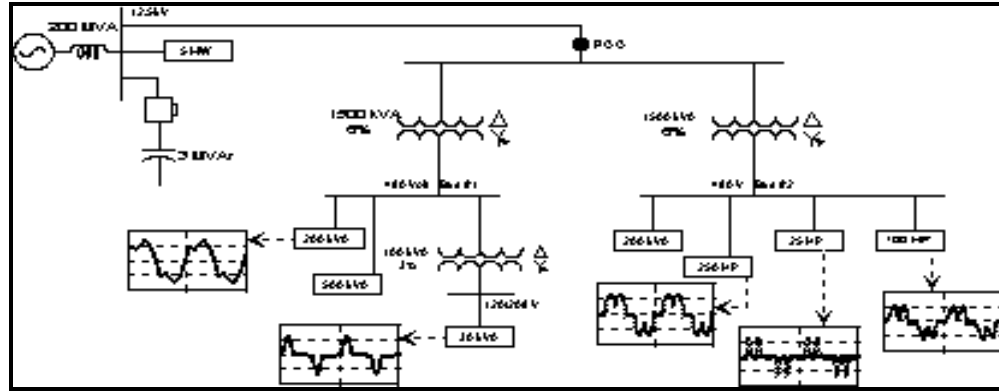|	
Office Load - SMPS (THD = 77.2%):	30 kVA

Figure 4 - Oneline Diagram for Interface Case Study

The initial case is with the plant operating as illustrated in the oneline (no power factor correction installed). The voltage distortion for each bus is:

12.5kV @ PCC - 0.3%   480 Volt Bus #1 - 0.6%

480 Volt Bus #2 - 2.7%   120 Volt Bus - 3.1%

As expected, there are no problems experienced with these distortion levels. In addition, harmonic current levels at the PCC are well within requirements. The current limits are determined from Table 1. The short circuit current at the PCC is 7288 amps and the maximum average demand load current is assumed to be 75% of the connected load value, or 45 amps. This yields a SCR of 162. Table 2 summarizes the harmonic current levels at the PCC for this case.

Table 2 - Harmonic Current Evaluation

	5th	7th	11th	13th	17th	19th	23rd	25th	TDD
519	5.4	5.4	2.5	2.5	2.5	2.3	0.9	0.9	6.8
Actual	3.1	1.3	0.9	0.5	0.5	0.2	0.4	0.1	4.2
Exceed	No	No	No	No	No	No	No	No	No

The next case investigates the effect of correcting the plant's power factor from approximately 90% to 98%. This is accomplished by installing 200 kVAr capacitors on both 480 volt buses. Recalling the hand calculation for estimating the resonance created when capacitors are added:

$$h \approx \sqrt{\frac{100 * kVA_{tx}}{kVAr_{cap} * Z_{tx}(\%)}} = \sqrt{\frac{100 * 1500}{200 * 6.0}} = 11.2$$

For this case, a resonance close to the 11th harmonic is created. This fact is significant due to the fact that 11th harmonic current is created by each of the nonlinear loads in the example system.

For this case, the voltage distortion for each bus is:

12.5kV @ PCC - 0.6%	**480 Volt Bus #1 - 2.3%**
480 Volt Bus #2 - 5.4%	**120 Volt Bus - 3.5%**

Table 3 summarizes the harmonic current levels for this case.

Table 3 - Harmonic Current Evaluation for the Case with
Power Factor Correction

	5th	7th	11th	13th	17th	19th	23rd	25th	TDD
519	5.4	5.4	2.5	2.5	2.5	2.3	0.9	0.9	6.8
Actual	4.1	2.4	2.9	0.8	0.3	0.1	0.1	0.1	5.3
Exceed	No	No	Yes	No	No	No	No	No	No

The 11th harmonic resonance, caused by the installation of the capacitor banks, has caused the 11th harmonic current limit to be exceeded.

The initial solution to this resonance case might seem to be installing 11th harmonic filters. However, it is important to remember that when installing filters, the tuning frequency should be below the lowest harmonic of concern.

The final case evaluates the effect of converting the 200 kVAr power factor correction banks into 4.7[th] harmonic filters. The impedance of the filter reactors can be determined using the following relationship:

$$X_R = \left[\frac{kV^2_{cap_{rated}}}{MVAr_{cap_{rated}} * h^2} \right] = \left[\frac{0.480^2}{0.25 * 4.7^2} \right] = 0.042\Omega$$

For the harmonic filter case, the voltage distortion for each bus is:

12.5kV @ PCC - 0.2%	**480 Volt Bus #1 - 0.6%**
480 Volt Bus #2 - 1.8%	**120 Volt Bus - 3.2%**

Table 4 summarizes the harmonic current levels at the PCC for this case.

Table 4 - Harmonic Current Evaluation for the Case with Harmonic Filters

	5th	7th	11th	13th	17th	19th	23rd	25th	TDD
519	5.4	5.4	2.5	2.5	2.5	2.3	0.9	0.9	6.8
Actual	1.1	0.9	0.7	0.4	0.4	0.2	0.3	0.1	2.9
Exceed	No	No	No	No	No	No	No	No	No

A more rigorous harmonic filter design [1] should be used when sizing the filter components. Basically, the filter capacitor size is determined by power factor correction requirements and the reactor design must be capable of dissipating the additional heat generated by the harmonic currents from the nonlinear loads and the utility system. The limits specified in IEEE Standard 18-1992 should be used to determine filter capacitor duty.

References

[1]   T.E. Grebe, M.F. McGranaghan, and M. Samotyj, "Solving Harmonic Problems in Industrial Plants and Harmonic Mitigation Techniques for Adjustable-Speed Drives," Presented at the ELECTROTECH 92, June 14-18,1992, Montreal.

[2]   D.E. Rice, "Adjustable Speed Drive and Power Rectifier Harmonics - Their Effect on Power System Components," IEEE Paper No. PCIC-84-52.

[3]   IEEE Standard 519-1992, "IEEE Recommended Practices and Requirements for Harmonic Control in Electric Power Systems."

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authors note: The SuperHarm datafile for this case study "HARMTECH.SHA" can be downloaded from the Electrotek bulletin board (HarmFlo User's Group section).

Large System Harmonic Analysis

Setting Up the Model:

The first step in any model is to obtain a oneline diagram. If this document is available from the customer, confirm all elements. When such a document is not available, take the information supplied from the customer and create your own. In both cases, there will be work to do once the base document is obtained.

Constructing the oneline diagram for the SuperHarm model should represent the elements as they will be entered into the data file. Information required for the data file, i.e. line reactance's, transformer voltage and impedance information, and system information, should appear on the oneline diagram. If it is possible to lump loads together, they should be represented as such on the oneline diagram. For those of you that have been modeling one or two bus systems this may seem to be a ridiculous amount of detail, but when your model represents several hundred elements it is crucial. The oneline diagram will be the flow chart to the data file. If it is a good representation of your system and is followed step by step in constructing the data file, testing and trouble shooting the model will be straight forward.
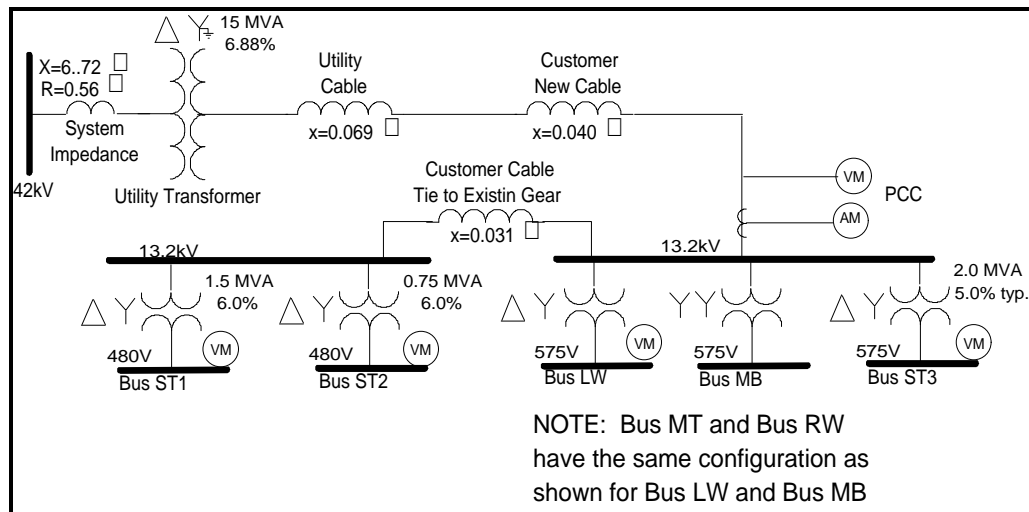

Figure 1

Constructing the SuperHarm Files:

When constructing a large model to be simulated in SuperHarm it is essential to use include files, so called 'modules' for those of you in the EMTP User's Group. This method of writing data files will result in smaller and simpler data files, because devices such as transformers that require four or five lines of code only have to be written once in the include file. The data file, figure 2, will call the include as many times as required passing unique parameters each time. Include files are used in three ways outlined below.

```
!Harmonic Analysis
!Brian Prokuda, ETK-PSE
!May 13, 1993

#include \projects\stl_tech\sims\stdata1.shd

!Source DE 41,560V 3569A 3ph fault
#include \shincl\3ph_src.shi (src,42kv,freq,srcv,rs,xs,rd)

!Utility Substation Transformer
#include \shincl\dy_xfmr.shi
(42kv,desb,tdesbmva,tdesbhkv,tdesbxkv,tdesbxt,tdesbrt,tdesbrn)
```

Figure 2

Define Files:

The first is the .SHD or Define include file. This makes running several unique cases very efficient. For instance, say it is necessary to analyze a plant in several load configurations. It is possible to write one data file and a define file representing each of the load configurations. To run each of the cases only the name of the define file needs to be changed in the data file, STDATA1.SHD in figure 2. Once the model is constructed and verified, this should make it very difficult to corrupt the data file. See a partial copy of STDATA1.SHD in figure 3 below.

It is useful to create the base case define file and modify the model as necessary to obtain reasonable results. Once satisfied with the model, the base case define file should be copied and renamed to represent each of the cases to be run. Even if only one value is to change, it is important to use a separate file so that other data isn't modified inadvertently. The define files are relatively small because they only contain three words per line and use little memory.

```
!stdata1
!Brian Prokuda ETK-PSE
!May 17, 1993

options
fbase = 60

retain voltagelist = {pcc2.a,lw.a,st1.a,st2.a,st3.a}
retain currentlist = {pcc2.a,lwdca}

#define         drviso              \shincl\dc40iso.shi

!setting switches to put devices in or out
#define         stocaps         0
#define         sto47           0

!defining transformers to be used at different loads
#define         lwxfmr              \shincl\dy_xfmr.shi
#define         mbxfmr              \shincl\yy_xfmr.shi
#define         mtxfmr              \shincl\dy_xfmr.shi
#define         rwxfmr              \shincl\yy_xfmr.shi
#define         3xfmr               \shincl\dy_xfmr.shi

!Source Data
#define         freq            60
#define         srcv            41560
#define         rs              0.56
#define         xs              6.72
#define         rd              2000

!utility transformer
#define         tdesbmva    15.0
#define         tdesbhkv    41.56
#define         tdesbxkv    14.1
#define         tdesbxt         6.88
#define         tdesbrt         1.60
#define         tdesbrn     0.0001
```

Figure 3

In combination with the 'if' command, a define statement may be used as a switch. An example of this may be seen in figure 4. A capacitor bank has been connected to the system, but will not be used in all of the cases to be run. If STOCAPS has been defined as a '1', then the capacitor bank is connected to the system. Otherwise the logical statement will be false and the include file will be ignored. The define command can also be used to define an entire path, i.e. DRVISO could be a keyword in a define statement and '\SHINCL\DC4OISO.SHI' is the path that DRVISO represents, see figure 3. In a second define file, representing another case, DRVISO might represent '\SHINCL\DC5OISO.SHI'. The directory 'SHINCL' is where the includes representing different type of system devices is located.

```
!   +++++++++++++++++++++ !
! start capacitors and filters
#if stocaps = 1
#include \shincl\lvcaps.shi (sto,cap_kva,cap_kv)
#endif

#if sto47 = 1
#include \shincl\mvfltr.shi (sto,sto47uf,sto47xl)
#endif
! End capacitors and filters
!   +++++++++++++++++++++ !
```

Figure 4

Includes that Represent System Elements:

Creating a separate directory, such as 'SHINCL', in a path independent of a specific project will allow SuperHarm cases to be constructed very quickly. Each time a new device is required for a project, it is saved in the library of include files. This way, it may be used for a study in the future. You will find that the majority of the files in the library will be non-linear load devices with harmonic spectrums from measured field data. That doesn't mean that other SuperHarm device models, such as motors, transformers, etc., can not be used. Often times it is useful to combine single branch devices into a three phase module. This should only be done if it results in a simpler data file. Below examples are shown for a DC drive and a delta-wye transformer.

```
!SuperHarm INCLUDE FILE
!40 HP DC Drive with isolation transformer

!BRIAN PROKUDA, ETK-PSE, May 13, 1993

!PASSED PARAMETERS (BUS, kVA 3ph, kV-LL)

!PHASE A
NONLINEARLOAD     NAME=%1^DCa
    BUS    =%1^.A          kVA    =@"%2 3 /"
    kV     =@"%3 3 SQRT /"    DF     =0.75
!
TABLE={{    1,     100.0,     -46},
!      {    3,       0.4,     -70},
       {    5,      16.9,     -53},
       {    7,       5.0,    -149},
!      {    9,       0.3,      84},
       {   11,       6.1,    -152},
       {   13,       2.8,     105},
       {   17,       3.5,     106},
       {   19,       2.1,       5}
       }
```

Figure 5 (Note: Phase B and C are similar to Phase A in this Include file)

```
!SUPERHARM INCLUDE FILE
!THREE PHASE DISTRIBUTION TRANSFORMER
!BRIAN PROKUDA, ETK-PSE, April 7, 1993
!PASSED PARAMETERS (BUS-H, BUS-X, MVA 3ph, kV-LL-H,
kV-LL-X,%x,%r,Rn)

TRANSFORMER     NAME     =%2^.DT
H     =DELTA     X     =WYE
X.A     =%2^.A     X.B     =%2^.B
X.C     =%2^.C     H.A     =%1^.A
H.B     =%1^.B     H.C     =%1^.C
X.N     =%2^.N
MVA     =%3     MVAB.HX     =%3
XRConstant     =Yes
kV.X     =%5     kV.H     =%4
%R.HX     =%7     %X.HX     =%6
BRANCH NAME = %2^ZN FROM = %2^.N TO = GROUND R=%8
CAPACITOR NAME = %2^CN FROM = %2^.N TO = GROUND uF= .0001
!
```

Figure 6

There are some pitfalls to guard against in using device includes. The first is obvious, if the include is wrong, it will be wrong each and every time it is used. It goes without saying that each include should be tested independently. A simple test case should be set up with no more than a source, source impedance, and the device being tested. Spectrums and wave forms of the test device should be printed for voltage and current. If the device was created from measured data, use it for sanity checking. Otherwise use your best judgment and any other resources available to determine if the simulated element is correct.

A second problem that can silently skew your modeled results are intermediate buses used in the include file. Say that a module is created to represent a filter bank, as shown in figure 7. The intermediate bus 'X7' connects the reactors with the capacitors. This bus may not be of interest for the simulation, so we are not concerned that the bus have a unique name. A problem results if the module is used more than once for the model. All of the capacitors will be connected to the same bus regardless of where the inductors are connected to the system. The danger in this is that the filters that you have specified aren't the same as those modeled and you haven't done anything that SuperHarm recognizes as an error. Further more, the effects can be subtle enough that frequency scans and other output may seem somewhat reasonable. It is important to name intermediate bus with unique names each time the module is called. This may be done by utilizing the device name for the bus or SuperHarm's increment command. This should raise enough concern to scrutinize the simulated results and investigate the model even if the results only appear slightly suspect.

```
!SUPERHARM INCLUDE FILE
!Three phase medium voltage harmonic filter
!BRIAN PROKUDA, ETK-PSE, December 17, 1992

!Med Voltage Harmonic Filter Design

!PASSED PARAMETERS (BUS, C in uF, Xl in Ohms)

BRANCH          NAME=%1^RXA FROM=%1^.A    TO=%1^X7A    X=%3
BRANCH          NAME=%1^RXB FROM=%1^.B    TO=%1^X7B    X=%3
BRANCH          NAME=%1^RXC FROM=%1^.C    TO=%1^X7C    X=%3

CAPACITOR       NAME=%1^C7A FROM=%1^X7A   TO=ground    uF = %2
CAPACITOR       NAME=%1^C7B FROM=%1^X7B   TO=ground    uF = %2
CAPACITOR       NAME=%1^C7C FROM=%1^X7C   TO=ground    uF = %2
!
```

Figure 7

Library Files:

The final type of include utilized is the .SHL or library file. This is an extension of the device includes described above. Using this module it is possible to group individual includes into one large include. An example where this might be used is PWM ASDs. Drives in different configurations, with and with out chokes, would have different harmonic spectra and would require an include to describe each case. Using the library include named 'PWM', all the different configurations could be combined and be associated with an identifier in the library file. This allows the include directory to be consolidated and more organized.

Testing the Model:

Before running the cases, it is important to verify steady state information. The least of which should be to check voltage on all three phases at each voltage level of bus. Entering an inappropriate value for a transformer impedance or shunt capacitor can result in unexpected voltage and currents. Two cases will prove to be most meaningful in determining the accuracy of the model and SuperHarm code. First is a no load test to verify sources and transformer ratios. This also helps identify network islands and inadvertent shunt impedance's. The second is to place short circuits in key locations of the model. If a short circuit program is at your disposal, results may be checked against it. Otherwise the IEEE Red book offers the straight forward MVA method of performing fault calculations. Promising results from these two test should give a fair confidence level in the accuracy of the skeleton model.

Running Cases:

The first observation when checking the steady state results after running a simulation under full load is that the bus voltages are significantly lower than nominal. Keep in mind that the model must represent the actual plant operations. Being the nominal line voltage was 42 kV, three single phase sources were created to provide a line voltage of 42 kV. Next transformers, cables, and loads were added. As the load current increases, so does the voltage drop across each of the system impedance's. In the plant, transformer taps will be adjusted and the source voltage may be higher than nominal. A combination of these practices should be reflected in the SuperHarm model so that the voltage distortion accurately represents that in the plant.

When a plant under construction is being modeled, engineering judgment plays a large role in determining the proper configuration. When analyzing these systems, results from similar analysis and engineering peers should be consulted. If an existing plant is being modeled, measurements representing a base case should be made. When the base case modeled, it will need to be run several times to become a representation of the actual plant. Between cases transformer ratios will need to be adjusted, damping resistors may need to be added in parallel with the source impedance's, and current sources representing harmonic loads may require adjustments. Ultimately it is engineering judgment that determines when the base case is accurately represented.

When running large cases, the use of voltage and current lists are crucial. If you allow SuperHarm to solve for all voltages and currents you might as well plan on going home when the case is ready to run. Critical voltages and currents should be identified and placed in the retain lists. This will reduce the solve time by an order of magnitude and reduce the elements that appear in the output file.

Verifying the results:

If you have made it this far in the modeling of the system, you should be feeling pretty good. You have gone through rigorous testing of each of the include files to assure that the spectra used is reasonable and that intermediate bus have not been duplicated. Intentional faults have been placed on the system to verify fault levels and three phase voltages and currents have been summed together to assure that they add to zero. Particular attention was paid to the steady-state results to assure that voltage ratios were a fair

representation of the plant configuration. The first case is run and the voltage and current wave forms look nothing like you expected that they would. It has been determined that there is yet another concern to beware of.

Often times when modeling a system it is necessary to add branches that allow the program to create a solvable set of equations, but may not truly represent the system out in the field. Remember when using the non-linear load model that it is a current source. Regardless of what the system impedance is at a given frequency, the model will inject the specified current. Where this can become a problem is using the include file of a device with a measured spectra from another system. For instance, a drive spectra was obtained on a system that allowed zero sequence current to flow. The same spectra is used for a model representing an ungrounded wye system. SuperHarm requires the neutral of the wye source to be connected to ground, so you put a small capacitive branch in. This is a reasonable representation of the system in the field. In the field, the impedance will be large enough as to not allow zero sequence current to flow. Our drive include file has a current source that pumps third and ninth harmonic current into the modeled system regardless of the impedance. The result is a highly distorted voltage that will not be present in the field.

Conclusions:

An appropriate comment when modeling large systems is, not to rest easy until the recommendations based on the simulation have been implemented in the field and were successful. At all times the engineer should remember that the program is a tool and requires an educated and alert user. In this article, a structure of modeling has been outlined to help users recognize common areas that engineers may go astray and ways to avoid following similar paths. It is encouraged for others to share there experiences with modeling in future articles so that the pitfalls for a variety of systems may be identified.

The power of having a well developed include library has also been shown. Using the techniques outlined above, it is possible to build three phase models in the same time as single phase cases. With three phase cases, the effects of cancellation and zero sequence currents can be identified. This results in a more accurate representation of the system under investigation.

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