EMTP
Tech Notes

for users of the Electromagnetic Transients Program

in this issue:

Letter from the Editor:

EMTP Tech Notes is the technical newsletter provided to members of the EMTP User's Group. The newsletter is a quarterly technical publication highlighting contributions from members of the User's Group. This newsletter is published using Microsoft Word for Windows 6.0. If you wish to contribute an article, please contact Susie Brockman or myself for appropriate text and figure formats. Contributions in the following areas are welcome:

Technical articles
Modifications / enhancements to the code
Case studies / unique simulations
Research projects
EMTP data preparation / model development
Modules 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 EMTP User's Group and this newsletter will help to serve the needs of the members. Thanks to the authors for helping to put this issue together. As always, I'm open for suggestions regarding this publication and the User's Group in general.
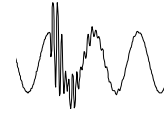
Thanks for your support

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EMTP Case Study Workbook

June 1995 Update

This article summarizes the changes that were made to the EMTP Case Study Workbook for the annual update. The workbook is a collection of case studies and EMTP data preparation examples that was originally created for members of the EMTP User's Group. The workbook has been distributed to the group for four years, and in addition, has been used as training material for a number of in-house training sessions and case study workshops.

This year's workbook remains a four volume set including:

Volume 1: EMTP Overview:

History of the EMTP, applications and capabilities of the EMTP. overview of the EMTP-PC Workstations (OS/2 and Windows)/

Volume 2: System Modeling Techniques:

Summary of system modeling techniques, with emphasis on switching studies. Includes examples of data for EMTP elements and auxiliary (AUX) routines.

Volume 3: Utility Transmission and Distribution:

Introduction to capacitor switching transients, the restrike transient, magnification at lower voltage capacitors, frequency scans, transients at transformer terminations. Case studies illustrating line and transformer energizing, ferroresonance, statistical simulations, motor starting, and steady-state phenomena.

Volume 4: Power Quality and Power Electronics:

Overview of TACS for power electronic modeling. Case studies for power electronic devices, such as rectifiers,

inverters, drives, and SVCs. Evaluation of power quality related events such as nuisance tripping of adjustable-speed drives.

This year's update includes a number of significant modifications:

1. EMTP data module tutorial (Volume 2)
2. Enhanced capacitor switching section (Volume 3)
3. Power electronics modeling using EMTP (Volume 4)
4. Technical reference material (papers, etc.) has been included at the end of each volume.

In an addition to the major changes, each volume has been revised to include the most up-to-date presentation material. The EMTP data module tutorial is essentially a stand-alone presentation regarding the creation (illustrated in Figure 1) and usage of modules. The user is stepped through the process of gathering the data for a module, creating the EMTP data, "compiling" the module into an include file, and finally, using the module in an EMTP data case.
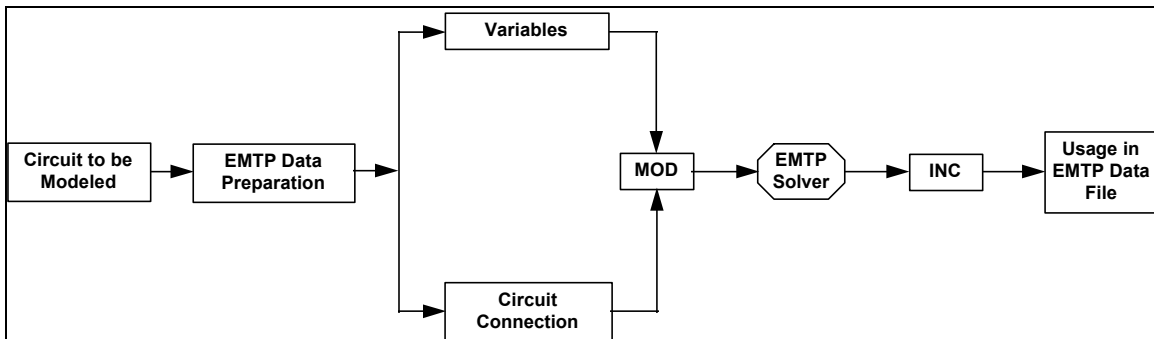

Figure 1 - EMTP Data Module Methodology

Additional material concerning modeling tips and techniques has been included in Volume 2. Examples include:

- modeling accuracy
- system simplification
- time step selection
- time step error
- selection of simulation length
- numerical oscillation and its elimination (illustrated in Figure 2)
- debugging the simulation model, including "kill codes"
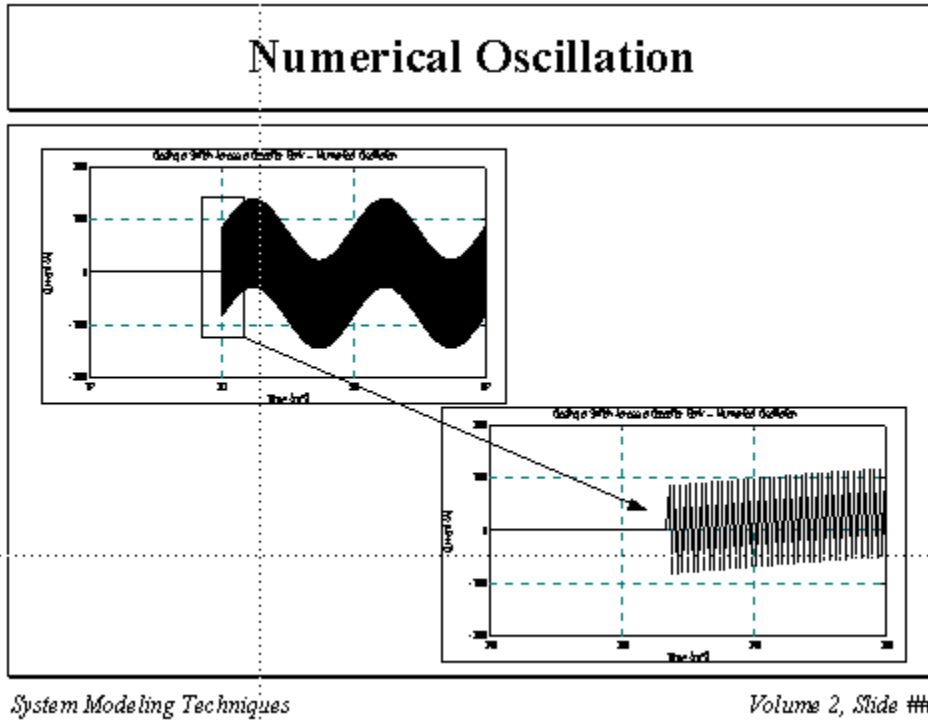- model verification.

Figure 2 - Illustration of Numerical Oscillation Slide

The capacitor case study section now includes many more examples of field measurements of various events, as well as statistics regarding quantities such as transient voltage magnitude, energizing frequency, duration of the event, and time-of-day.
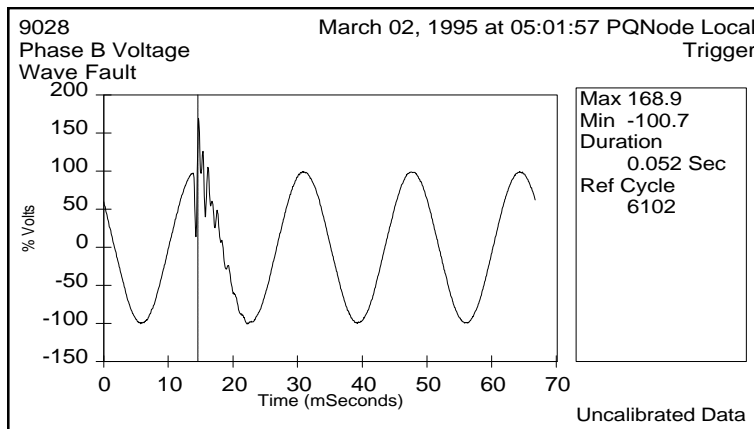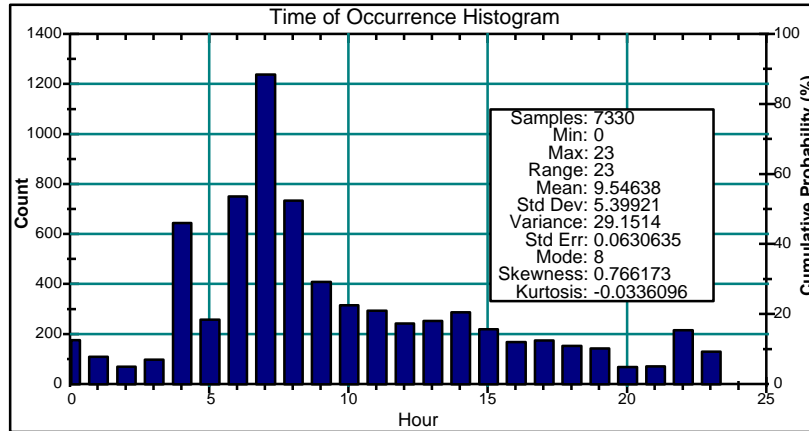

Figure 3 - Example Distribution Capacitor Switching Event

In addition, several examples of overvoltage control techniques are now illustrated: synchronous closing control, pre-insertion resistors, and pre-insertion inductors.

Time of Occurrence Histogram

Samples: 7330
Min: 0
Max: 23
Range: 23
Mean: 9.54638
Std Dev: 5.39921
Variance: 29.1514
Std Err: 0.0630635
Mode: 8
Skewness: 0.766173
Kurtosis: -0.0336096

Figure 4 - Voltage Transient, Time of Occurrence

A beginning of the tutorial concerning distribution system modeling techniques has also been included in Volume 3 this year. This work, as well as an EPRI project (Distribution System Power Quality / Cold Load Pickup Modeling Guide) currently underway, will serve as the basis for the upcoming workshop.

Volume 4 has been expanded to include more information regarding power electronics / TACS modeling.

In addition to the workbook, the EMTP Lab book has been included this year. The lab book is a collection of example cases from the Power System Analysis Using the EMTP course held each January in San Francisco (sponsored by University of Wisconsin-Madison). The lab book provides a useful set of exercises for a new user to work through during the initial stages of the EMTP education process. The exercises are based on one system (illustrated in Figure 5) that adds new power system elements with each successive case, as well as changing the phenomena of interest.
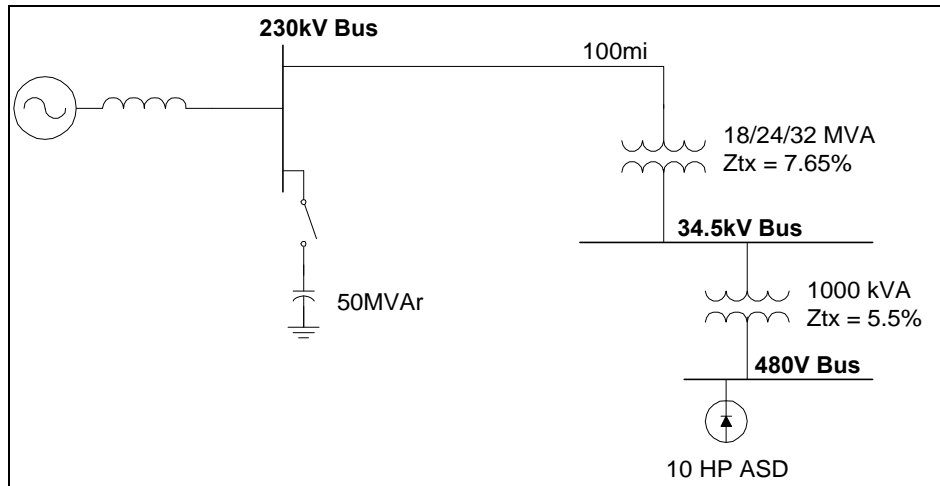
Figure 5 - One-line Diagram for EMTP Lab Book Exercise

I am hopeful that the changes made to the workbook will be useful to the members of the group and I would expect that the workbook will continue to grow. For additional information concerning the workbook, feel free to contact me (tgrebe@electrotek.com). **To order an update, please contact Susie Brockman (susieb@electrotek.com).**

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Transient Analysis
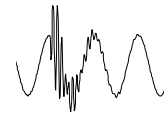
Transient Overvoltage Phenomena from Drive Operation

Introduction

In a previous issue of the EMTP Tech Notes (94-4) several of the voltage notching concerns, associated with large induction motor adjustable-speed drives (ASDs)were discussed. Building on the concept of steep wavefronts exciting circuit resonances, a brief review of the tested affects and remedies of the adverse voltage notching was presented. An update to that study is included below.

During the last several months, two utilities were experiencing problems on their distribution system during initial startup of large drive installations. In both cases, a large 4160V, 6000 HP drive was installed for pumping operations. After startup of these drives, complaints were received about clocks running fast and in one particular area, (over ten miles away), a power line carrier communication system was not operating properly. The power line carrier frequency was about 5700 Hz. It appeared as though there was indeed a way to get more hours out of a day.

In another location, several miles from the pumping station, a unique problem had emerged. Apparently some of the farmers in the area had automated feeding schedules for the farm animals and the fast running clocks were causing the livestock to get fed more frequently than usual. This may have satisfied the hogs, however the farmers were using more grain than expected.

It was suspected that the problems encountered on the distribution system were directly caused by voltage notching affects from the newly installed drives. The two pumping stations were identical, with the only difference being- the surrounding distribution system. Figure 1 shows a simplified one-line diagram of the pumping stations.
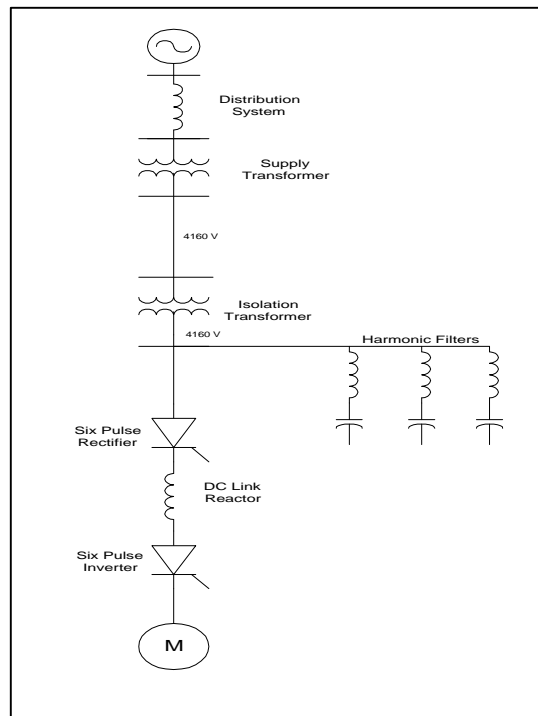
Figure 1 - Simplified One-line Diagram of Pumping Station

To better understand the problems that were encountered, on site measurements were taken at each facility.   Figure 2 shows a typical voltage and current waveform that was recorded at one of the pumping stations. From the current waveform, it is observed that the site was running the drive without the filters in service (which was not expected).   Figure 3 shows the voltage that was recorded at the primary of the distribution transformer for the same site.

Expansion of the voltage waveform showed that the high frequency ringing superimposed on the voltage waveform was about 2000 Hz. The other site had similar voltage and current waveforms except that the ringing frequency was about 6000 Hz, which was close enough to cause problems with the power line communication circuitry.

Measurements were also made at the farms involved to determine to extent of the voltage disturbance on the distribution system. The measurements showed that ringing was also apparent at the farms and that the high frequency ringing crossed voltage zero several times a cycle, thus explaining the fast running clocks.

The pumping station with the 6000 Hz disturbance was shut down pending solution of the notching problem and the other site threatened to have the plug pulled if an immediate solution was not found.
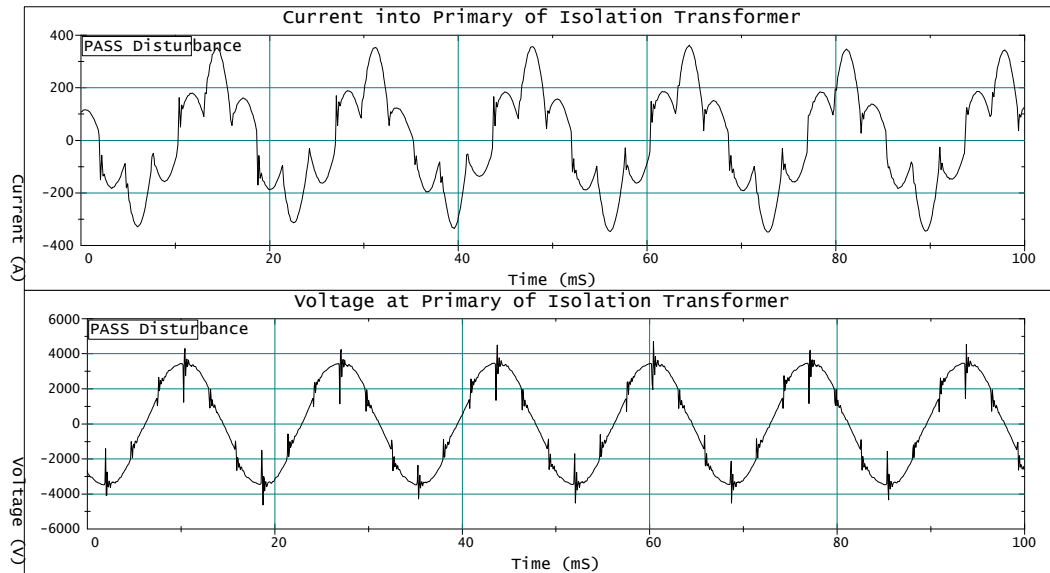
Figure 2 - Typical Voltage and Current Waveform Recorded at Primary of Isolation Transformer
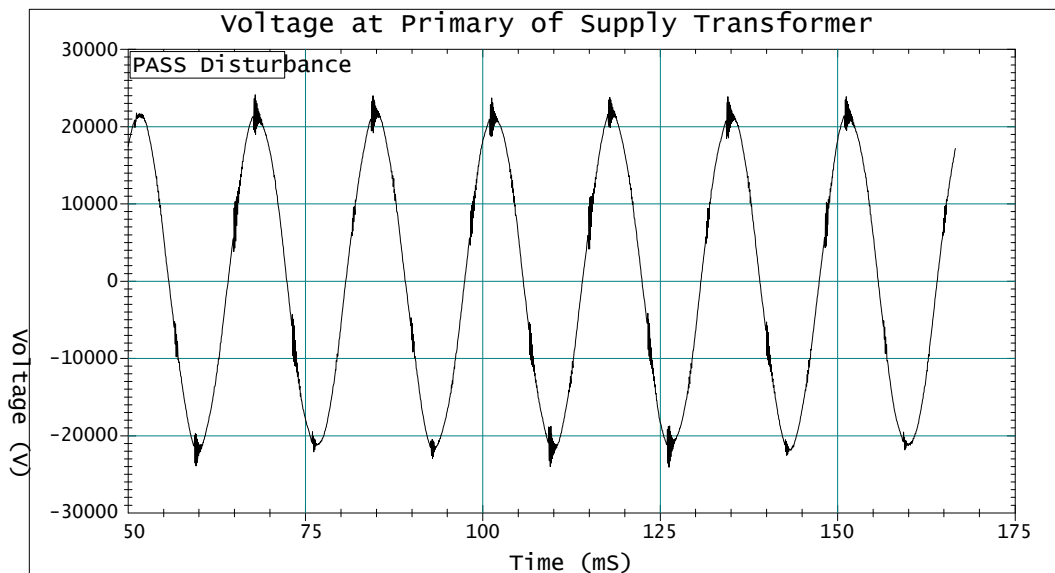

Figure 3 - Typical Voltage Recorded at Primary of Distribution Transformer

Cause and Effects of High Frequency Ringing

The high frequency, high amplitude disturbance superimposed on the voltage waveform is due to the high di/dt of the load current during commutation (i.e. turn-on current rate-of-rise through each thyristor switch). From Figure 2, it

can be seen that the high frequency ringing occurs on the 4160 bus voltage during each current commutation.

Since all loads will have some capacitance whether in the form of stray capacitance, power factor correction, surge suppressers, motor surge capacitors, cable capacitance or even snubber capacitance; the abrupt change in voltage and current during commutation will excite natural resonances of the circuit in a oscillatory manner. If the capacitance involved is large enough, ringing will occur (as seen in the figures).

It is not clearly understood, without extensive modeling or testing, how the high frequency disturbance passed through the isolation transformer or substation transformer virtually unaffected. It may be necessary to develop high frequency models of the isolation transformer and substation transformers to fully understand this phenomena. For this type of analysis, a transformer can be modeled by numerous pi sections, where a mathematical matrix is formed representing winding inductance, winding-to-winding capacitance, winding-to-case capacitance, and winding-to-ground capacitance. It may also be necessary to model mutual coupling between the phases. Information for this type of analysis has to be provided by the transformer manufacturer and is usually difficult to obtain.

Since the transient can propagate past the transformers into the distribution system, there may be more remote effects. In some cases, local resonances could result at locations remote from the point of common coupling (PCC). It is noteworthy to recognize that high frequency oscillations can be excited on the primary distribution system if the following conditions exist:

1. The system is lightly loaded. Resistive loads on the distribution system will provide damping at the high frequencies excited by the notching.

2. There are no shunt capacitors on the distribution system. Shunt capacitor banks move the system resonance to lower frequencies that can be excited by the drive's characteristic harmonics, rather than the high frequencies that can be excited by the notching transients.

3. The system is relatively weak. If the step down transformer impedance is very large compared to the short circuit impedance on the high side, notching transients should not be as severe on the primary.

Control of Transient Overvoltages from Drive Operation - - - There are several methods that have been investigated to control the effects of the transient

overvoltages seen from drive commutation. If the amplitude and frequency is excessive, it is necessary to dampen and change the resonant effects by providing a shunt for the transient.

Since a capacitor is a low impedance path for high frequency transients, it may be applied to absorb the transient provided other problems are not created. The best general solution is to add a capacitor to the primary distribution system that does not cause a problem at lower resonant frequencies. If the drive installation includes 5th, 7th, and 11th harmonic filters, it should be possible to add a capacitor on the primary that tunes the system below the 11th harmonic. It is recommended that the drive never be run without filters; harmonic currents injected from the drive without filters may be high enough to result in significantly higher current duties for the capacitor. The sizes successfully installed to date have varied from about 1200-1600 kVAR.

The main disadvantage to this application is that high transient conditions could still exist internal to the facility. The impact on other equipment connected to the 4160 V bus could see high voltage stresses and may result in early degradation of insulation and equipment. If the facility already has a large amount of filter vars, it is possible that there will be leading power factor during light load conditions.

Adding a capacitor to the secondary voltage level can also control the notching, but is generally less effective. As mentioned earlier, the impulse nature of the drive current and voltage notch will cause the added capacitor to ring with the equivalent inductance of the circuit. Since each notch is like a momentary short circuit, the resonant circuit with the added capacitance, is excited multiple times in each 60 hertz cycle. The result is almost a continuous oscillation since the transient condition does not have enough time to decay to zero before the next commutation (Figure 5). Since capacitor application at the 4160 V buses can still result in ringing, but at a lower frequency, it is not the best solution to the problem.
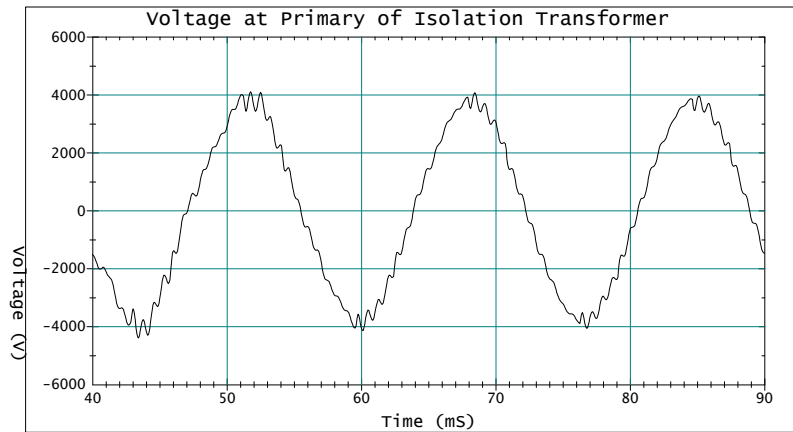
Figure 5 - Voltage at Primary of Isolation Transformer with 150 kVAR Capacitor Applied at Primary of Isolation Transformer

A capacitor located at the primary distribution system however, seems to provide better attenuation effects. The capacitor would supply two functions, first if there is a distribution resonance the capacitor detunes the distribution system resonance to eliminate amplification of the transient. Second, the capacitor absorbs a significant amount of the transient and prevents propagation of the transient into the distribution system. Although the capacitor is slightly affected by the voltage notching, there is enough inductance and resistance between the drive and shunt capacitor to significantly limit adverse effects. The capacitor would have to be sized such that other harmonic problems are not produced. This would vary on a site to site basis.

Another method that has been recently tested successfully is the installation of a small RC network at the primary side of the isolation transformer. As mention earlier a small capacitor at the 4160 bus does provide a path for the high frequency transient however it also created a lower frequency transient voltage that didn't have enough time to decay before the next commutation (above).

It was thought that a small resistance added in series with a 4160 V capacitor bank would be enough to dampen the transient before the next commutation. If the method worked, it would be a more cost effective solution than the distribution system capacitor application. To investigate the effectiveness of an RC network, a detailed EMTP model of the pumping station that had the 6000 Hz ringing was developed. The distribution system was modeled about 30 miles back from the pumping station. The model was verified by comparing the simulated waveforms with the measured waveforms. Figure 6 shows a comparison of measured waveforms and the EMTP waveforms which shows good

correlation. The measured waveform does not have as high of peaks as the simulated waveform due to the digitizing rate of the monitoring equipment; the peak was missed by the A/D card.
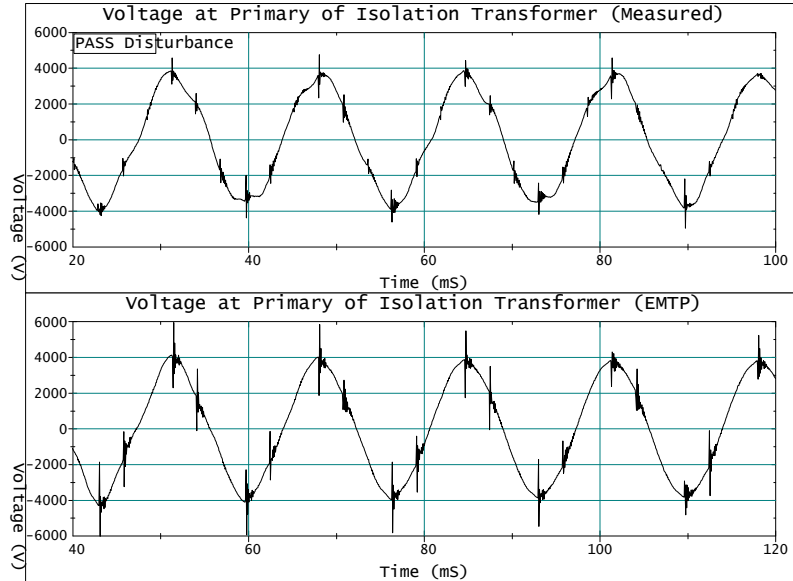
Figure 6 - Comparison of Voltage Waveforms Between Measured and Simulated

Several sizes of RC networks were evaluated to determine the lowest size capacitor and resistor that would effectively reduce the voltage notching effects. For this site it was found that a 150 kVAr capacitor in series with 1 ohm was sufficient enough to trap the high frequency transient and not cause additional problems. Figure 7 shows the voltage at the primary of the isolation transformer with the RC network. Although there is some ringing present on the 4160 V bus the distribution system voltage is substantially cleaner as shown in Figure 8.

Voltage at Primary of Isolation Transformer

Figure 8 - Voltage at Primary of Isolation Transformer with RC Network
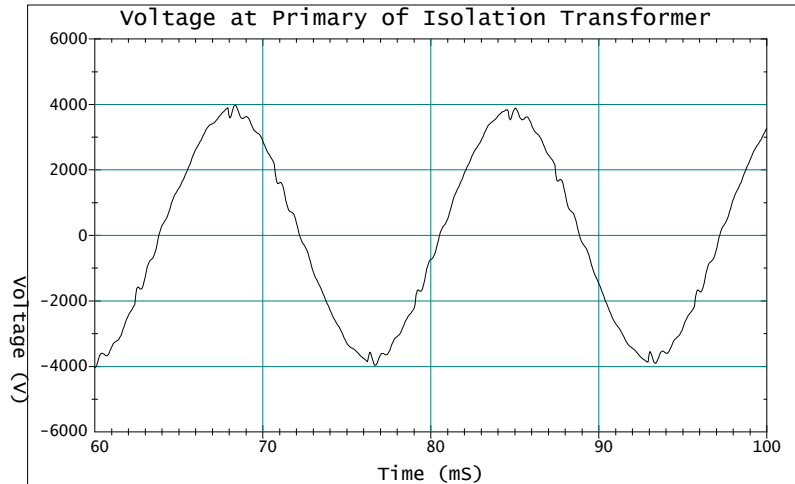
Voltage at Primary of Distribution Transformer
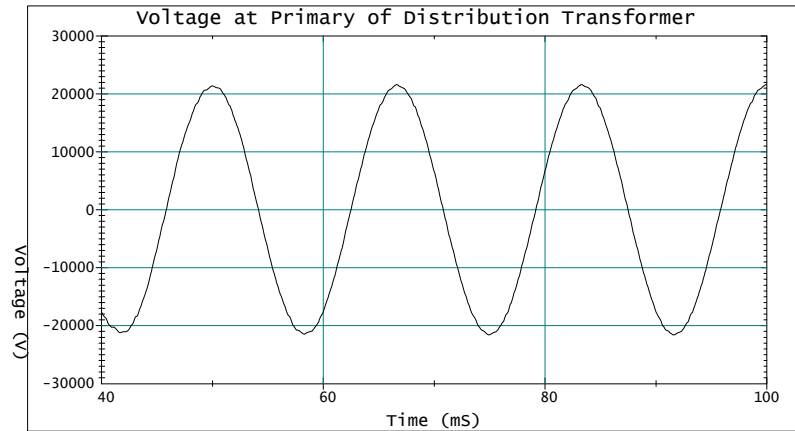
Figure 9 - Voltage at Primary of Distribution Transformer with RC Network

The RC network was implemented at the pumping site and the site was restored to service and has been operational for several months without complaints or problems. The only disadvantage to this method is the losses associated with the resistor, however it is much better than loss of revenue due to downtime and more cost effective than purchasing a distribution capacitor.

The site with the 2000 Hz ringing decided to implement a 1600 kVAr capacitor at the primary of the distribution transformer to control the ringing. The plug was never pulled and the site has been operational since --- *everybody is happy.*

Additional Comments

The classic method to control notching effects is to add enough inductance in series with the drive so that the notching at the source side is minimal (notching voltage drop across the insulating inductance). For large drives on relatively weak systems, this may not be a feasible solution because of voltage regulation concerns at the drive. Also the isolation inductance would probably be significantly more costly than the capacitor solution.

Another possible method to control the voltage transient is to limit the high di/dt of the drive current. This can be done with modification of the converter thyristor circuits through addition of delay reactors that have square saturation characteristics and with sufficient turn-on voltage/current support capability. An isolation inductance should have a fairly low X/R ratio to significantly change the slope of the drive current waveform during commutation; this will help to significantly lower L*di/dt effects.

Conclusions

As larger drives are added to the power system, unique problems have begun to surface. If you have experienced a unique problem, please feel free to contact Electrotek Concepts, Inc. for possible publication in the EMTP Tech Notes. Any other suggestions about practical solutions to the voltage notching problems that were discussed are welcomed.

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Flicker Meter Module
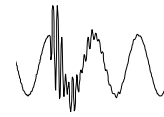
Introduction

To facilitate the overall system model development for industrial and utility studies, an EMTP input data module approach is being implemented by Electrotek (Refer to Tech Notes 93-1 and 94-4). With this approach, EMTP models of power systems can be logically organized. An overall system model is structured by interconnecting a set of circuit block modules. As a result, the developed system model is easy to read and modify. The usage of the EMTP input data modules can be found in Chapter 19 of the EMTP Rule Book. A newly developed module, the flicker meter module, has been implemented with success for the accurate analysis of flicker.

Before proceeding with description of the flicker meter module, it is worthwhile to discuss the procedure implemented in the EMTP simulations for analyzing flicker since there are many differences in flicker definitions. Some examples are given below.

1) *Percentage RMS Flicker*

Sinusoidal Flicker	Square Wave Flicker
$100*(A-B)/(A+B)$	$100*\sqrt{2}*(A-B)/(A+B)$

2) *Percentage Peak Flicker (for any waveform)*

$$100*\sqrt{2}*(A-B)/(A+B)$$

3) *dE Flicker*

$$2*(A-B)/(A+B)$$

In the above expressions, A and B are the maximum and minimum peak magnitudes of the instantaneous voltage respectively with the same polarity at the monitoring location.

From these expressions, one can find that percentage RMS flicker by these definitions is accurate only for sinusoidal or square wave voltage disturbances. However, in practice, it has been observed that the voltage flicker changes frequently and cannot be described by any simple variation rules such as sinusoidal or square waves.

The peak flicker and dE flicker definitions are supposed to be applicable for any waveform. However, it is observed that both of these definitions use a factor of $\sqrt{2}$ to convert the RMS voltage magnitude to the corresponding peak voltage magnitude. As shown in the following example, the $\sqrt{2}$ conversion factor is not always applicable. In the given example, Figure 1, the RMS value of a saw tooth waveform is calculated. Using the definition of the root-mean-square, the RMS to peak magnitude conversion factor for the saw tooth waveform is found to be $\sqrt{3}$ instead of $\sqrt{2}$.
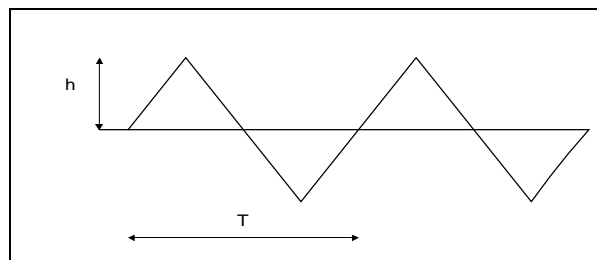
Figure 1   Saw Tooth Waveform

To avoid the confusion in voltage flicker definitions, a demodulated flicker voltage waveform and its frequency spectrum are used to characterize voltage flicker. An EMTP TACS module for the voltage flicker calculation was developed. The module reads the instantaneous voltage at a monitoring location and outputs a demodulated flicker voltage waveform. The method used to separate voltage flicker from its 60 Hz carrier voltage is outlined in Section 6 of the CEA research Report: "Contract NO O42 T 178, Analysis of Flicker from Arc Furnaces", prepared by Ontario Hydro in 1983. In this CEA report, instantaneous voltage flicker is obtained through a signal processing procedure containing the following four steps:

1. Voltage signal full-wave rectification
2. Hz notching filtering
3. Hz low-pass filtering
4. DC voltage buckoff

In this study, minor modifications on this procedure were made. The signal processing in the EMTP voltage flicker calculation module is illustrated in Figure 2.
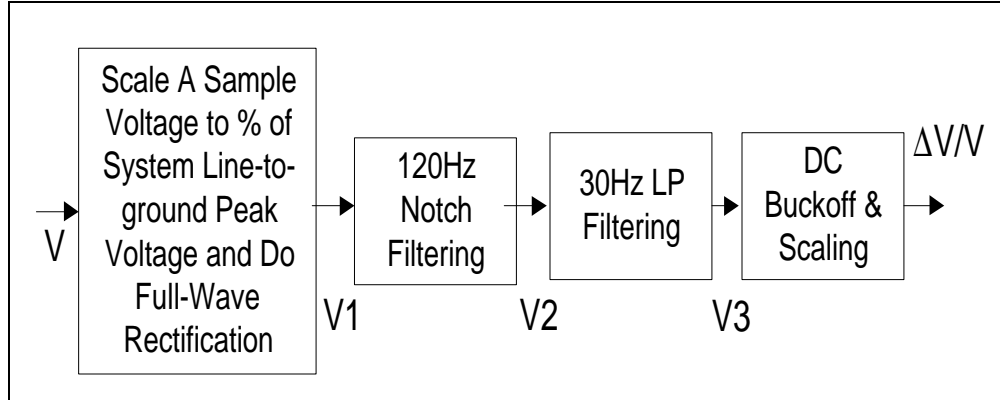
Figure 2 Flow Chart for Instantaneous Voltage Flicker Calculation

The module was tested using a known disturbance signal.   The sampled voltage waveform, intermediate values of the signal processing, and the output flicker voltage waveform from a simulation are presented.

The waveform of the given disturbing voltage is shown in Figure 3. This voltage consists of the 60 Hz carrier component and 5 Hz modulation component. In the simulation, the waveform was produced using EMTP TACS voltage source defined as follows:

$$V(t) = \sqrt{2}\{A + B\sin(5\boldsymbol{w}t)\}\cos\boldsymbol{w}t$$

Where: A=10,000 Volts

B=200 Volts

w=377 Rad/s

In Figure 4, the close-up of the top part of the monitored voltage waveform is given to show the voltage fluctuations clearly. The quantity presented in Figure 5 is the signal after the input voltage scaling and rectification. In Figures 6 and 7, the voltage signals after 120Hz notch filtering and 30Hz low pass filtering are plotted. Finally, the dc component of the V3 signal is removed to obtain the instantaneous voltage flicker as shown in Figure 8.
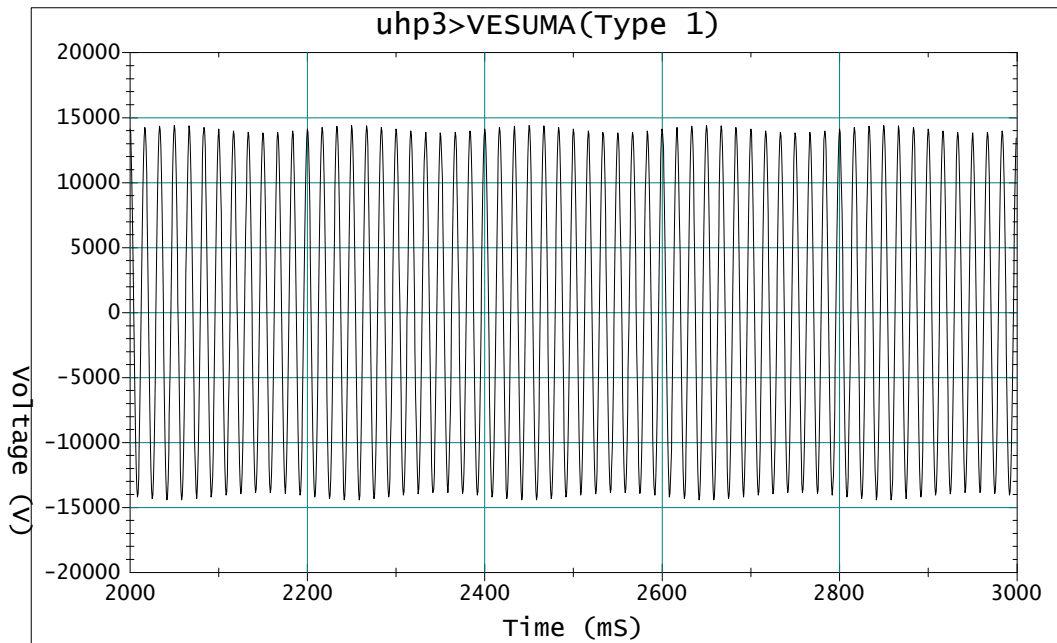
Figure 3 Voltage Waveforms for Flicker Meter Test (V)
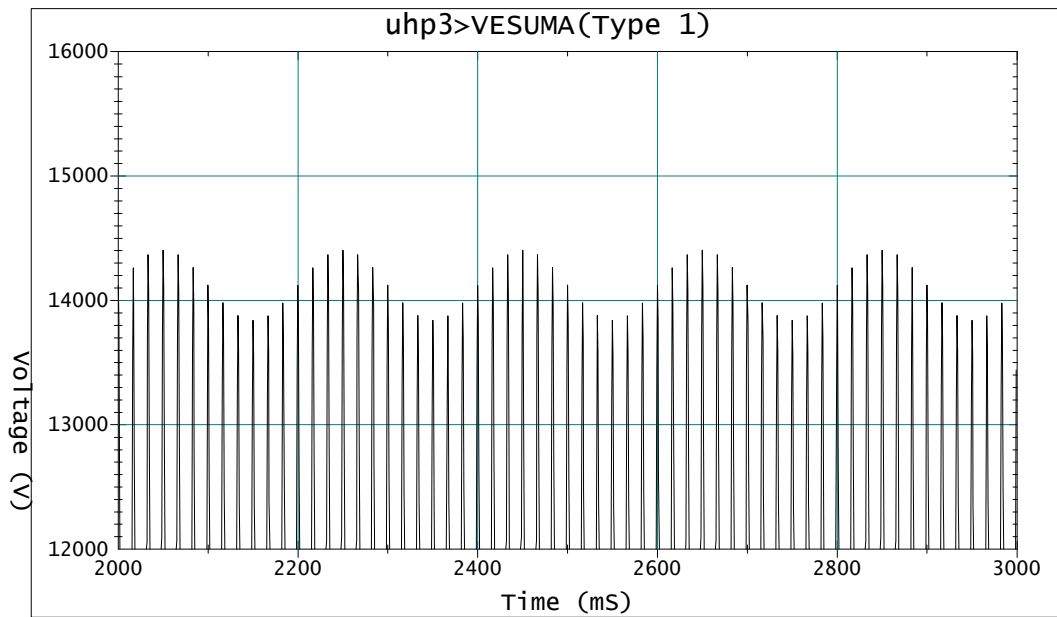
Figure 4 Test Voltage Close-up (V)
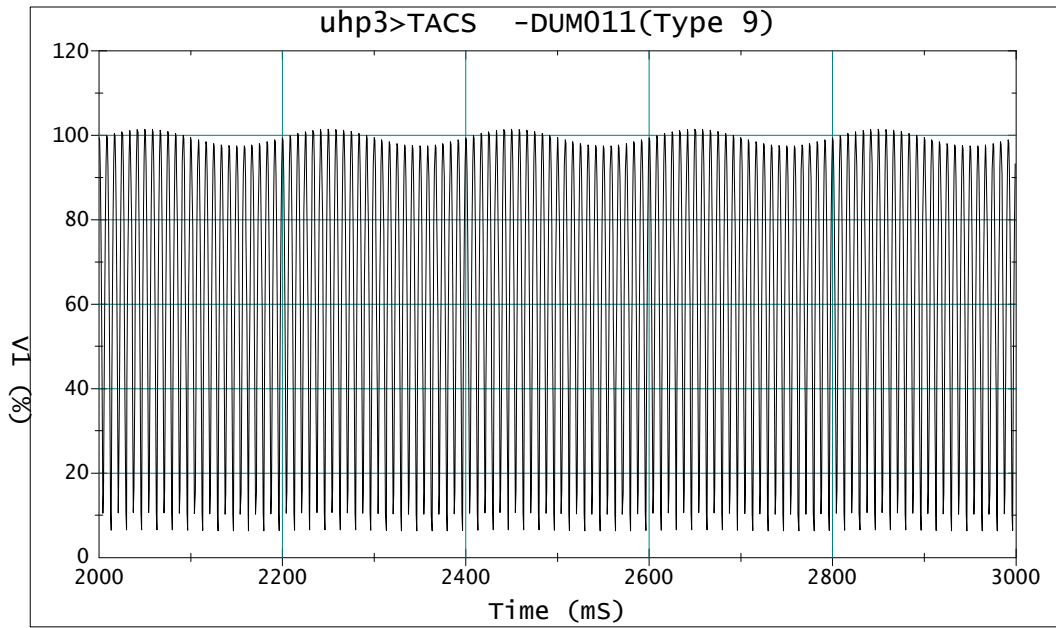
Figure 5 Percentage Voltage after Scaling and Full-Wave Rectification (V1)
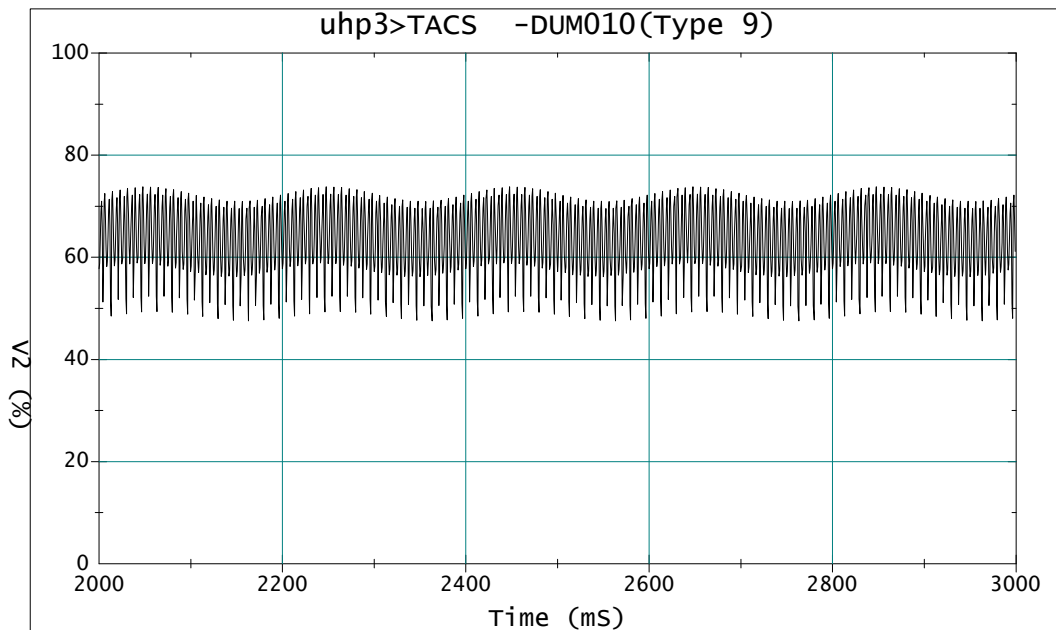
Figure 6 Percentage Voltage after 120 Hz Notch Filtering (V2)

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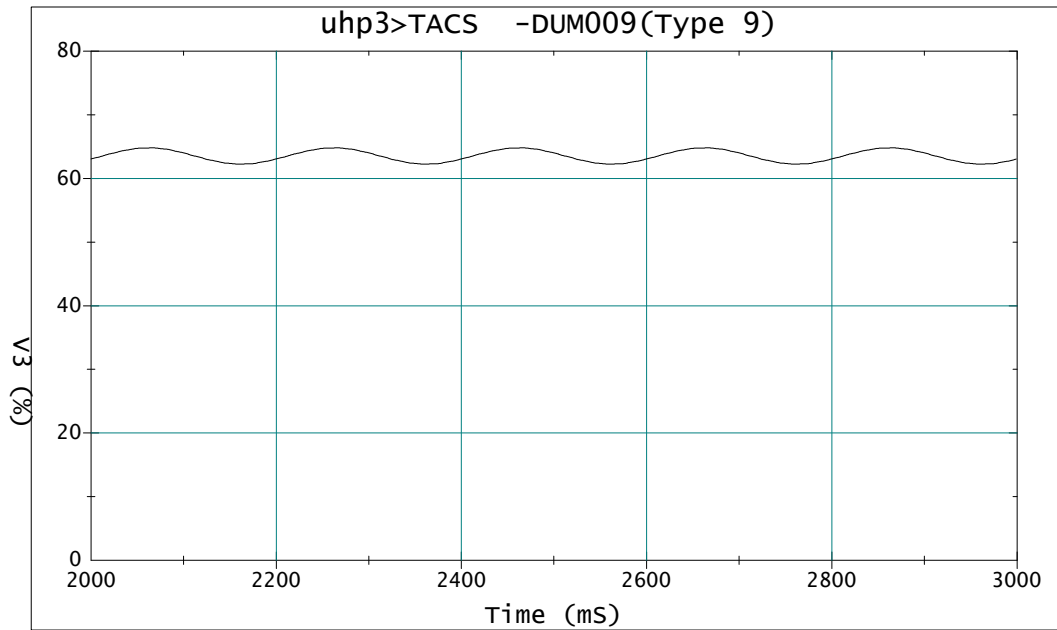
Figure 7 Percentage Voltage after 3O Hz Low Pass Filtering (V3)

uhp3>TACS   -DVMPCA(Type 9)
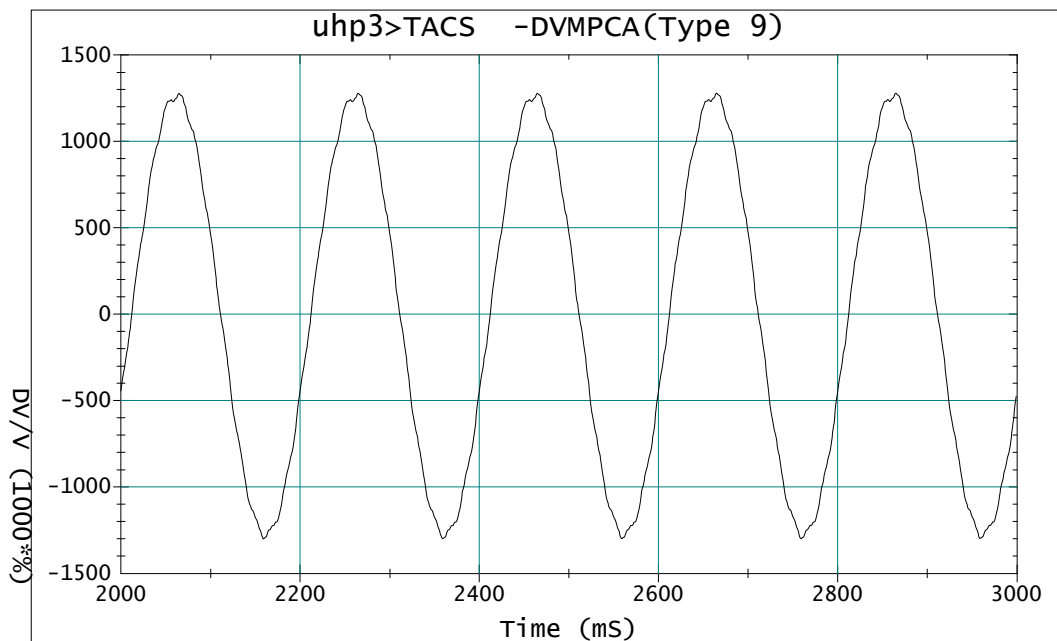
Figure 8 Instantaneous Voltage Flicker (DV/V) after DC Buckoff

The obtained output from this processing is the demodulated flicker voltage waveform, DV(t). The coordinate of the signal is selected to present the instantaneous flicker voltage magnitude in 1000 times the percent of the mean

value of the carrier frequency line-to-ground peak voltage.   Consequently, a vertical scale reading of 1000 indicates that the instantaneous value of the demodulated flicker voltage is 1% of the mean value of the system line-to-ground peak voltage. This instantaneous voltage flicker measure is commonly adopted and is an essential piece of information required by almost any voltage flicker definition for a flicker calculation. The DV(t) can be further processed for comparison with other voltage flicker levels definitions.

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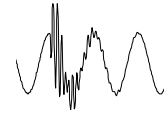
PQ Network™

Electrotek Introduces an On-line Service for Power Quality Information

The PQ Network™ is an on-line service developed by Electrotek Concepts, Inc. to assist electrical engineers in the exchange of information involving power quality. PQ is based on the popular Internet service - the World Wide Web (WWW).

To access the PQ Network™ with any WWW browser like Netscape, point your WWW browser to: http://www/pqnet.electrotek.com/. Follow the directions for becoming a registered to fully utilize the service

Tutorials, analytical tools, terms and definitions, are all freely available on the PQ Network.™

One of the most useful sections on the server is the vendor information area. This area contains information on a variety of products and services and is full text searchable. Links to other WWW servers are provided for those manufacturers who have then available.

A measurement data library provides example waveforms and descriptions of many types of power system disturbances, to help identify and analyze power quality disturbances.

The PQ Calendar™ lists activities of interest to power quality engineers. Items include IEEE meetings, training seminars, workshops, conferences, etc. The format provides an interactive form which allows you to enter meetings and conferences not already posted.

PQChat™ is a message board that allows you to post topics for discussion with other members of the group.

On-line analytical tools such as a tuned filter design tool are available to solve power quality problems on-line.

Tutorials, references, and links to other sources help you keep current in the field and serve as a training tool for your staff.

This service is provided free to all registered users. To browse the service before registering, simply enter as a "guest" and use "password" to login. Registered users can view more documents and search more levels than guests.

The PQ Network™ is expanding and evolving as feedback is given to us by our registered users. New topics will continue to be added. We invite you to submit suggestions, contributions, or comments by e-mail at pqnet@electrotek.com.

<div align="right">

Susie Brockman
Communication Specialist
Electrotek Concepts, Inc.
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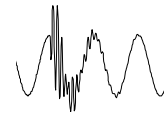
Benchmarking SuperHarm Frequency Scans Using EMTP and Excel

INTRODUCTION

Engineering, like a host of other fields, has benefited greatly since the introduction of the personal computer (PC). Its availability has enhanced our productivity. It also allows us to perform calculations "in the comfort of our homes" that could only be accomplished, if at all, at some mainframe site just a few years ago. Even though we have reaped bountiful technical benefits, the PC oftentimes extracts a heavy ethical toll. We recognize that most of us have neither the time nor the ability to develop the necessary software tools to make our PC's useful. For this reason, we rely on others to provide this service. This is good; it leaves us to do what we do best which is solve problems. In fulfilling our duties, however, we are still responsible for the results even if we use tools provided by others. Some areas of our business are more acutely aware of this than others. Those dealing with nuclear power, for instance, must have all their software "certified" prior to use on a project. This basically means that a given version of software on a specified PC must be able to reproduce expected results when tested against recognized benchmarks. If EMTP is used, for instance, it must be able to recreate the expected output files from all of the supplied benchmark cases. This scenario brings us to the question addressed in this paper, "Can SuperHarm be benchmarked?" When the most recent version of SuperHarm was made available, it was indicated that benchmarking was an area that needed to be addressed and was, in fact, being worked on. For the purpose of an immediate project, however, we found it necessary to proceed with our own benchmarking.

To begin, we first thought it best to utilize that which has already been accepted: EMTP's benchmark files. Our goal would be to use the EMTP files to benchmark SuperHarm. We would run the EMTP files and compare the outputs to a those created by SuperHarm. By reproducing a similar output, SuperHarm could be certified using EMTP as a benchmark. Because the area of interest was frequency scans, the EMTP benchmark files were searched to find files on that topic. Our search turned up only one such data file, DC51.DAT. This file does perform a frequency scan, but only on an RL circuit. Because it contains no capacitance, the scan just produces a straight-line, as expected. For this

reason, we chose not to use this file for benchmarking purposes, even though it has acceptance for certification. Instead, we created a circuit containing four filters, representative of a typical static VAr compensator (SVC). From this circuit, data files for EMTP and SuperHarm were created, along with an Excel spreadsheet. The results of all three programs were compared and the results follow.

TEST SYSTEM DESCRIPTION

The test system for the benchmark studies is representative of a typical SVC installation used in support of an arc furnace load. The SVC consists of the thyristor-switched reactor (TCR) and four single-tuned filters constructed using the bias capacitors. The equivalent circuit of Figure 1 provides the topological information needed to construct the EMTP, SuperHarm, and Excel data sets.
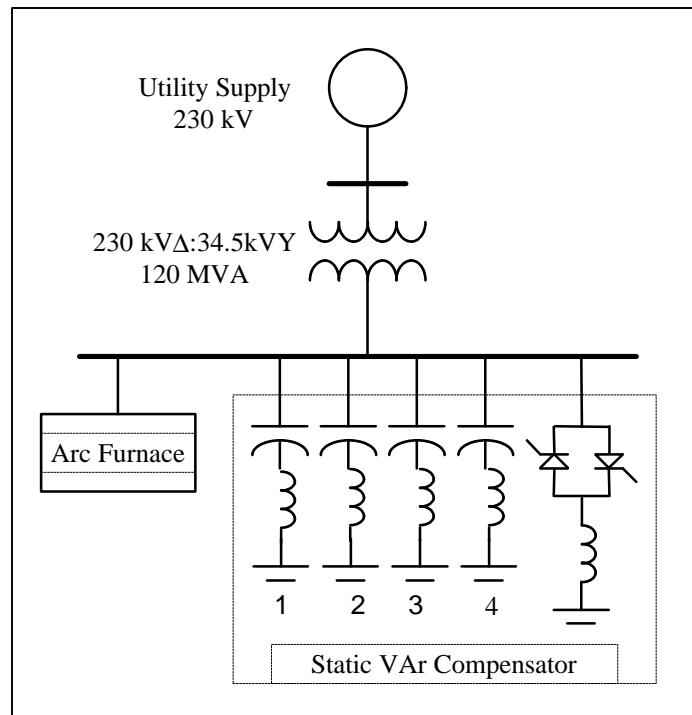
Figure 1. Static VAr System used in Arc Furnace Support

The data for the circuit of Figure 1 is given in Tables 1 and 2. The frequency scans are performed at the 34.5 kV bus assuming balanced conditions, so only positive sequence or "per-phase" data are given. Because they are neglected in

the frequency scan analysis, data for the harmonic-producing arc furnace and TCR are not provided.

Table 1. System Data

System Connection	
Voltage:	230 kV$_{LL}$
S.C. MVA:	38.15 MVA
X/R:	7.81
Transformer	
VA Rating:	120 MVA
HV Rating:	230 kV$_{LL}$
LV Rating:	34.5 kV$_{LL}$
Impedance:	10%
X/R:	20.0

Table 2. Static VAr Compensator Data

	Voltage:	34.5 kV$_{LL}$			
	Total VAr:	176.4 MVAr			
Filter #1	Voltage:	34.5 kV$_{LL}$	Filter #3	Voltage:	34.5 kV$_{LL}$
	VAr:	79.4 MVAr		VAr:	46.5 MVAr
	C:	97.67mF		C:	98.7 mF
	L:	18.55mH		L:	3.37 mH
	X/R:	20 (assumed)		X/R:	20 (assumed)
Filter #2	Voltage:	34.5 kV$_{LL}$	Filter #4	Voltage:	34.5 kV$_{LL}$
	VAr:	15 MVAr		VAr:	35.5 MVAr
	C:	29.7 mF		C:	77.9 mF
	L:	26.31 mH		L:	1.39 mH
	X/R:	20 (assumed)		X/R:	20 (assumed)

<u>STUDY RESULTS</u>

The results of the frequency scans revealed several interesting results. These are summarized in the following recommendations for case comparisons using the different programs.

    1) The frequency interval in SuperHarm should be selected as small as possible for comparisons to avoid "loosing" information.

2) The values of component resistances (which determine the quality factor, Q, for each filter) should be carefully compared in each data set.

3) The filter VAr rating must be consistently determined to be either the rating of the capacitor used in the filter or the rating of the complete filter. While these suggestions are not new, the comparison case studies served to illustrate the sensitivity of frequency scans to the various parameters and demonstrated the need to know not just what, but also how, various computer programs calculate model parameters from input data.

Figure 2 shows the results obtained from the three solution methods using a frequency increment of 1.0 Hz. Each of the programs constructed a system model from simple component models (such as the "Linear Branch" in EMTP and the "Branch" in SuperHarm) using the RLC data given in Table 2. It is clear that each of the methods produces very similar results; the three plots appear as a single graph. However, these results were not obtained without careful consideration of modeling and analysis assumptions in each program. For example, component resistances are often neglected or not represented accurately in frequency scan studies due to the fact that including them does not change the resonant frequencies. However, proper representation of component resistance can have a marked effect on the peak values (at resonance) as well as the "shoulders" of the resonant peaks. This modification of the "shoulders" was very apparent in the filter study due to the close proximity of the resonant frequencies.

Figure 3 shows the SuperHarm results obtained using a frequency increment of 10 Hz. It is clear that the scan increment is an important parameter to consider when high accuracy is required. Based on the studies conducted in this work, we recommend the following guidelines for choosing a scan increment. Realizing that some accuracy will be lost, start with a large scan increment (10 Hz was appropriate in this work) to identify the resonant frequencies. If more accuracy is needed, gradually reduce the scan increment until differences in results obtained from two successive runs are negligible.

Figure 4 shows the results of two different scans performed with SuperHarm. The waveform shown with the "dashed" line resulted from an analysis using the built-in "SeriesFilter" SuperHarm model. The other waveform, shown as a "solid" line, was produced by SuperHarm with each filter section constructed using the "Branch" and "Capacitor" component models and is identical to the results shown in Figure 2. The graphical comparison reveals differences in both resonant peak amplitudes and resonant frequencies. These differences are the direct result of the different methods used to specify filter ratings by different consultants and manufacturers. The SuperHarm "SeriesFilter" component model assumes that the filter VAr rating applies only to the capacitor bank,

which is consistent with some vendors. The values for the "Branch" and "Capacitor" component models used to construct a series filter were purposefully calculated assuming that the filter VAr rating applied to the total filter (consisting of reactive power *supplied* by the capacitor and *absorbed* by the tuning inductor), which is consistent with other vendors. The exact values used in these studies are provided in the EMTP and SuperHarm data files included in Appendices 1 and 2.
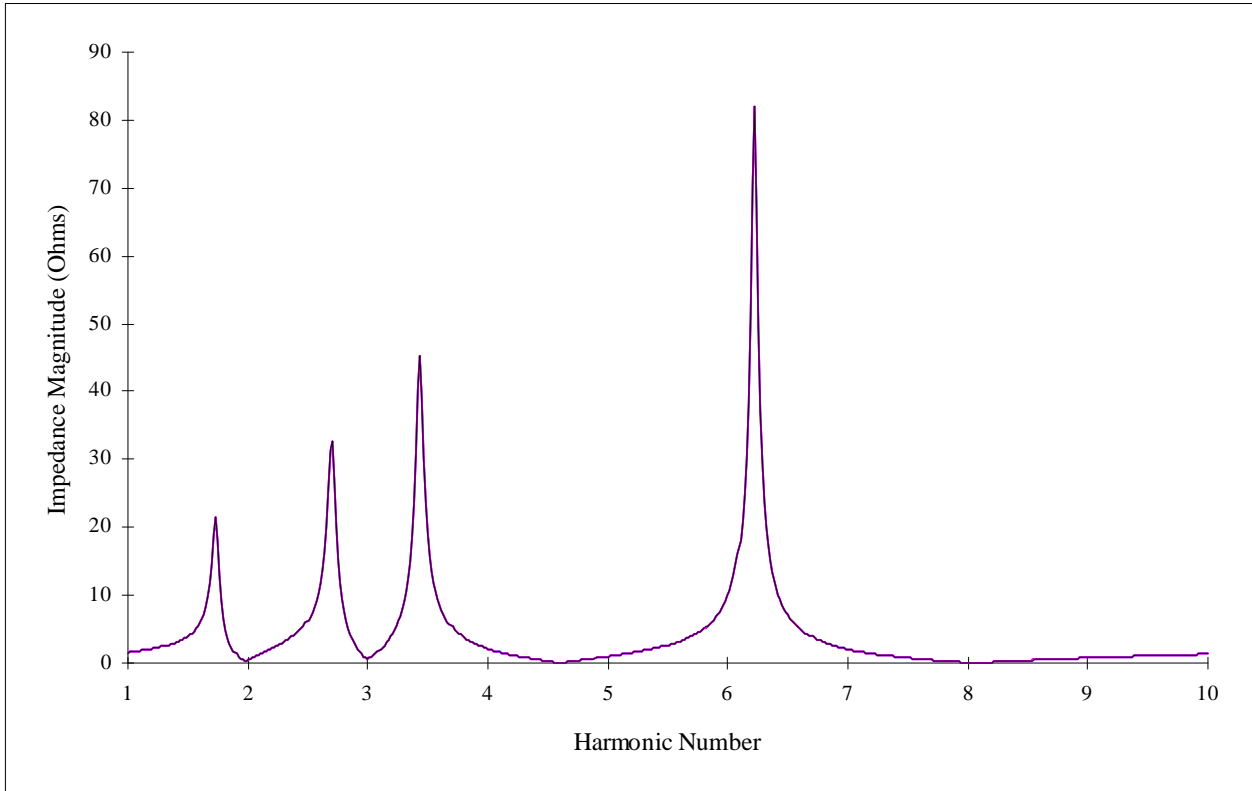
Figure 2. Base Case Frequency Scan Results: 1.0 Hz Increment
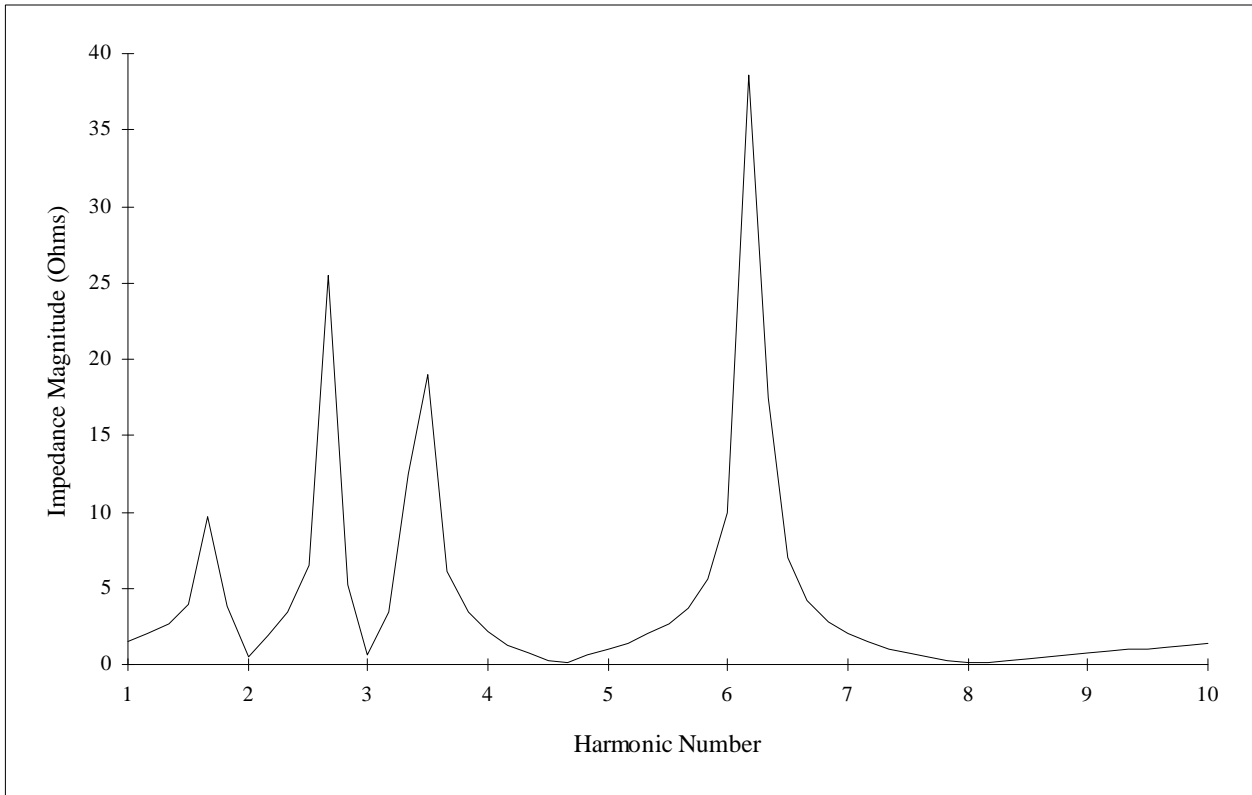
Figure 3. Base Case Frequency Scan Results: 10 Hz Increment
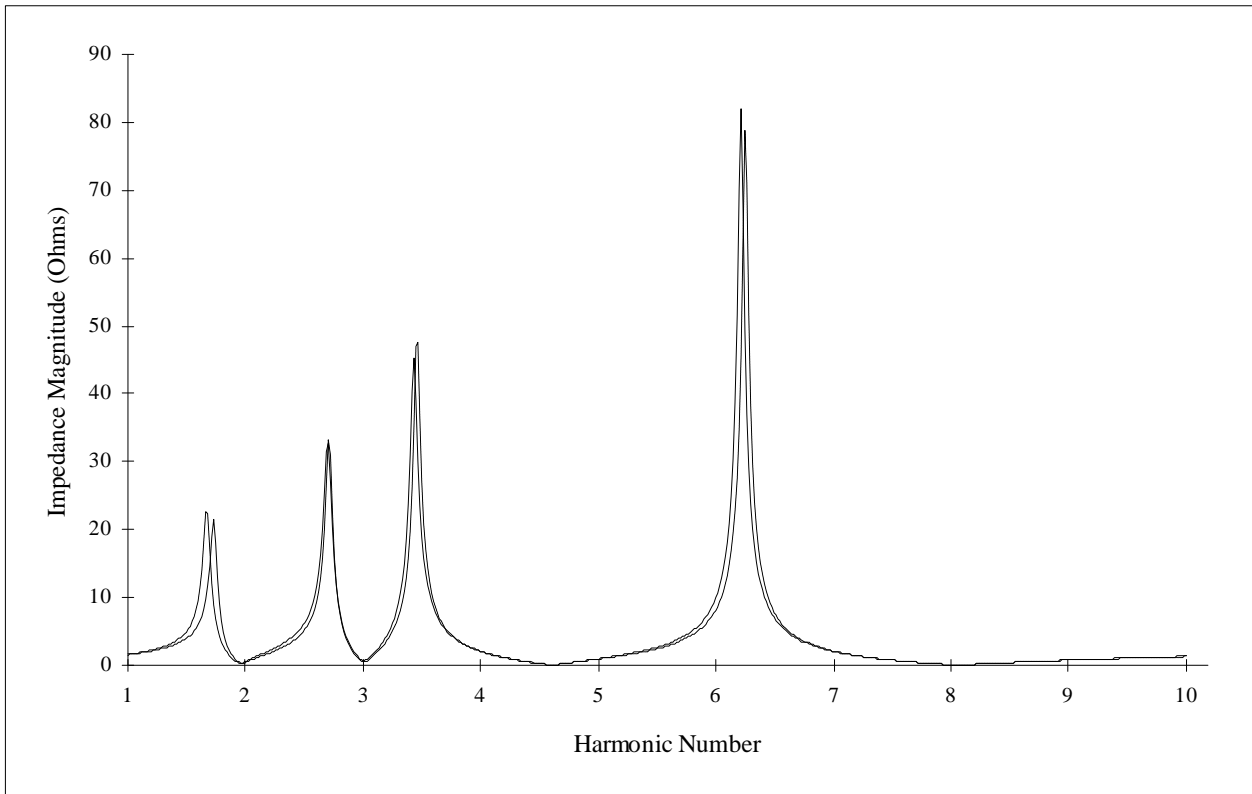
Figure 4. Frequency Scan Results Using Different Filter Models

CONCLUSIONS

The results of this work have partially validated the SuperHarm program for application in sensitive utility areas. While only a limited case has been considered, the results are very promising. During the comparisons, however, it became evident that great care was required when choosing programs, models, and parameters for a given application. When accuracy is extremely important, every application engineer should be aware of program limitations and built-in assumptions concerning component models and parameter specification so that inadvertent errors are not introduced into study results. Programs designed for specific analyses (SuperHarm for harmonic analyses) are more likely to encourage "operator error" than more general purpose programs (EMTP) because of their built-in modeling and analysis assumptions designed to make them easier to use.

References

[1] Electromagnetic Transients Program (EMTP) Revised Rule Book, Version 2.0, EPRI EL-6421-L, 1989.

[2] SuperHarm Harmonics Simulation Program User's Guide, Version 2.0, Electrotek Concepts, 1995.

[3] Fitzgerald, Higginbotham, and Grabel, Basic Electrical Engineering, New York, McGraw-Hill, 1981.

[4] Microsoft Excel User's Guide, Version 5.0, Microsoft Corp., 1994.

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APPENDIX 1. EMTP Data File

```
C Case test.dat
C <--------------------------------------------- Frequency Scan Case
C <---------- w/SVC
BEGIN NEW DATA CASE
FREQUENCY SCAN         60.0    1.0     601.0
C xxxxxxxxxxxxxxxxxx.....^.......^.........^
C
C ----dt<---Tmax<---Xopt<---Copt<-Epsiln<-Tolmat<-Tstart
     1.0     1.0
C .....^.......^.......^.......^.......^.......^.......^
C -Iprnt<--Iplot<-Idoubl<-Kssout<-Maxout<---Ipun<-Memsav<---Icat<-Nenerg<-Iprsup
    1001       3       1       1       1       0       0       2
C .....^.......^.......^.......^.......^.......^.......^.......^.......^.......^
C <--Isw<--Itest<--Idist<--Aincr<-Xmaxmx<-Degmin<-Degmax<-Statfr<-Sigmax<--Nseed
C
C .....^.......^.......^.......^.......^.......^.......^.......^.......^.......^
C --Kchg<---Mult<---Kchg<---Mult<---Kchg<---Mult<---Kchg<---Mult<---Kchg<---Mult
C
C .....^.......^.......^.......^.......^.......^.......^.......^.......^.......^
C
C System Equivalent
C 100MVA 115kV 0.333+J2.60%
C
C <---Nodes--><---Refer--><-Ohms<---mH<---uF<------------------------OutputÄÄÄ¿
C Bus1->Bus2->Bus3->Bus4-><----R<----L<----C                                 V
          SRCA               1.762036.484
C         SRCA                200.0
C .....^.....^.....^.....^.....^.....^.....^xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxx^
C
C Step Down Transformers
C 2-230.0/34.5kV , Ztx = 10.0 % @ 60 MVA, X/R = 20
C
C TRANSFORMER <--Ref<----><--Iss<--Phi<-Name<-Rmag<--------------------------
O
  TRANSFORMER                       XFMR1
C ...........^.....^xxxxxx.....^.....^.....^.....^xxxxxxxxxxxxxxxxxxxxxxxxxxxxx^
          9999
C
C <---Nodes--><----------><-Ohms<---mH<---kV
C <-Bus1<-Bus2<----------><---Rk<---Lk<-Volt--------------------------------->O
01  SRCA               1.100758.400230.00
C .....^.....^xxxxxxxxxxxx.....^.....^.....^xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxx^
02  345A               0.02481.314034.500
C .....^.....^xxxxxxxxxxxx.....^.....^.....^xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxx^
C
C SVC filter
C ********************************************************************************
C 2H filter
C <---Nodes--><---Refer--><-Ohms<---mH<---uF<------------------------OutputÄÄÄ¿
C Bus1->Bus2->Bus3->Bus4-><----R<----L<----C                                 V
```

```
     345A                0.349718.55097.670
C .....^.....^.....^.....^.....^.....^.....^xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxx^
C
C 3H filter
C <---Nodes--><---Refer--><-Ohms<---mH<---uF<-----------------------OutputÄÄÄ¿
C Bus1->Bus2->Bus3->Bus4-><----R<----L<----C                                 V
     345A                0.684426.31029.700
C .....^.....^.....^.....^.....^.....^.....^xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxx^
C
C 5H filter
C <---Nodes--><---Refer--><-Ohms<---mH<---uF<-----------------------OutputÄÄÄ¿
C Bus1->Bus2->Bus3->Bus4-><----R<----L<----C                                 V
     345A                0.06353.370098.700
C .....^.....^.....^.....^.....^.....^.....^xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxx^
C
C 8H filter
C <---Nodes--><---Refer--><-Ohms<---mH<---uF<-----------------------OutputÄÄÄ¿
C Bus1->Bus2->Bus3->Bus4-><----R<----L<----C                                 V
     345A                0.02621.390077.900
C .....^.....^.....^.....^.....^.....^.....^xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxx^
C
C ****************************************************************************
C
C TCR
C <---Nodes--><---Refer--><-Ohms<---mH<---uF<-----------------------OutputÄÄÄ¿
C Bus1->Bus2->Bus3->Bus4-><----R<----L<----C                                 V
C    345A                  55.320
C .....^.....^.....^.....^.....^.....^.....^xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxx^
C
BLANK END OF CIRCUIT DATA
C
C <-Bus1<-Bus2<---Tclose<----Topen<-------Ie<----Flash<--Request<-----Target<--O
C    SRCA  CAPA -16.67E-3      9999
1
C .....^.....^.........^.........^.........^.........^.........^..........^xxx^
BLANK END OF SWITCH DATA
C <--Bus<I<-----Ampl<-----Freq<----Phase<-------A1<------T1><---Tstart<----Tstop
C  SRC1A    28169.1     60.0       0.0                       -1.0E-03      9999
14  345A-1     1.0      60.0       0.0                       -1.000        9999
C .....^.^.........^........^.........^.........^........^..........^........^
BLANK END OF SOURCE DATA
C
C Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->
    SRCA  345A
C .....^.....^.....^.....^.....^.....^.....^.....^.....^.....^.....^.....^.....^
BLANK END OF OUTPUT REQUEST
BLANK CARD ENDING PLOT CARDS
BLANK END OF DATA CASE
BEGIN NEW DATA CASE
BLANK END OF ALL CASES
```

APPENDIX 2. SuperHarm Data File

```
TITLE   TITLE1  =  "Frequency Scan Case"
    TITLE2  =  "Proposed 230kV Normal feed"
    TITLE3  =  "w/SVC & TCR"


#DEFINE KVH @"230.0 3 SQRT /"
#DEFINE KVL @"34.5 3 SQRT /"


SCAN  NAME = SCAN1 BUS = BUS3   ANG = 0
     FMIN = 60  FMAX = 600  FINC = 10


// Source equivalent 230kV H.S. bus
// 0.333+J2.60% on 100MVA 230kV
BRANCH NAME = EQUIV FROM = GROUND TO = BUS2
       R = 1.762 X = 13.754


// Transformer
// 120MVA 230/34.5kV Z=10.0%, X/R=20
TRANSFORMER NAME = TRF1 MVAb.HX = 40.0
    H.1 = BUS2   X.1 = BUS3
    H.2 = GROUND X.2 = GROUND
    kV.H = KVH  kV.X = KVL
    %X.HX = 9.9875  %R.HX = 0.4994 MVA = 40.0 XRConstant = No


// ************************************************** //
// METHOD ONE:  FILTER BUILT FROM DISCRETE COMPONENTS //
// ************************************************** //
// Filter Bank #1
     BRANCH Name = BF1
     From = Bus3 To = F1
     R = 0.3497 X = 6.9934
     CAPACITOR Name = CF1
     From = F1 To = GROUND
     uF = 97.67
// Filter Bank #2
     BRANCH Name = BF2
     From = Bus3 To = F2
     R = 0.6844 X = 9.9189
     CAPACITOR Name = CF2
     From = F2 To = GROUND
     uF = 29.7
// Filter Bank #3
     BRANCH Name = BF3
     From = Bus3 To = F3
     R = 0.0635 X = 1.2705
     CAPACITOR Name = CF3
     From = F3 To = GROUND
     uF = 98.7
// Filter Bank #4
     BRANCH Name = BF4
     From = Bus3 To = F4
```

```
     R = 0.0262 X = 0.5240
     CAPACITOR Name = CF4
     From = F4 To = GROUND
     uF = 77.9
// ******************************************************** //
// METHOD TWO:  FILTERS MODELED USING SERIESFILTER COMPONENT //
// ******************************************************** //
/*
 SERIESFILTER NAME = FLTR1
    CAPBUS = BUS3  MIDBUS = FLT1
    INDBUS = GROUND   KV = KVL
    HARMONIC = 1.9712  MVA = 19.6667
    XRRATIO = 20
 SERIESFILTER NAME = FLTR2
    CAPBUS = BUS3  MIDBUS = FLT2
    INDBUS = GROUND   KV = KVL
    HARMONIC = 3.0008  MVA = 5.0
    XRRATIO = 20
 SERIESFILTER NAME = FLTR3
    CAPBUS = BUS3  MIDBUS = FLT3
    INDBUS = GROUND   KV = KVL
    HARMONIC = 4.5993  MVA = 15.5
    XRRATIO = 20
 SERIESFILTER NAME = FLTR4
    CAPBUS = BUS3  MIDBUS = FLT4
    INDBUS = GROUND   KV = KVL
    HARMONIC = 8.0611  MVA = 11.8333
    XRRATIO = 20
*/
RETAIN CURRENTS=YES

// End of file
....
```