Improving Power Quality and Reliability with T&D Design, Maintenance, and Planning

Harmonic Analysis and Applications Guidelines

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Technical Update, December 2009

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PRODUCT DESCRIPTION

EPRI has published numerous guidebooks, reports, and technical briefs on subject matter pertaining to harmonics. Overall, the full EPRI library of document on harmonics is highly comprehensive and spans the entire range of subject matter from the effects of harmonic voltages and currents on customer and utility equipment to methodologies useful in conducting harmonic studies.

Even though this large selection of harmonic-related documents exists, the individual documents are fragmented and not all still available. Therefore, this document consolidates many of those publications with new work in this area. The material focuses primarily on transmission and distribution (T&D) study aspects of the subject matter to include load interactions, investigative procedures, and many case study examples.

Results & Findings

The result of this effort is a 2010 era state-of-the-art harmonics guidebook that addresses the T&D side of harmonic assessments in a very comprehensive and systematic manner. The materials presented include the following:

- Details on harmonic load proliferation and distortion trends
- Reference studies, documents, and analytical package information
- Measurement equipment and special measurement considerations
- Distribution study and investigation processes
- Transmission study and investigation processes

Challenges & Objective(s)

This report is intended for utility engineers who need to make decisions regarding the impact of adding capacitors to power systems or are trying to understand large customer load impacts on power distribution and delivery systems.

Applications, Values & Use

This guidebook is comprehensive in scope and enables utility investigators to access relevant harmonics-related materials in a single document. The material additionally serves as the basis for a potential larger-scale analytical software tool. The benefits of such an effort enable sponsors of the work to have access to one document covering the entire selection of subject matter.

EPRI Perspective

Related to the harmonics subject matter, there is an overall industry need for general guidelines for evaluating system harmonic problems, designing power systems to avoid these problems, and implementing standardized solutions for problems when they occur. In addition, guidelines for applying limits to equipment and individual customers are needed with standardized language for contracts with customers. EPRI is leading the efforts in developing the knowledge and the guidelines through core research and modeling and simulation work.

Approach

Goals for this development effort were to create guidelines for evaluating T&D system harmonic problems, designing power systems to avoid these problems, and implementing standardized solutions for problems when they occur. This was accomplished by drawing on EPRI experiences with harmonic assessments and by applying real world examples and case studies to the report.

Keywords

Harmonics
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Current distortion
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INTRODUCTION

Background

EPRI has published numerous guidebooks, reports, and technical briefs on subject matter pertaining to harmonics. Overall, the full EPRI library of document on harmonics is highly comprehensive and spans the entire range of subject matter from the effects of harmonic voltages and currents on customer and utility equipment to methodologies useful in conducting harmonic studies.

Even though this large selection of harmonic-related documents exists, the individual documents are fragmented and not all still available. Therefore, the sponsors of EPRI's 2009 project 1.002 defined a need for an updated harmonic assessment guidebook for T&D. The directive was to develop a single guidebook that would first, enable utility investigators to access the relevant harmonics-related materials in a single document, and second, become the basis for a potential larger-scale analytical software tool. The benefits of such an effort enables all P1.002 funders to have access to the one document covering the entire selection of subject matter.

To that end, the project team performed a comprehensive literature survey that identified all of the relevant materials that could be consolidated into the proposed harmonic assessment guidebook. Next, the team and the utility advisory committee developed a draft and final outline of materials that deemed useful in populating the guidebook. Once the outline was completed, it was clear that about half of the material required for the guidebook would be either completely new material or an update to existing methodology and documents, while the other half could come from existing EPRI publications with only slight modifications.

The result of this effort is a 2010 era state-of-the-art harmonics guidebook that addresses the T&D side of harmonic assessments in a very comprehensive and systematic manner. The materials presented include:

- Detail on Harmonic Load Proliferation and Distortion Trends
- Reference Studies, Documents and Analytical Package Information
- Measurement Equipment and Special Measurement Considerations
- Distribution Study and Investigation Processes
- Transmission Study and Investigation Processes

Objectives

This document is intended to meet the need for comprehensive guidelines for evaluating T&D system harmonic problems, designing power systems to avoid these problems, and implementing standardized solutions for the problems when they occur. In addition, the document is intended to provide practical examples and case studies in conjunction with guidelines for applying limits to equipment and individual customers are needed with standardized language for contracts with customers.

Executive Summary

The typical harmonic study involves either an affected customer or an interfering customer and usually focuses heavily on the customer side of the meter. While this is certainly important, this particular document is intended to focus on the transmission and distribution side. As such, the report is intended to treat the T&D investigation and system design methodologies very thoroughly.

Three problems have become important on transmission and distribution systems as a result of the increasing harmonic generation and the characteristics of T&D systems. These problems include; harmonic resonances, current distortion, and increase in earth currents. Each of these topics is summarized as follows:

Resonance – Resonance occurs when the harmonic currents injected by nonlinear loads interact with system impedance to produce high harmonic voltages. Resonance can cause nuisance tripping of sensitive electronic loads and high harmonic currents in feeder capacitor banks. In severe cases, capacitors produce audible noise and sometimes bulge. Harmonic voltage distortion levels can become problematic when the resonance conditions result in high impedance near the fifth or seventh harmonic. It can even be a problem on transmission systems with the application of large transmission capacitor banks.

Current Distortion – Harmonic current levels may become high and cause a number of different problems. High harmonic currents can cause additional conductor and cable heating, transformer heating, capacitor loading, telephone interference, and induced voltages onto parallel conductors, pipe and rail lines. Higher harmonic currents in transformers result in greater voltage drops across the transformer impedance thereby creating greater voltage distortions and greater need to operate the transformers below their rated loading levels to avoid overheating.

Ground Currents – Distribution system ground currents can become excessive due to the zero sequence harmonic components. This is probably the most important effect of increasing harmonic levels on many distribution systems in North America. Problems can include telephone interference, touch potentials (harmonic neutral to earth voltages), and misoperation of protection equipment.

Overall, we find that there is a need for general guidelines for evaluating system harmonic problems, designing power systems to avoid these problems, and implementing standardized solutions for the problems when they occur. In addition, guidelines for applying limits to equipment and individual customers are needed with standardized language for contracts with customers. It is also becoming important to develop guidelines for harmonics at transmission interface points. Finally, a method of applying economic penalties for customer injection of harmonics is of high interest, similar to approaches used by utilities for penalizing customers with low power factor.

Study Distinctions for Transmission versus Distribution

Relative to the objectives of this document, it is important to understand the distinctions between the different harmonic evaluations that can be accomplished for the various aspects of the electric power system. With these distinctions clearly identified, one can see why a unique methodology is applied to transmission studies as compared to distribution studies or end-use customer studies.

Harmonic concerns in transmission systems typically stem from the addition of capacitor banks. Usually, capacitor banks for transmission systems are large enough to cause significant change to the overall system frequency response characteristics. For certain system configurations, the addition of bank may result in unacceptable harmonic distortion values.

Transmission systems require a much more detailed model than distribution systems in order to accurately determine frequency response characteristics. This is because of the many paths available for the harmonic currents to flow. For transmission system studies balanced three-phase conditions are assumed and positive sequence (or single-phase) model is often sufficient. These assumptions are valid as neglecting the effects of mutual coupling and phase imbalance in transmission systems has not been found to have a significant impact on harmonic analysis. Due to the need of including a relatively large portion of the system in the model, single phase modeling helps to keep the model relatively simple and it is quicker to arrive at the solution.

The extent of the model should include the nearby transmission capacitor banks as well as the capacitor banks in the LV systems. It is necessary because the range of possible frequencies at the bus of interest is largely influenced by these banks. Typically, it is enough to model the system three or four buses away from the bus of interest and include everything in between. Rest of the system should be represented by short circuit equivalent network that can be obtained by reducing the system.

The connection of transformers between the end user loads and the transmission system prevent the injection of zero sequence harmonic components from lower voltages. Although zero sequence harmonics can be generated by wye-grounded transformer winding connections on the transmission system, these harmonics are small compared to the harmonics from loads. Note that the positive sequence model is still appropriate for evaluating the system response to unbalanced third harmonic components that may flow onto the transmission system from lower voltages.

There are some situations when a three-phase model is required. These situations include interference with communication systems, presence of single-phase capacitor banks, single-phase or unbalanced harmonic sources, and presence of triplen harmonic voltage sources. These situations are more likely to occur in distribution systems than transmission systems. Therefore, the distributions systems are invariably represented using a full three phase model. Typically, the substation equipment (transformers, capacitor banks etc.) and outgoing feeders are explicitly modeled. The part of the system that is upstream of the HV side of the substation transformers may be represented by the short circuit equivalent.

2
HARMONIC TRENDS – HISTORICAL AND FUTURE

When evaluating the need for changes in harmonic design requirements, revisions to standards, and possible development of equipment harmonic limits, it is useful to evaluate actual existing levels of harmonic distortion around the world and see whether this helps to put the problem in context. Just a few interesting developments that could change the landscape relative to harmonic-load proliferation include: plug-in hybrid vehicles, LCD televisions, compact fluorescent lighting, LED lighting, and numerous other distortion power factor loads. While some of these are already being addressed via standards and limits (such as for PHEV chargers), it is useful to at least understand what the penetration levels might do to typical T&D systems.

Are Harmonic Levels Increasing?

One question that often comes up is whether or not harmonic levels are increasing over time due to higher penetration of nonlinear loads such as power electronic equipment. There are many factors that affect the changes in harmonic levels over time, and this makes it hard to determine whether or not increasing penetration of nonlinear loads could actually be causing harmonic levels to increase or whether there may be other more dominant factors. Factors that could be important include:

- Changing system characteristics:
  - More underground systems (more capacitance)
  - More power-factor-correction capacitors (especially at transmission voltages, which could be affecting harmonic levels at all voltages)
- Changing load characteristics:
  - Increasing nonlinear loads such as variable-speed drives, electronic lighting technologies, computer power supplies, and LCD televisions
  - The effect of electronic loads on the damping of resonances (this could be an important factor but it is not clear whether it would be making distortion levels higher or lower)

Regardless of the reason, electric utilities have substantial amounts of harmonic data from long-term power-monitoring programs, and we can derive from the trend data that there is a general trend toward increasing levels of harmonics. The following graph provides a sample harmonic trend over time.

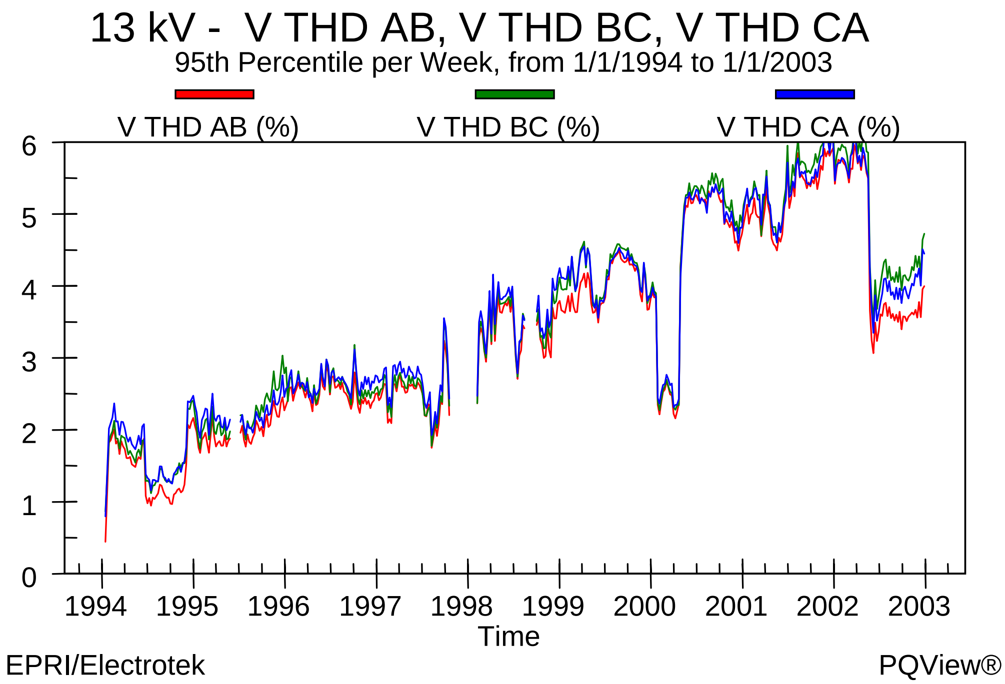


Figure 2-1
Example of 13-kV System Harmonic Distortion Increasing over Time

Clearly, it is important to monitor and track harmonic trends over time and be able to benchmark harmonic levels. Worldwide, there is quite a bit of data on harmonic trends, and some conclusions from the data include:

1. Harmonic levels on distribution systems are approaching or exceeding the IEEE 519 limits for the fifth harmonic (3%). This limit is probably overly conservative, and levels of 5 to 6% are not considered excessive in most cases. Most surveys indicate that the average of 95% values for distribution harmonic distortion levels are around 3.5%. The dominant harmonic on these systems is usually the fifth harmonic and can easily be in the range of 3%. Some systems (such as in Germany) are significantly exceeding these levels. Regarding fifth-harmonic voltage distortion levels in particular:

    a. V5 or the 5th harmonic voltage is the most important component for the overall system.

    b. The levels are determined by impedance of the medium-voltage (MV) system (and sometimes high-voltage (HV) system).

    c. The levels are not dependent on low-voltage (LV) system characteristics or impedance (except for customers that have power-factor correction).

    d. Average V5 (95%) of MV sites is in the range 2 to 3%.

    e. 95% of sites have a V5 (95%) that is less than about 4%.

   f. A few systems have V5 (95%) levels exceeding 5%.

   g. For the sites with problems, it is almost always due to MV system response (unless there is a single large disturbing customer) and can be solved on the MV system.

2. In general, harmonic distortion levels at customer locations are approximately the same as harmonic distortion levels on the distribution system, except at the third harmonic where higher levels can exist at customers because the third harmonic can be blocked by transformer connections for some customers.

   Some conclusions related to the third harmonic in particular are:

   a. The concern depends on LV location.

   b. Worldwide, the concern is not generally a problem on MV systems.

   c. For mitigation modeling, generally an LV model can be used.

   d. MV neutral-to-earth voltages in multi-grounded systems (North America) are becoming a larger concern.

3. Harmonic levels on transmission systems are often exceeding the limits in the standards. Levels exceeding 3% at the fifth harmonic are not uncommon and have the potential of exciting local resonances on distribution systems or within customer facilities.

4. Monitoring of harmonic distortion levels can be an effective way to identify problem locations and provide information to help evaluate the problems and develop appropriate solutions to control the harmonics.

Measurements

Measurements in Hamburg, Germany, have shown that harmonic distortion levels on some distribution systems can be approaching or exceeding even the European standards. Fifth-harmonic measurement results at customer service-entrance locations across Hamburg are illustrated in Figure 2-2.

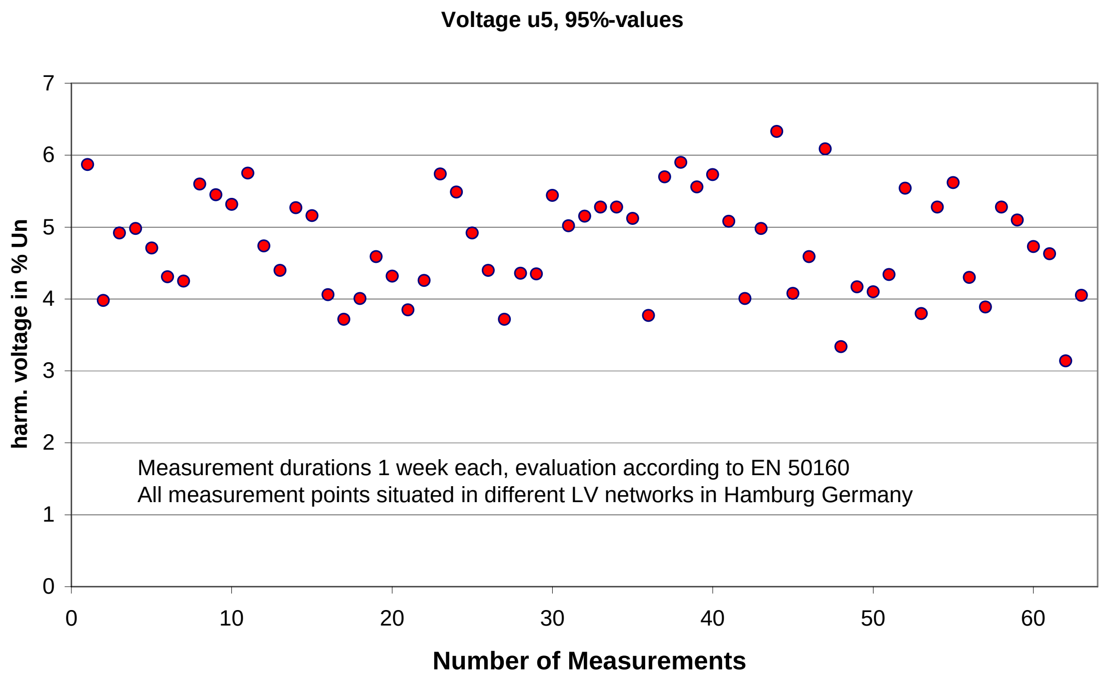


Figure 2-2
Example of 5th Harmonic Measurement Results from Customer Service Entrance Sites from around Hamburg, Germany (from [1])

3
IMPACT ASSESSMENTS – PENETRATION OF POWER ELECTRONIC TECHNOLOGIES

In terms of the impacts of both individual harmonic generating technologies and trends toward greater density of harmonics loads on the systems, this chapter provides some discussion on that subject matter and some potential thoughts on how proliferation of harmonic generating loads might be proactively addressed over time with either system design or harmonic limits

Electric Vehicle Battery Chargers

Perhaps the first and the most significant penetration studies related to the proliferation of a ‘major’ harmonic load was the work done in the early to mid 1990’s to address the potential penetration of large numbers of electric vehicle (EV) battery chargers. While the penetration levels anticipated did not ever materialize, the assessment process and the modeling and simulation conclusions are extremely relevant in terms of the procedures necessary for any non-linear load penetration study. Approximately 30 EV charger modeling studies were identified during a 1996 literature survey and they provide a unique roadmap that applies to generic penetration studies. The key to the studies was to:

1. Identify the type of load that could be used to represent the EV charger penetration

2. Develop a methodology for placement of this harmonic load on the power system

3. Develop the circuit models representative of various utility systems

4. Adjust the percent penetration levels based on the load model.

As it turns out, this 4 step methodology is the basis of all penetration studies regardless of the load type.

Electronically Ballasted Lighting and PC Power Supplies

Back in the 1980’s one of the earliest power electronic proliferation concerns came to the forefront of the electric utility industry. The new electronic ballasts for fluorescent lighting touted a near 40% energy savings opportunity over the standard magnetically ballasted technology and the entire utility industry was being pressed to quickly adopt the technology and offer incentives as part of their demand side management programs.

The only unique challenge here was the potential that the standard current distortion of less than 15% generated by a magnetic ballast could easily exceed 90% with the full wave rectifier (diode) front end on the new electronic power supply. The unique cooperation between the lighting manufacturers and the electric utility industry led to a voluntary standard that limited the amount of current distortion for the electronic ballasts to no more than 15%. In essence a potential for significant harmonic load proliferation was averted.

In the early 1990s as computer power supplies began to proliferate, the exact concerns experienced with the electronic ballasts once again emerged with the exception that this time the concern with non-canceling triplen harmonics on the building neutral wiring actual did present an overheating problem at some installations. Interestingly, the models used to evaluate these concerns are similar to the models that can be used on a distribution system with some distinct exceptions.

The unique aspect of the triplen harmonic concerns with the PCs and Servers is that harmonic limits did end up getting implemented in Europe via International Electrotechnical Commission (IEC) European Norms but the limits for North America did not occur which results now in a large quantity of PC power supplies on the system contributing to the overall increasing trends in harmonics.

The bottom line on the proliferation of harmonic rich PC power supplies is that models extrapolated to the power system can and have been accomplished and there is clearly an opportunity to reduce I^2R losses across the system (wires, transformers and cables) by a net of more than five percent by simply specifying power factor corrected power supplies in PCs and servers.

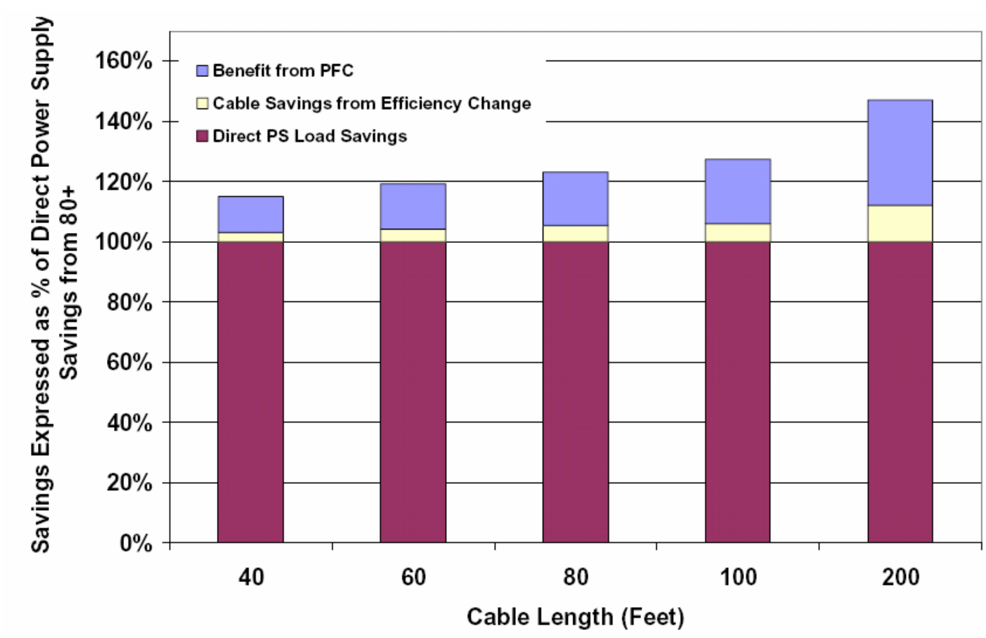


Figure 3-1
Model Projections for Energy Savings with PFC vs Non-PFC Computer Power Supplies [2]

The next proliferation: CFLs, Gaming Systems, LCD TVs and Variable Speed HVAC

The newest concerns and a very valid reason to consider new distribution and transmission modeling for harmonic load proliferation is the recent trends in proliferation of the following harmonic rich commercial and residential load types:

- Compact Fluorescent Lighting (CFLs)
- Liquid Crystal Display (LCD) Flat Panel TV sets
- High Power PC Based Gaming Systems
- Variable Speed HVAC systems

Each of these load types is proliferating on the electric power system and as a whole they all can be modeled adequately with representative harmonic load spectrums for various T&D system configurations and load mixes. This particular subject of the load models is addressed in the associated modeling chapters of this document and as such will not be replicated here. However, the conclusion is that with the guidelines presented in the modeling chapters, new insights into the impacts of a proliferation of harmonic end use loads can be accomplished.

4
HARMONIC MEASUREMENT EQUIPMENT AND PROCEDURES

Instrumentation suitable for harmonic measurement and evaluation procedures has progressed significantly over the past dozen years in terms of lower cost and easier to use software analytical packages. Interestingly, the core technology for conducting the survey or the measurements has not really changed, other than some more convenient packaging.

In order to obtain measurements of harmonic distortion relative to the power frequency, a true rms sample of the voltage or current of interest is required. The most popular method is to obtain a digitized sample of the waveshape and perform a fast Fourier transform (FFT) computation. The result of the FFT analysis yields the percentages for the fundamental frequency and for the multiples of the fundamental. Power line waveshape analyzers and hand held instruments with FFT options are popular choices to perform this harmonic analysis. These devices are generally capable of both waveshape display and harmonic frequency analysis. Oscilloscopes with FFT options and low-frequency or broadband spectrum analyzers may also be used to perform harmonic analysis, but this is not common in the field today.

This section provides insight into the measurements of interest for harmonic surveys and discussion on the instrumentation and key measurement considerations. One key consideration is the equipment and the calculation of the harmonics. There is significant discussion in the literature on this subject and EPRI has done extensive testing on meters as well. Before selecting any harmonics measurement equipment it is a good idea to read through some of the existing literature to understand the issues. It is not the intent of this chapter to be fully comprehensive on the subject, but rather it is intended that the reader become familiar with some of the more common measurements and sources of error.

Instrumentation

- A wide variety of measuring equipment is available to support the harmonics investigator. The largest challenge is obtaining the proper information to use for the diagnostics and the modeling and simulation efforts. This section provides the reader with an overview of the types of measurements of interest, the available equipment, its functions, capabilities, and suitability for field use.

Voltage Measurements

Accurate measurements of voltage potentials are paramount to proper analysis of harmonic concerns because a Fourier transform of the waveform defines the actual harmonic content and the meter must take the measured waveshape and do the computations.

Voltage Readings – It is *recommended practice* that all readings are taken with "true RMS" responding voltmeters. True RMS reading voltmeters indicate the square root of the sum of the squares of all instantaneous values of the cyclical voltage waveform. These meters will indicate the correct or true RMS value for every type of waveform from sinusoidal waves to pure square waves, and they are therefore the preferred voltage-measuring instrument for the stray voltage survey. Most of the PQ monitoring equipment today is true RMS equipment, but this is still a consideration to be confirmed.

Average-responding RMS voltmeters and peak-responding voltmeters are not recommended because they assume a sinusoidal waveform and calculate the RMS equivalent based on that assumption. With the average-responding voltmeter, a multiplier called the *form factor* is used to convert the averaged value to the equivalent RMS value. The 1.1 multiplier used by these instruments is based on the assumption that the RMS value of a sine wave is 1.1 times the average value of the same rectified sine wave. With peak-responding voltmeters, the peak value of the waveform is detected and a 0.707 multiplier is used to convert the peak value to the equivalent RMS value. Like the average-responding circuit, the waveform must be sinusoidal or the displayed value will be erroneous.

The following figure shows several waveforms and the percent error recorded by the peak- and averaging-responding meters. This emphasizes the importance of using a true RMS meter.

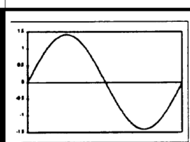
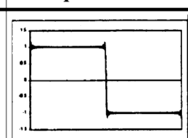
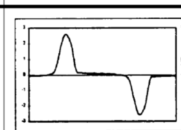
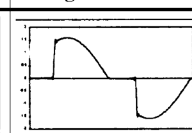
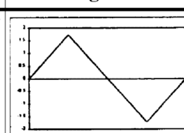
Meter type	Circuit	Sine wave	Square wave	Distorted wave	Light dimmer	Triangle wave
						
Peak method	Peak/1.414	100%	82%	184%	113%	121%
Average responding	Sine avg. 1.1	100%	110%	60%	84%	96%
True rms	RMS converter	100%	100%	100%	100%	100%

Figure 4-1
Percent Error versus Type of Instrument Used for Differing Waveforms

Current Measurements

AC current measurements are slightly more difficult to perform during a site survey compared to voltage measurements, but there are many instruments available to simplify the process. As with voltage measurements, *recommended practice* is to use true RMS-reading meters when performing a site survey. True RMS ammeters include two types of indirect reading ammeters: current transformers and Hall-effect types.

Current-transformer (CT) ammeters – A transformer is commonly used to convert the current being measured to a proportionately smaller current for measurement by an AC ammeter. There is very little resistive loading with these ammeters, and when a split-core transformer is used, the circuit to be measured is not interrupted. Clamp on CTs cannot be used to measure DC currents. Caution is recommended when interpreting readings obtained with a CT-type device because some of these ammeters may not be true RMS-reading meters. The current transformer should be one that is designed to operate with the meter of choice and should have good frequency response to 3 kHz.

Spectral content (harmonics)

In the presence of harmonic currents, it is important to capture the full spectrum of currents up to approximately 3kHz.There are a number of documented cases where an elevated NEV concern is caused by harmonic currents flowing through the power distribution system neutral conductor and the earth. Because these currents do not cancel like the 60-Hz currents, they can be the dominant component in some NEV investigations. A true RMS meter will quantify the total voltage, but a harmonic analyzer with resolution to capture frequencies out to at least the 50th harmonic (3000 Hz) must be used to determine the harmonic content and the individual harmonic contributions. It is therefore *recommended practice* to measure the harmonic spectrum for stray voltage investigations where the suspected source is a multi-phase wye-grounded distribution system or where the suspected source of the elevated NEV is from customer equipment.

Trending Equipment versus Snapshots

In certain situations, a single snapshot of the voltage or the current is inadequate and IEEE 519 makes numerous recommendations about the time intervals for harmonic measurements. The basic conclusions are that a harmonic spectral analysis should be performed on a minimum of ten cycles of the power frequency and for significant compliance measurements the minimum window over which decisions are made depends upon the severity of the distortion.

Additional Measurement Considerations

There are several factors related to either capabilities or limitations of measurement equipment that must be taken into consideration before deciding upon the appropriate instrument for a given measurement. These factors include, but are not limited to bandwidth, sampling rate, refresh rate, resolution, and true rms response capability.

Bandwidth

The frequency spectra within which accurate measurements can be obtained is limited to the bandwidth of the equipment being used. The bandwidth of the instrument used should be wider than the frequency spectra of the expected events to be monitored. For 60 Hz steady- state monitoring this bandwidth issue is likely not a problem, but if the event of interest is a high-frequency transient caused by a switching event or by a lightning surge, the bandwidth must be higher than the rise time of the event to be captured (typically MHz ranges).

Sampling rate

This specification is important when the power waveshape in question must be digitized in order to perform computational analysis. The sampling rate should be at least twice the highest frequency of interest for a given computation. For example, a harmonic analysis out to the 50th harmonic (3000 Hz) would require a sampling rate of at least 6000 Hz. For sampled data, anti-aliasing filters built in to the metering device are typically necessary to insure accuracy of the reported information.

Resolution

The vertical resolution of a waveshape is dependent upon the sampling rate as well as the number of bits available for storage or processing of the acquired sample. Most digitizing instruments utilize between 8 and 16 bits to obtain reasonable vertical resolution. At 8 bits, this yields measurement accuracy roughly within ±3% of the actual value for ac voltage waveshapes.

Phase Angle Reference

When summing currents (or other phasor quantities) vectorally, it is necessary to have a common, or known, voltage reference. Without such a reference the only useable information are the individual magnitudes of the fundamental quantity (and its harmonics).

Waveshape Analysis and Higher Order Harmonics

As a note of caution relative to measurement equipment, EPRI performed harmonic waveshape testing on a selection of twelve different commercially available harmonic analyzers with notably different results between them. Among the many tests conducted on the monitors, four different harmonic waveshapes were applied simultaneously to all of the monitors and the results are shown in Table 4-1. The results are reasonably close in terms of Vthd except for the column that shows results of waveform A (Figure 4-2). This was a simulated SCR voltage notching waveform, which is a common phenomenon in industrial facilities and on feeders where large DC drives are a major portion of the system load. Interestingly the monitors are not even close on the reported Vthd for this waveshape (ranging from 2.6% to 9.2%!).

In conclusion, the user must be very careful about making sure they have an understanding of the voltage or current waveform before making any significant conclusions about a monitoring result

Table 4-1
Range of Monitor %Vthd readings from different PQ analyzers when evaluating five different V and I waveshapes

Monitor	Wfm A %Vthd	Wfm B %Vthd	Wfm C %Vthd	Wfm D %Vthd	SMPS %Ithd
A	6.0	18.4	14.9	6.5	113
B	7.1	18.4	14.8	6.4	109
C	**2.6**	18.4	14.8	6.6	110
D	6.3	18.2	14.9	7.2	112
E	4.9	18.7	14.8	**3.3**	N/A
F	5.8	18.5	15.1	7.0	110
G	**2.6**	18.4	14.9	6.2	N/A
H	4.5	19.0	15.5	6.6	120
J	8.0	18.3	14.8	6.3	107
K	N/A	N/A	N/A	N/A	N/A
L	6.1	18.6	14.9	6.2	**90**
M	6.4	17.7	14.8	7.1	N/A
N	**9.1**	19.0	15.0	**3.8**	102
P	**9.2**	19.0	15.1	**3.7**	103

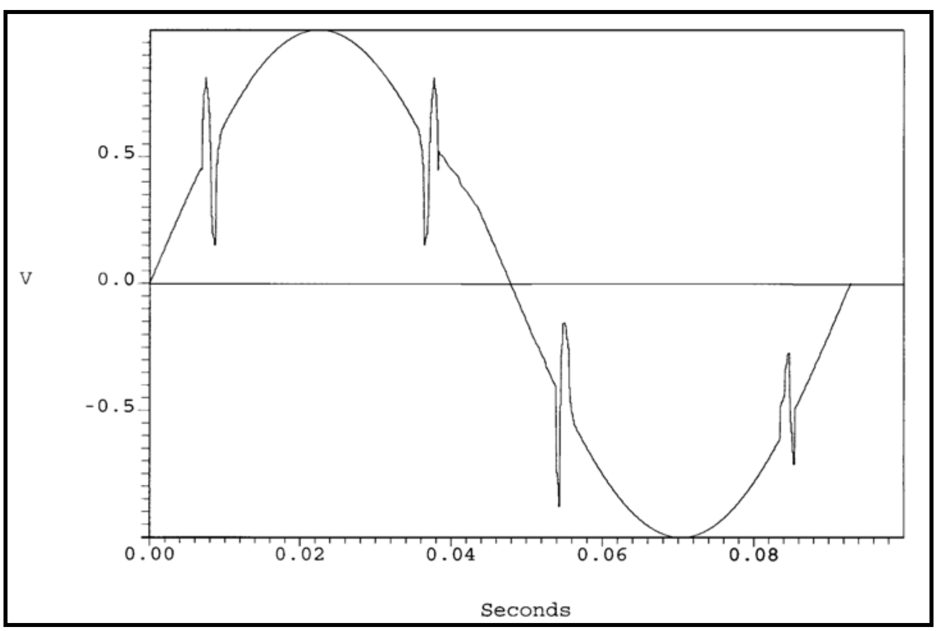


Figure 4-2
Waveshape A – Simulating DC Drive Notching and Confusion the PQ Meters

CT Clipping

As an additional consideration the test case shown in Figure 4-3 was taken at a site where the harmonic current spectrum and the current imbalance had previously been evaluated and both confirmed to be around 15 to 18 percent of the total facility load, however, the technician did not set the CT ratio correctly when re-installing the monitor which resulted in an erroneous measurement of total current distortion. In this particular case the percent current distortion was to be used by the facility to determine whether or not they needed to install their new power factor correction system in a filter configuration or not. The incorrect Ithd number would have made the difference between a major interaction without a filter and no interaction with a filter.

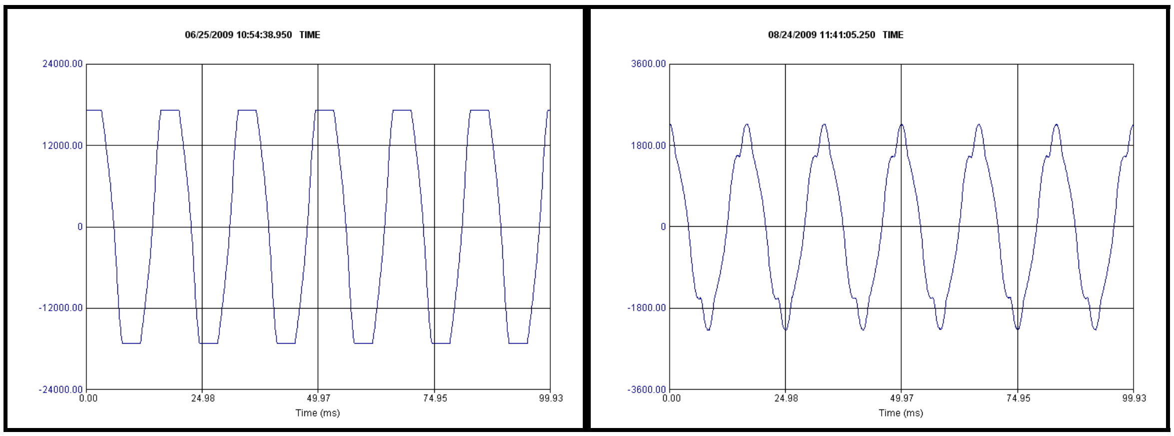


Figure 4-3
Two Waveform Captured by the Same Meter with the CT Settings Incorrect on the Left Resulting in Erroneous Harmonic Conclusions and Erroneous Unbalance Conclusions

Revenue Meters and Harmonic Loads

As one last consideration, it is important to understand that it is not only power quality instruments that are challenged in their measurement accuracy relative to harmonic currents and voltage – but every instrument including revenue meters. To support this comment, EPRI previously tested 12 revenue meters as part of a System Compatibility Research Task [3]

During that work, twelve individual revenue meters were characterized in the project. As expected, meters showed errors in registration based on their calculation method and the quality of the waveforms supplied to them. Significant issues included simultaneous voltage and current distortion, reactive and apparent power calculation, phase sequence and voltage unbalance. Conclusions from this work included the following:

- There is a definite relationship between current distortion and meter kVAh error. This is mainly because the meters often do not account for any distortion in their reactive power measurements.
- Voltage distortion alone does not have a significant effect on meter registration.
- Power levels at harmonic frequencies are more pronounced when both the voltage and the current are significantly distorted. As commonly reported in the literature, this

situation leads to Wh registration errors by the revenue meters. Although there were no tests specifically designed to show this, it was found to be true in some of the tests used, when the voltage distortion was over 8-10% and current distortion was over 50%.

- Manufacturers may differ in their methods of calculating apparent power. In many cases, only the fundamental frequency is considered when measuring reactive power. If apparent power is determined based on this value, VAh errors can be significant. If apparent power is measured directly by the meter, these errors can be minimized. In the case of the VA meter tested, registration errors were similar to those of the VAR meters, where distortion was largely unaccounted for.
- Meter registration error does not appear to be frequency dependent. Variations in harmonic content did not yield any trend with frequency.
- There was concern that phase sequence could cause meter errors as well. Reactive power measurement could be affected by phase sequence, leading to errors in reactive and apparent power registration. This means any negative sequence harmonics could play a role in causing meter error. Tests involving negative sequence harmonics did not indicate any impact on meter registration.
- Unbalanced voltage can cause significant current unbalance in motor drive systems. This leads to unbalanced power consumption by the three phases of the load. Under these conditions, revenue meters are particularly prone to error, depending upon the method used for calculation of apparent power. Vector summation versus arithmetic summation is the key to accuracy here.

5
STUDY TYPES AND ROADMAP

Relative to the objectives of this document, it is important to understand the distinctions between the different harmonic evaluations that can be accomplished for the various aspects of the electric power system. With these distinctions clearly identified, one can see why a unique methodology is applied to transmission studies as compared to distribution studies or end-use customer studies.

Harmonic concerns in transmission systems typically stem from the addition of capacitor banks. Usually, capacitor banks for transmission systems are large enough to cause significant change to the overall system frequency response characteristics. For certain system configurations, the addition of bank may result in unacceptable harmonic distortion values.

Transmission systems require a much more detailed model than distribution systems in order to accurately determine frequency response characteristics. This is because of the many paths available for the harmonic currents to flow. For transmission system studies balanced three-phase conditions are assumed and positive sequence (or single-phase) model is often sufficient. These assumptions are valid as neglecting the effects of mutual coupling and phase imbalance in transmission systems has not been found to have a significant impact on harmonic analysis. Due to the need of including a relatively large portion of the system in the model, single phase modeling helps to keep the model relatively simple and it is quicker to arrive at the solution.

The extent of the model should include the nearby transmission capacitor banks as well as the capacitor banks in the LV systems. It is necessary because the range of possible frequencies at the bus of interest is largely influenced by these banks. Typically, it is enough to model the system three or four buses away from the bus of interest and include everything in between. Rest of the system should be represented by short circuit equivalent network that can be obtained by reducing the system.

The connection of transformers between the end user loads and the transmission system prevent the injection of zero sequence harmonic components from lower voltages. Although zero sequence harmonics can be generated by wye-grounded transformer winding connections on the transmission system, these harmonics are small compared to the harmonics from loads. Note that the positive sequence model is still appropriate for evaluating the system response to unbalanced third harmonic components that may flow onto the transmission system from lower voltages.

There are some situations when a three-phase model is required. These situations include interference with communication systems, presence of single-phase capacitor banks, single-phase or unbalanced harmonic sources, and presence of triplen harmonic voltage sources. These situations are more likely to occur in distribution systems than transmission systems. Therefore, the distributions systems are invariably represented using a full three phase model. Typically, the substation equipment (transformers, capacitor banks etc.) and outgoing feeders are explicitly modeled. The part of the system that is upstream of the HV side of the substation transformers may be represented by the short circuit equivalent.

Harmonic Assessment Plan Requirements

This section addresses the core requirements for a transmission and distribution harmonics assessment plan. As previously mentioned, much of the published material to date involves issues and evaluations on the customer side of the point of common coupling (PCC) so this work on the utility side of the PCC is an important supplement that enables better planning and evaluation methodology. The evaluation methodology involves a systematic process for:

1. Adequate customer complaint call handling and response procedures
2. Adequate power system hardware failure assessment procedures
3. Adequate instrumentation and personnel training
4. Accurate measurement and diagnostics protocols
5. Consistent documentation for reporting and analysis
6. Evaluation of Modeling Options
7. Preventive maintenance and spot monitoring
8. Design guidelines

Adequate customer complaint call handling and response procedures

Adequate complaint call handling implies that there is a methodology in place that when a complaint about either equipment damage or equipment malfunction that the call goes to personnel trained in troubleshooting and understanding of potential harmonic interaction on the serving power system. All too often a harmonic complaint is not recognized until monitoring has been implemented or the customer experiences multiple issues with the same equipment. While there is no recommended procedure here, documentation of past harmonic problems and a customize trouble shooting flow chart is useful

Adequate power system hardware failure assessment procedures

This particular procedure is similar to the last in the fact that very often a harmonic complaint is not recognized until monitoring has been implemented or the customer experiences multiple issues with the same equipment. Once again documentation of past harmonic problems and a customize trouble shooting flow chart is useful. For example, telephone noise complaints should be included in the list of items that might trigger a harmonic investigation just as a UPS nuisance alarm would be included.

Adequate instrumentation and personnel training

In terms of instrumentation and personnel training, the recommendations on measurements set forth in chapter 4 of this document in conjunction with the material in IEEE 519 [4], IEEE 519A [5], IEC 61000-3-2 [6]and IEC 61000-3-12 [7] important for any harmonics investigator to have a working understanding of.

Accurate measurement and diagnostics protocols

There is no replacement for experience, however the recommendation set for in the previous instrumentation and personnel training apply here equally where the recommendations on measurements set forth in chapter 4 of this document in conjunction with the material in IEEE 519, IEEE 519A, IEC 61000-3-2 and IEC 61000-3-12 important for any harmonics investigator to have a working understanding of.

Consistent documentation for reporting and analysis

It is recommended that a custom methodology and data sheets be developed for the harmonics investigation. This enables consistency among investigators and help with new staff training. Measurement protocols should be included to have step by step processes, data required, waveforms required and metering duration requirements.

Evaluation of Modeling Options

To evaluate modeling options, the information set forth in chapters 6, 9, and 12 of this document provide state of the art information to support modeling options. Modeling is a very useful option before implementing solutions in order to evaluate the potential effectiveness of the solution.

Preventive Maintenance and Spot Monitoring

Once a solution for a specific concern has been implemented, it is extremely important to follow up with spot measurements or some sort of hardware maintenance plan (if that is part of the solution). Often times the solution works for a while and then something happens with a setting or a fuse that removes the solution from the circuit only to have complaints return

Design guidelines

Harmonic design guidelines are recommended anytime a large harmonic customer load greater that approximately five percent of the feeder capacity is added or if a new feeder circuit is considered or any time capacitors are going to be added to existing circuits or systems. The discussion in chapters 7,8,10 and 11 of this document provide practical insight into how these design guidelines might be established. This of course depends on the circuit configurations for any given utility (underground, overhead, transmission, distribution).

6
HARMONIC SOURCE REPRESENTATIONS

In order to evaluate harmonic concerns, it may not be feasible and/or necessary to represent the characteristics of individual loads. With extensive system models and distributed sources, aggregated representations of harmonic production from customers are needed. Some examples of aggregated harmonic-source representations that have proven to be useful in the case studies are described here.

Generation of Harmonics by Residential Loads

As described in Chapter 3, a growing percentage of the load in a household is electronic, and these loads may use switch-mode power supplies. These loads are currently dominated by televisions and PCs. ASDs for heat pumps and air conditioners, compact fluorescent lights (electronic ballasts), and electric vehicle battery chargers can also use diode bridge rectifiers in the front end. These loads when aggregated have the potential to become a significant source of harmonics on the distribution systems.

Table 6-1 provides example harmonic characteristics for various types of residential loads and harmonic characteristics for a few example residential customers. Some of these households have high levels of current distortion as a result of ASD heat-pump applications.

A major concern associated with the proliferation of electronic loads on the distribution system is that all of these loads tend to draw current waveforms that are similar and in phase with each other. As a result, the lower-order harmonics from these loads tend to add in the distribution system with little cancellation. The triplen harmonics can be of particular concern on systems that supply single-phase loads with transformers connected line-to-neutral.

Table 6-1
Examples of Residential Load and Whole-House Harmonic Current Characteristics

Type of Load	RMS Load Current	THDi (%)	I3(%)	I5(%)	I7(%)	I9(%)
Clothes Dryer	25.3	4.6	3.9	2.3	0.3	0.3
Stovetop	24.3	3.6	3.0	1.8	0.9	0.2
Refrigerator #1	2.7	13.4	9.2	8.9	1.2	0.6
Refrigerator #2	3.2	10.4	9.6	3.7	0.8	0.2
Desktop Computer & Laser Printer	1.1	140.0	91.0	75.2	58.2	39.0
Conventional Heat Pump #1	23.8	10.6	8.0	6.8	0.5	0.6
Conventional Heat Pump #2	25.7	13.2	12.7	3.2	0.7	0.2
ASD Heat Pump #1	14.4	123.0	84.6	68.3	47.8	27.7
ASD Heat Pump #2	27.7	16.1	15.0	4.2	2.3	1.9
ASD Heat Pump #3	13.0	53.6	48.8	6.3	17.0	10.1
Color Television	0.7	120.8	85.0	60.6	34.6	14.6
Microwave #1	11.7	18.2	15.7	5.1	3.2	2.1
Microwave #2	11.7	26.4	23.3	9.6	2.2	1.6
Vehicle Battery Charger	0.5	51.7	43.2	26.9	2.6	4.2
Light Dimmer	1.6	49.7	41.2	16.0	12.1	10.0
Electric Dryer	25.3	4.6	3.9	2.3	0.3	0.3
Fluorescent Ceiling Light	2.5	39.5	36.9	13.8	2.3	1.4
Fluorescent Desk Lamp	0.6	17.6	17.1	3.4	2.0	0.6
Vacuum	6.0	25.9	25.7	2.7	1.8	0.4
House #1	72.0	4.8	3.6	3.2	0.2	
House #2	51.3	7.7	7.2	2.6	0.8	0.2
House #3	41.6	10.9	8.6	6.5	1.5	0.2
House #4	19.9	6.4	5.5	2.7	1.1	1.2
House #5	6.6	16.2	11.7	10.2	4.1	1.2
House #6	60.8	8.5	6.9	4.9	0.6	0.2
House #7	30.4	11.8	10.7	5.0	0.3	0.3
House #8	62.6	31.6	29.5	6.9	6.8	5.0

Commercial Facility Harmonic Generation

Commercial facilities, such as office complexes, department stores, hospitals, and internet data centers, are dominated by high-efficiency fluorescent lighting with electronic ballasts, adjustable-speed drives for the HVAC (heating, ventilation, and air conditioning) loads, elevator drives, and sensitive electronic equipment supplied by single-phase switch-mode power supplies. In commercial buildings, sources of harmonic-current generation are usually small in size and large in number. Depending on the diversity of the different load types, these small harmonic currents may add in phase or cancel each other.

Figure 6-1 illustrates harmonic current measurements at various locations in a commercial office building. This building has a high percentage of electronic loads and conventional magnetic ballasts and uses adjustable-speed drives only for air-handling equipment (not pumps) in the HVAC system. The waveforms at various locations in the building demonstrate the high levels of current distortion that can exist on circuits that serve electronic loads but that these harmonic currents are cancelled and attenuated by the time that they reach the service entrance.

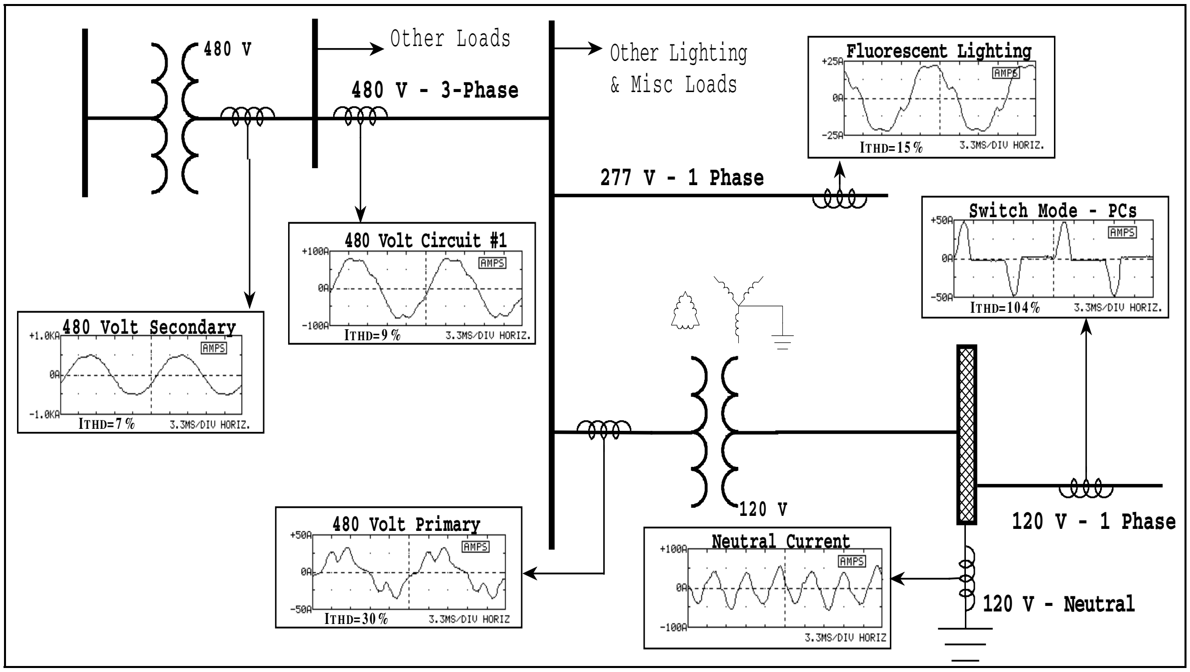


Figure 6-1
Example of Harmonic Cancellation in a Commercial Building

The net effect of the different load types can often be analyzed with a relatively simple system representation, such as the one in Figure 6-2.

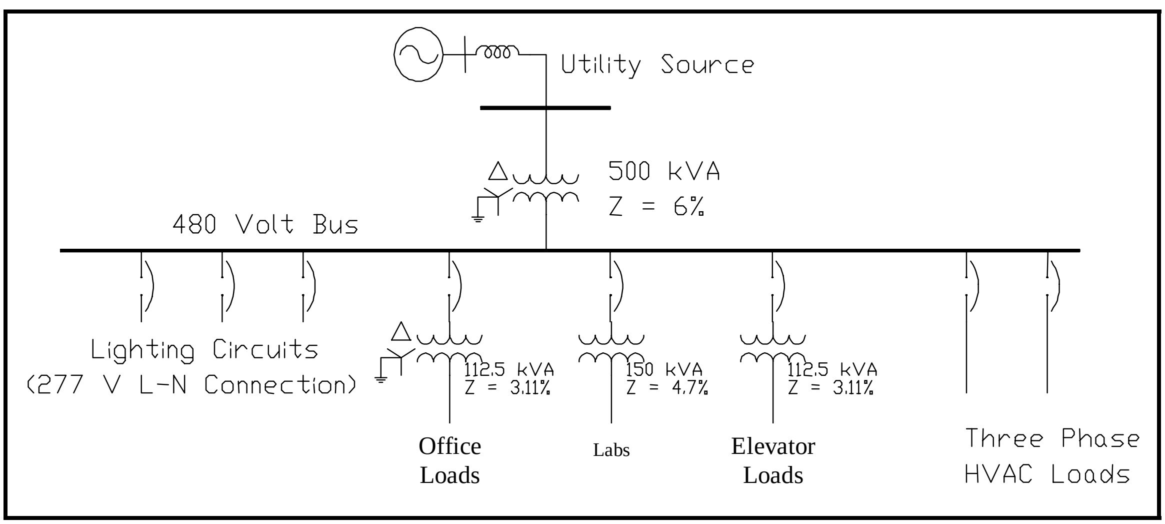


Figure 6-2
Example of Simplified Representation for Commercial Building Harmonic Evaluation

With this type of model, the harmonic levels for the facility can be estimated by breaking the building load into major components and either measuring or assuming the harmonic content for each of these components. Important components include the electronic load (usually supplied at 120/208), lighting load, HVAC load (that may include ASDs), and other load in the facility. An example of this type of analysis based on assumed characteristics for the major load types is summarized in Table 6-2.

Table 6-2
Estimated Harmonic Current Content for Commercial Buildings

Case	Description	Nonlinear Load Levels (% of Total Load)			Harmonic Distortion Levels of Service Entrance (% of Fundamental)	
		Electronic	Lighting	ASDs	Voltage	Current
1	Base case	20	30	5	3.5	14.5
2	High lighting load	20	60	5	3.9	17.1
3	High electronic load	40	30	5	5.7	21.8
4	High ASD load	20	30	10	5.1	20.3

General Harmonic Source Representations for Distribution Studies

When harmonic characteristics must be represented for groups of customers with unknown characteristics, it is possible to assume some general harmonic characteristics. It is often possible to derive this representation from some system-level harmonic measurements (such as harmonic measurements for individual feeder circuits or groups of customers that do not include capacitor banks). Table 6-3 gives an example harmonic spectrum that can be used for relative harmonic magnitudes typical of customers on distribution systems. This representation would apply for some percentage of the total load (on the order of 15% is appropriate for residential distribution systems).

Note that the spectrum in Table 6-3 assumes that the load transformers are included in the model separately and that the nonlinear load is being represented at the LV level. This is also appropriate for aggregated single-phase customers that are supplied with line-to-ground connections. If the representation is at the high side of three-phase delta-wye transformers, the third and ninth harmonic components should be reduced to about 20% of the value shown.

Table 6-3
Example Harmonic Spectrum Used in Case Studies to Represent Aggregated Harmonic Characteristics in Distribution Studies (Nonlinear Load Modeled on Low Side of Transformers)

Harmonic	Magnitude (% of Fundamental)
3	15
5	10
7	8
9	3
11	2
13	1

General Representations of Harmonic Sources for Transmission Studies

Harmonic sources are required to be included in the models of transmission systems as well in order to represent the harmonic generation throughout the system. Table 6-4 gives example harmonic spectrum characteristics that can be used for a portion of the load associated with distribution systems supplied from the transmission system. The values given include a low third harmonic component to account for the delta-wye connections between the transmission system and distribution systems or customers. The fifth harmonic component is dominant because many distribution systems are resonance around the fifth harmonic, and this is likely to be the dominant component being injected into the transmission system. Note that this spectrum would be associated with only a portion of the distribution-system load. For instance, this spectrum might be associated with 40% of the load for a typical distribution system. The percentage could be higher for some industrial customers, and the spectrum should not be considered representative of all distribution systems.

Table 6-4
Example Harmonic Spectrum That Can Be Used for an Aggregated Transmission System Nonlinear Load Representation

Harmonic	Magnitude (% of Fundamental)
3	1.5
5	20
7	4
11	2
13	1

Harmonic Considerations for Distributed Generation

Soon after the PURPA law was passed in the late 1970s, many different types of generators began to appear on the utility system. Some technologies produced significant distortion in the current, and there were some bad experiences. Some still associate DG with excessive harmonic distortion due to electronic power converters. Fortunately, inverter manufacturers have adopted switching technologies that largely eliminate the main harmonic-distortion problems of the early DG devices. Some issues with harmonics and DG remain. Four of the more significant are:

- Inverter characteristics resulting in a distorted waveform
- Synchronous generators with excessive neutral currents
- DG with capacitors being installed near a distorting load
- Over-excitation of transformers from high voltages when DG is operating

7 DISTRIBUTION-RELATED STUDY OBJECTIVES

Distribution-related harmonic concerns can be difficult to deal with because a large harmonic source can create resonance or voltage-distortion issues along the entire feeder as well as adjacent feeders connected to the same substation transformer. This is different from the customer facility cases where the distances are smaller and the offending load can usually be identified by turning candidates off and on while observing area voltage waveforms with an oscilloscope or spectrum analyzer.

The focus of this section is on investigating problems on a distribution feeder where the combination of harmonic current injection and resonant networks act together to create objectionable harmonic levels.

The overall plan or the need for a distribution harmonics study can involve some or all of the following:

- Response to a complaint investigation
- System benchmarking
- Field measurements and monitoring
- System redesign assessments
- Modeling and simulation

Because these study aspects are not necessarily conducive to a single methodology, they will be treated individually. It is assumed that the more common procedures necessary for the majority of distribution assessments will have been covered.

Field Measurements

In some cases, field measurements alone can be used to identify the source of a harmonics problem. To do this, consider the following:

1. It is important to remember that utility-side harmonics problems are almost always created by primary-metered customers, and the culprit is usually a 500-kVA (or higher) ASD, rectifier, or induction furnace. Therefore, if the problem appears suddenly, it is prudent to ask questions within your company to find out which large customers on the feeder (or adjacent feeders) may have added a large distorting load.

2. It is wise to make field measurements before contacting the customer. The basic tool needed is a portable spectrum analyzer that can monitor and record harmonic voltages and currents. Voltage measurements can be made at capacitor-control circuits or at metering points. The frequencies of interest (such as 1,500 Hz and below) are low enough that standard metering, control, and service transformers accurately portray feeder voltage waveforms. Usually, the feeder voltage distortion is high near the harmonics source, but when there are many shunt capacitors, remote points may also have high voltage distortion. It is desirable, but perhaps impossible, to turn off all shunt capacitors when the measurements are made.

3. Next, it is prudent to monitor and record voltage and current harmonics at the customer's metering point for at least two days, and perhaps more. This data will help to correlate the customer's daily work shift patterns or nonlinear loads with distortion levels. THD_V , THD_I , the 5th and 7th harmonic magnitudes, and, if possible, harmonic power should be recorded. The main indicator is the customer's THD_I .

4. Although there is debate on the subject, most power quality engineers believe that harmonic power is a good indicator of the source of harmonics (the 5th harmonic usually has the largest harmonic power). In fact, if a distribution feeder has one large distorting load, then that load is the source of all harmonic power on the feeder. Some spectrum analyzers compute harmonic power. If the customer is the source of harmonic power, then you can expect the net harmonic power (a few percent of fundamental power) to flow out from the customer onto the feeder, which further confirms that the harmonics source is inside the customer's facility.

5. If Steps 1 – 4 are inconclusive, then it is sometimes possible to track down a harmonics source by taking harmonic power measurements at convenient points along the feeder. For example, voltage measurements can be made at capacitor control boxes. Current measurements can be made with fiber optic-linked current transformers that connect directly to the feeder conductors. Based on these voltage and current measurements, net harmonic power can be calculated. The operative assumption is that the net harmonic power flows away from the source.

A wire loop (search coil) can be connected to the voltage input of a spectrum analyzer to monitor the current-induced $N\frac{d\varphi}{dt}$ signal that exists below an overhead feeder. Telephone companies have used the search coil for decades to detect the presence of high harmonic currents. Although the search coil gives no power or voltage information, it is useful because large harmonic currents exist on either side or both sides of a resonating capacitor bank. Resonating capacitor banks are sometimes turned off, moved, or filtered in an attempt to relieve the harmonics problem.

Computer Simulations

Field measurements are useful when a harmonics problem already exists. However, computer simulations are needed to study potential harmonics problems. A harmonics study proceeds in much the same way as a load-flow, short-circuit, or motor-starting study with basic information gathering on the circuit, the circuit elements, and the loads. For example, if a customer plans to add a 5,000-HP ASD, then an preliminary harmonics study is needed to resolve harmonics problems before the ASD is installed.

Unless a distribution system is badly unbalanced, or there is a very large single-phase harmonic-producing load such as an electric train, a harmonics analysis can usually be performed with the assumption that the distribution system is balanced. This assumption can be safely made because most problem-causing loads are large three-phase balanced loads, such as ASDs. Other reasons why this assumption should be made include:

- Distribution capacitors are usually applied in the form of three-phase banks, having a balancing effect on the propagation of harmonics.
- Phase identification of single-phase loads and load levels may not be available or easily obtained.
- The quality of harmonics data for the distorting loads may be poor, so that injection "rules of thumb" must be used.
- Systems are often studied early in the investigative process many times before all of the actual data are available.

In spite of these difficulties, experience has shown that harmonic simulations of distribution feeders accurately match real-world measurements very well, and that simulation is a reliable tool for studying solutions such as passive filtering. The term *accurately* generally means that simulated voltage distortions match field measurements within a few percent (on a 100% base). To obtain this accuracy, these eight rules must be obeyed:

1. When modeling a distribution feeder, include in your model all of the feeders that are attached to the same substation transformer (and in equal detail). On the transmission side of the substation transformer, establish a simple Thevenin equivalent using the short-circuit impedance. Capacitance of the transmission line can be added on the substation high side, but it usually is not important to the study results.
2. Ten to twenty aggregated busses per feeder is usually adequate detail.
3. Load distributions along actual feeders are not known with great accuracy. However, total feeder kVA load and kVA ratings of individual transformers are known. Load distributions are typically estimated by assuming that the total feeder kVA load is distributed in proportion to individual load transformer ratings.
4. Harmonics models for conventional loads must be included. These can be simple shunt resistances, where the resistances are sized according to active power.
5. The worst-case scenario for harmonics is usually when the harmonic-producing loads are at full power, and the conventional loads are at low power. Conventional loads add damping and reduce distortion levels, and their sinusoidal currents dilute the nonlinear load currents.
6. Capacitor banks are very important and must be included in the study. Usually this means a case with all capacitors on and a case with only the fixed capacitors on. Other likely capacitor scenarios may also be needed.

7. If there are significant lengths of underground cables, cable capacitances may be important and should be lumped onto the trunk feeders in the form of shunt capacitors. *Important* is relative to the size of the other shunt capacitors. “At least 100 kVAr” is a good rule for being *important.* The capacitance of power cables is approximately 125 pF per meter per phase.
8. When the system has multiple sources operating at various power levels (10 or more sources), then it is important to consider harmonics cancellation achieved through phase-angle diversity. The simplest way to consider diversity is to multiply the harmonic injection currents for each load by the following:
   a. Third harmonic, multiply by 1.0 (no diversity).
   b. Fifth and 7th harmonics, multiply by 0.9.
   c. Eleventh and 13th harmonics, multiply by 0.6.
   d. Higher harmonics, multiply by 0.2.

There are two basic techniques for performing harmonics computer simulations: time-domain and frequency-domain.

Time-domain modeling is usually performed with full three-phase detail and precise models of nonlinear loads. Time-domain modeling is often used to study small networks where the focus of attention is inside specific equipment such as ASDs.

Frequency-domain modeling is most often used for harmonics simulations where the focus of attention is on the network. Approximate models are used for nonlinear loads. Each harmonic is studied individually, and the results are superimposed to produce time-domain waveforms.

Five-Bus Computer Simulation Example

An industrial customer will be served electricity by constructing a three-mile, 12.5-kV overhead feeder from a dedicated 138/12.5-kV substation transformer. The customer will have 5 MW @ dpf = 0.85 of conventional load and a 2,000-HP, six-pulse adjustable-speed drive (ASD). The customer also has 1,800-kVAr of shunt power-factor-correction capacitors.

The 138-kV substation bus has the following characteristics:

- Z^{+} = 0.4 + j2.5% (100-MVA base).
- 50 miles of 138-kV transmission lines are connected to it (line charging = 0.13 MVA per mile).

The dedicated substation transformer has the following characteristics:

- P_{base} = 15 MVA
- 138 kV delta/12.5 kV grounded-wye connection
- 0.95 per-unit tap on the 138-kV side

- $Z^+ = 0.5 + j10.5\%$ (15-MVA base)

The overhead feeder will be constructed with 477 ACSR arm-type construction that has the following characteristics:

- $R^+ = 4.01\ (10^{-5})\ \Omega$ per ft.
- $X^+ = 11.8\ (10^{-5})\ \Omega$ per ft. (@ 60 Hz)
- $C^+ = 3.37\ (10^{-12})$ Farads per ft.

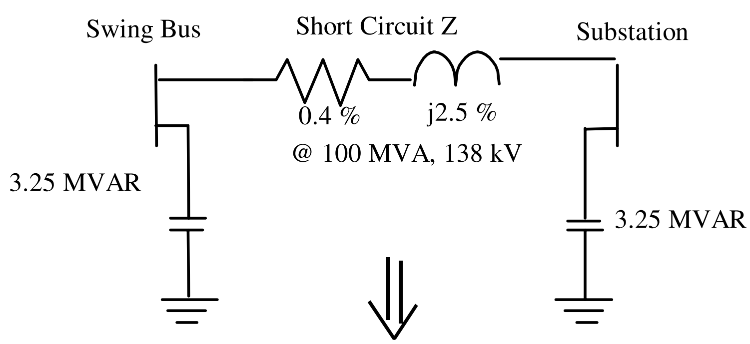
The conventional load transformer is rated at 7.5 MVA and has $Z^+ = 0.50 + j5.0\%$ (7.5-MVA base).

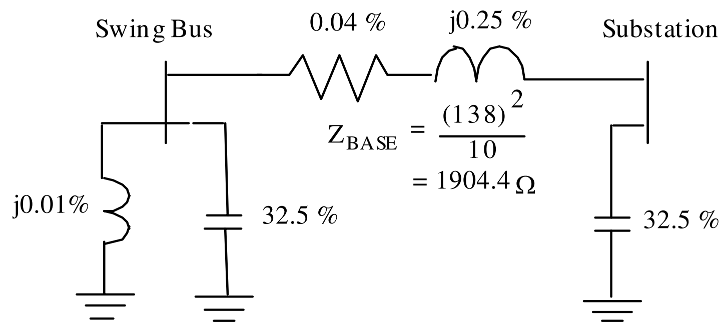
Once the data have been gathered, the next step is to draw a one-line diagram with all impedances and loads expressed on a common base. The base values are selected as 10 MVA throughout, and 12.5-kV on the feeder section. The voltage base varies throughout the circuit according to nominal transformer turns ratios.

The swing bus is effectively grounded for harmonics with a j0.01% "harmonics-only subtransient impedance." The purpose of this grounding impedance is to model the ability of the "far-distant" system to absorb harmonic currents without incurring appreciable voltage distortion.

Calculations for the above steps are shown below.

For the transmission system,





For the distribution feeder,

$R^+ = 4.01\ (10^{-5})$ •/ft • 5280 ft / mile • 3 miles = 0.635•

$X^+ = 11.8\ (10^{-5})$ • 5280 • 3 = 1.869•

$C^+ = 3.37\ (10^{-12})$ • 5280 • 3 = $53.38\ (10^{-9})$ F

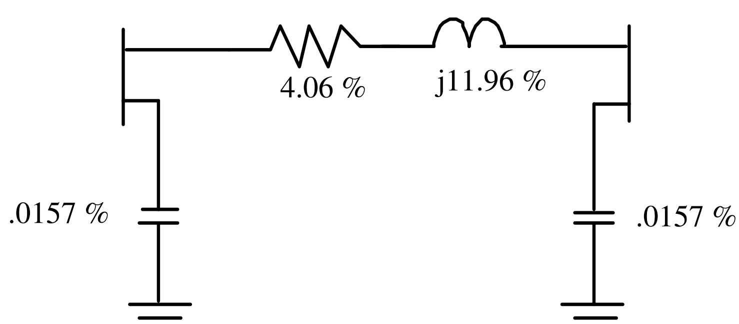
$Z_{BASE} = (12.5)^2 / (10) = 15.625$•

Line Charging $= 3 \left(\frac{12500}{\sqrt{3}}\right)\left(\frac{12500}{\sqrt{3}}\right)(377)(53.38 \bullet 10^{-9})\ \text{VA}$

= 3.144 kVAr = 0.03144% @ 10MVA

$R_{pu} = \frac{0.635}{15.625}(100) = 4.06\%$

$X_{pu} = \frac{1.869}{15.625}(100) = 11.96\%$



For the substation transformer,

For the conventional load transformer, the 1,800 kVAr of shunt power-factor-correction capacitors becomes 18% on a 10-MVA base.

The final one-line diagram is shown in Figure 7-1.

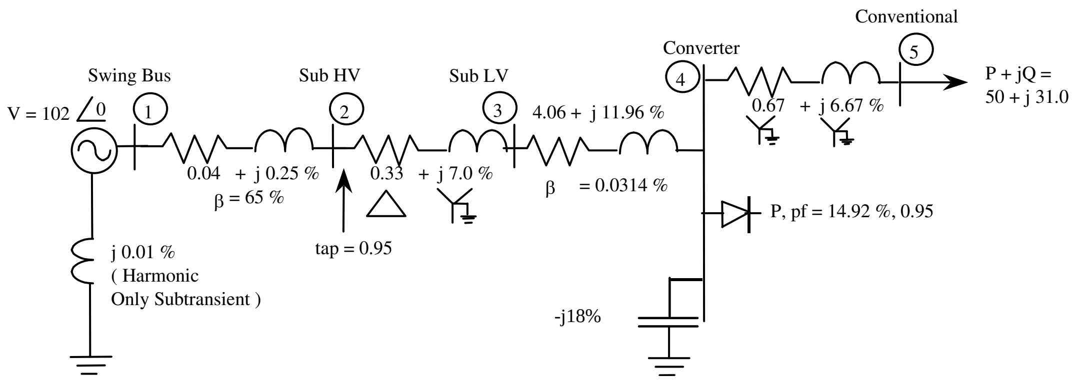


Figure 7-1
System One-Line Diagram for Five-Bus Example

Passive Filters Solution Options

Filters accomplish two objectives: power-factor correction of nonlinear loads and shunting one or more harmonic currents to ground. A series-tuned filter can be constructed from each phase to ground by placing a choke in series with a shunt capacitor and then tuning the choke so that the inductive and capacitive reactances are equal but opposite at the desired harmonic. Tuning a filter slightly below the desired harmonic, for example at the 4.7th instead of the 5th harmonic, helps to reduce capacitor voltage without significantly degrading filter performance. Often, the addition of a 4.7th filter (that is, a 5th filter) is adequate to solve harmonics problems.

Care must taken to dedicate enough kVAr to the filter. In most cases, the filter kVAr should be approximately the amount needed to correct the power factor of the nonlinear load. Filters with smaller kVAr will have sharp tuning curves and will be easily overloaded by stray harmonics that are present in the network.

Because a filter capacitor usually experiences 1.2 to 1.3 per-unit RMS voltage, plus significant harmonics, the capacitor voltage rating must be adequate. The fact that kVArs decrease by the square of the voltage must also be taken into consideration.

To illustrate filter design, the five-bus system illustrated in the previous section is modified by converting the 1,800-kVAr capacitor bank into a 4.7th harmonic filter. First, a new bus (#6) is created, and the 1,800-kVAr capacitor bank is moved from Bus 4 to Bus 6. In reality, the 1,800-kVAr bank would be replaced with a higher-voltage-rated bank, with sufficient kVArs so that it produces 1,800 kVAr at system voltage. Then, Bus 4 is connected to Bus 6 with a series choke that has the appropriate reactance. The tuning formulas for harmonic *k* are:

Let $\dfrac{-X_C(pu@60Hz)}{k} = kX_L(pu@60Hz)$, so that

$$X_L(pu@60Hz) = \frac{-X_C(pu@60Hz)}{k^2}$$

In this example,

$$X_C(pu@60Hz) = \frac{1}{-0.18pu} = -5.55pu \text{, so that}$$

$$X_L(pu@60Hz) = \frac{5.55pu}{4.7^2} = 0.251pu \text{, or } 25.1\%$$

Assuming

$$\frac{X_L(pu@60Hz)}{R} = 50$$

for the choke, the choke resistance is estimated to be $R = \dfrac{25.1\%}{50} = 0.502\%$. The modified system diagram is shown in Figure 7-2.

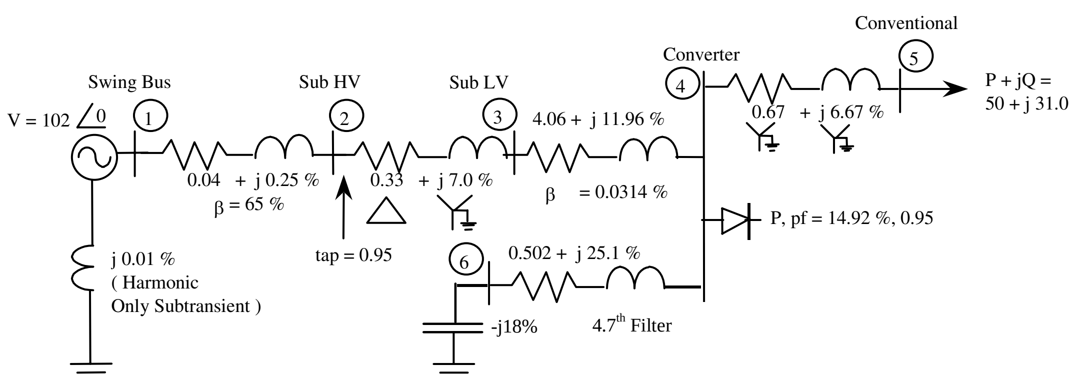


Figure 7-2
System One-Line Diagram for Five-Bus Example with Filter

The filter performance is checked using three steps:

1. Perform impedance scans, without and with the filter. The filter notch should be at the design harmonic.
2. Examine the converter bus voltage waveform, without and with the filter. The 5th harmonic filtering is usually adequate. However, if the voltage distortion is still more

than 4 or 5%, it may be necessary to add a larger 5th filter, or possibly 7th, 11th, and 13th filters, in that order. Usually, the higher the harmonic, the fewer kVArs are committed to a filter. A good rule for dedicating kVAr when multiple filters are needed is to stair-step the kVAr as follows: If Q kVArs are used for the 5th harmonic, then Q/2 should be used for the 7th, Q/4 for the 11th, and Q/4 for the 13th. Of course, actual sizes must match standard sizes. The total kVAr should power-factor-correct the nonlinear load. For best performance, a filter should have at least 300 kVAr.

3. Check the filter current waveform to make sure that it is absorbing the appropriate harmonic and that the filter current is within rating.

Simulation results for the five-bus system, without and with the filter, are given in Figures 7-3 to 7-5.

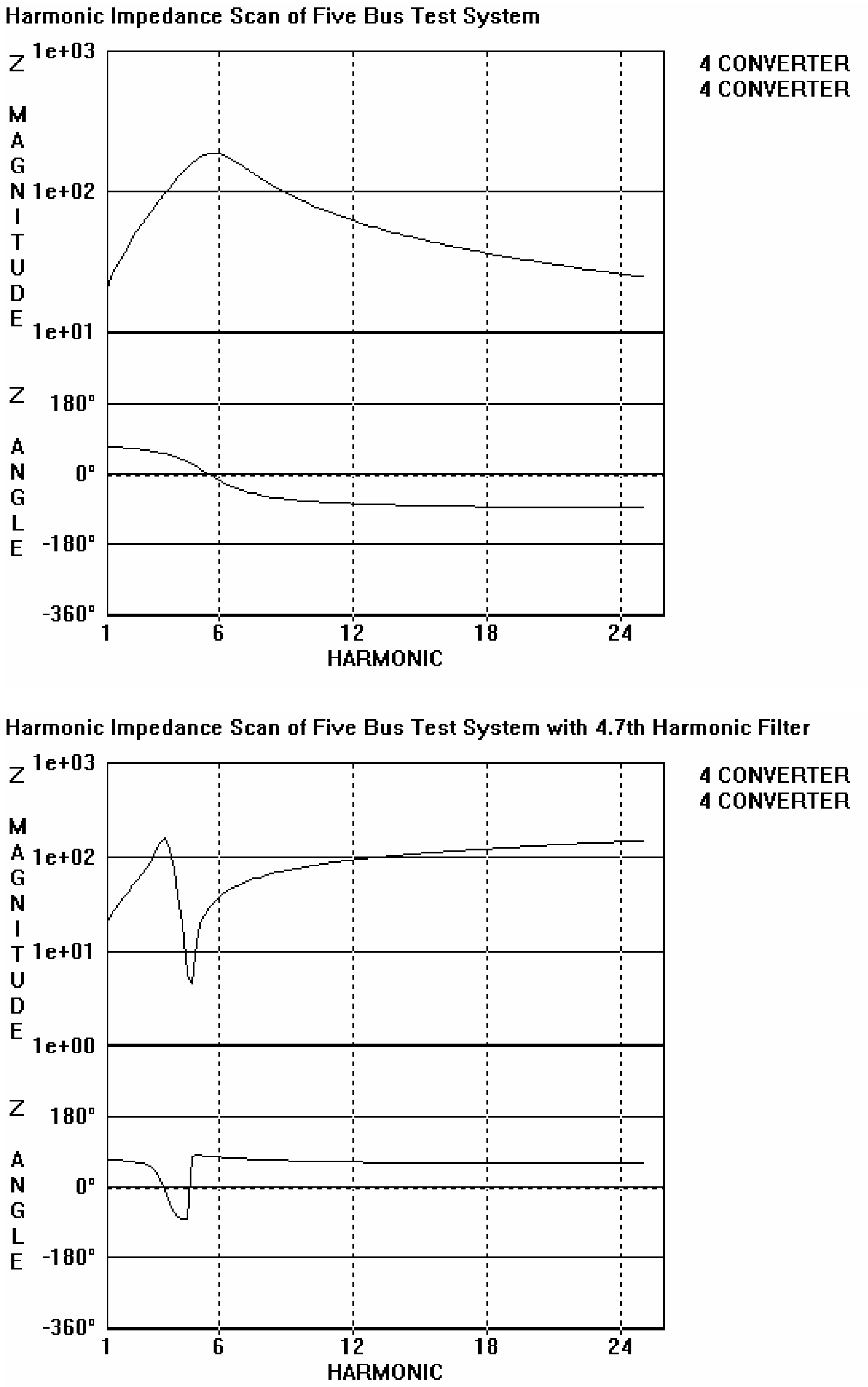
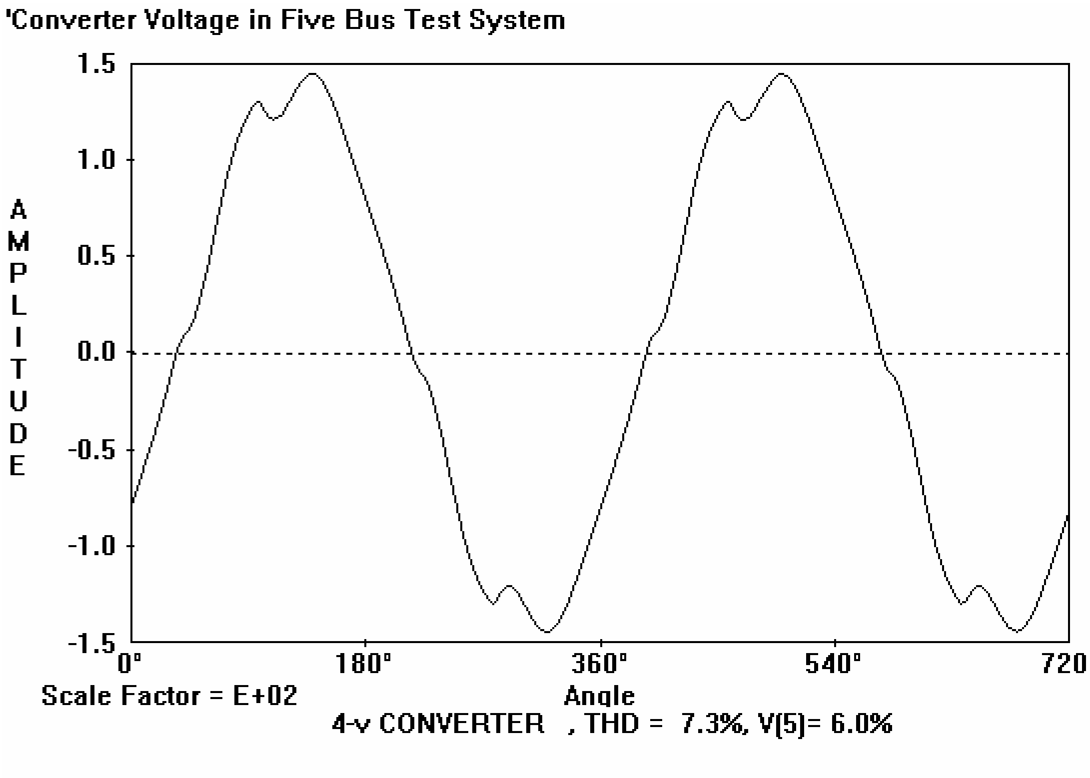


Figure 7-3
Impedance Scans at Converter Bus (without Filter at Top, with Filter at Bottom)



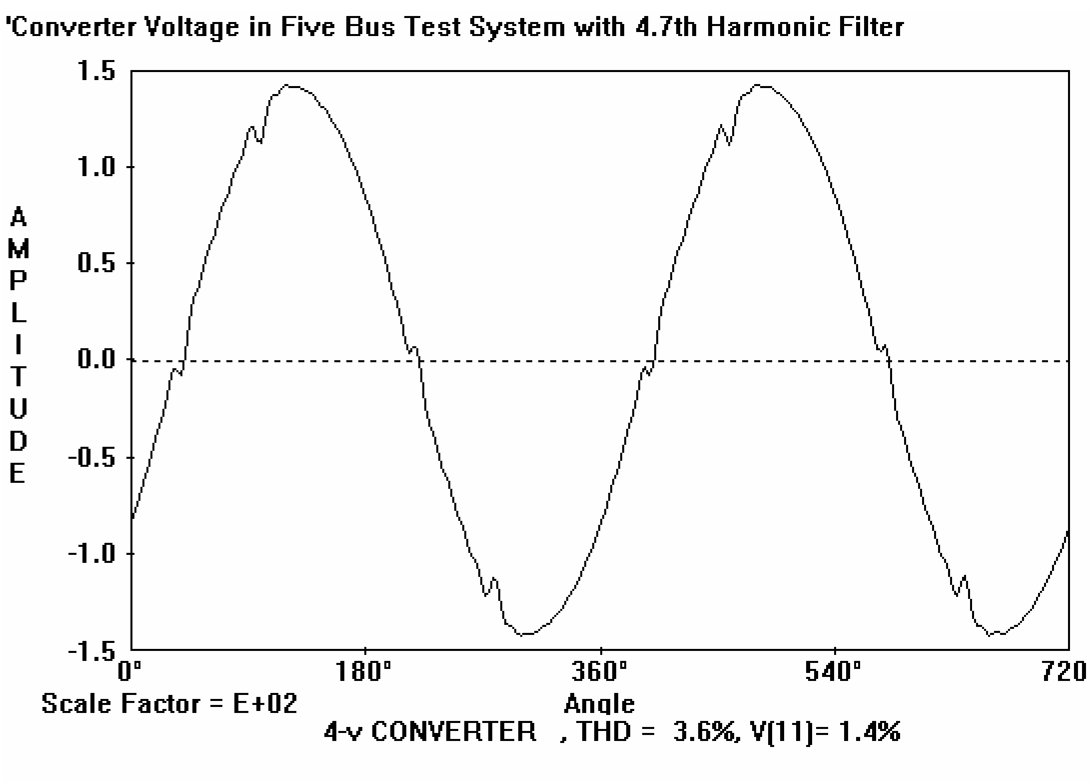


Figure 7-4
Converter Bus Voltage Waveforms Bus (without Filter at Top, with Filter at Bottom)

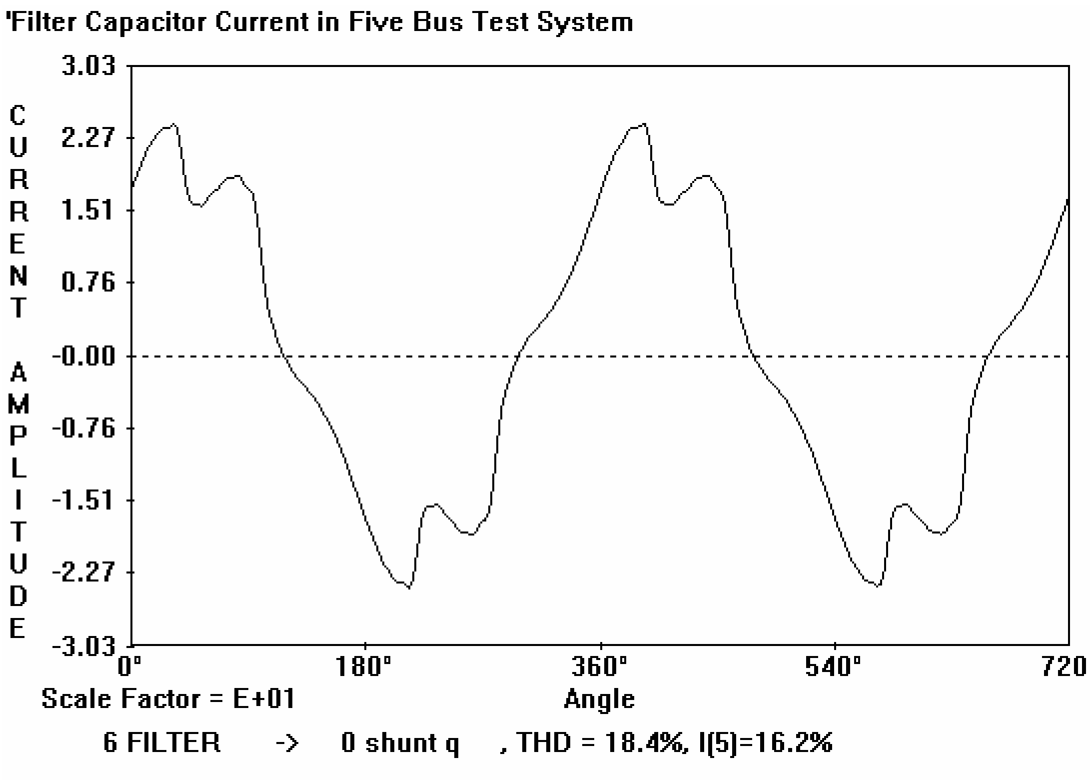


Figure 7-5
Filter Current Waveform

Harmonics and Power Factor Policies

Utilities encourage industrial customers to install power-factor correction through the application of power-factor penalties in the rates. This can be dangerous if the power-factor policies are not accompanied with guidance for customers about potential problems that can occur when they add capacitor banks. Customers size capacitor banks based on the displacement power factor in the facility and may not consider the impact that the capacitors could have on their own voltage distortion levels or the harmonic injection from their facilities onto the distribution system.

Resonance is the main concern. Power-factor-correction capacitors installed in the plant can dramatically increase harmonic distortion levels. The reactance of the distribution transformer and the capacitance of the capacitors form a parallel resonant circuit. If this resonance occurs at a characteristic frequency of a harmonic-producing load, the harmonic voltage distortion could become quite severe. Figure 7-6 illustrates the effect of the capacitor size on the resonance for a typical 1,500-kVA transformer supply to a facility. Resonances at the seventh harmonic and below should particularly be avoided when a facility includes nonlinear loads.

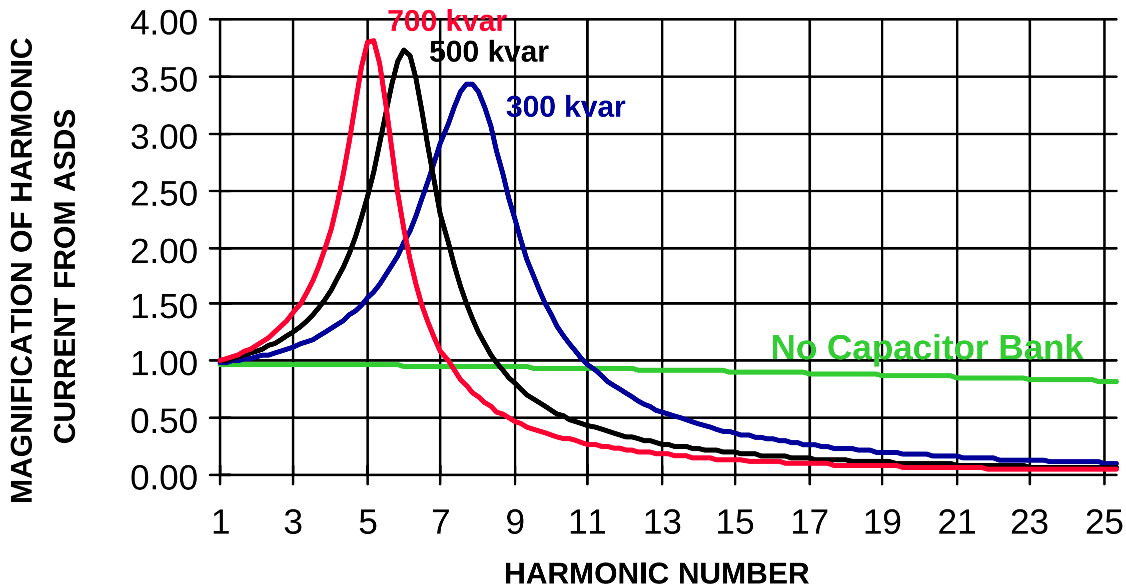


Figure 7-6
Example Frequency Response Characteristics Showing the Magnification in Harmonic Currents Injected into the Utility System as a Function of Power-Factor Correction in an Industrial Facility (6%, 1m500 kVA Step-Down Transformer)

Resonance problems can be avoided by tuning the capacitor bank to a frequency below the first characteristic harmonic of the nonlinear loads at the facility. An example of the effect of the tuned capacitor on the system resonance is shown in Figure 7-7. There is a new resonance introduced below the tuned frequency, but this resonance should not line up with any of the harmonic components from nonlinear loads like ASDs. The tuned capacitor bank costs more than a capacitor bank without a tuning reactor, but it can avoid major problems associated with harmonic resonance conditions.

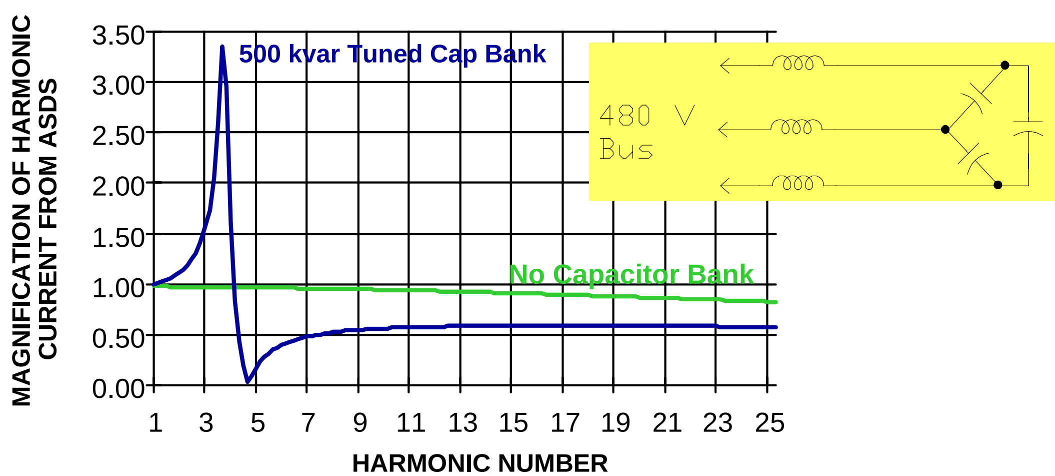


Figure 7-7
Frequency Response Characteristics Showing the Effect of Tuning the Capacitor Bank Below the Fifth Harmonic (4.7) – This Avoids the Fifth Harmonic Parallel Resonance

Customers have to be careful even when they implement their power-factor correction as tuned banks. The tuned bank should be designed to handle harmonics from the supply system as well as harmonics from the facility. The bank should be designed based at least on an assumption of 3% 5th harmonic voltage distortion on the distribution system supplying the facility.

Utilities should provide these guidelines for customers installing power-factor correction to avoid the potential for resonance problems and interaction issues between the supply system and the customer’s power-factor-correction equipment.

8

DISTRIBUTION-RELATED PROBLEM INVESTIGATION PROCEDURE

The general procedures for investigating problems for both transmission and distribution systems was described in Chapter 5 in a general way. The methodology can also be broken down into an analytical flow chart as shown in Figure 8-1. However, as mentioned in the previous chapter, *because many harmonic study aspects are not necessarily conducive to a single methodology, they are generally treated individually, and it is assumed that the more common procedures necessary for the majority of distribution assessments will have been covered.* Therefore this chapter will focus on specific evaluation to address the common procedures starting with a commonly investigated concern centering around arc furnaces

Harmonic Evaluation Procedure

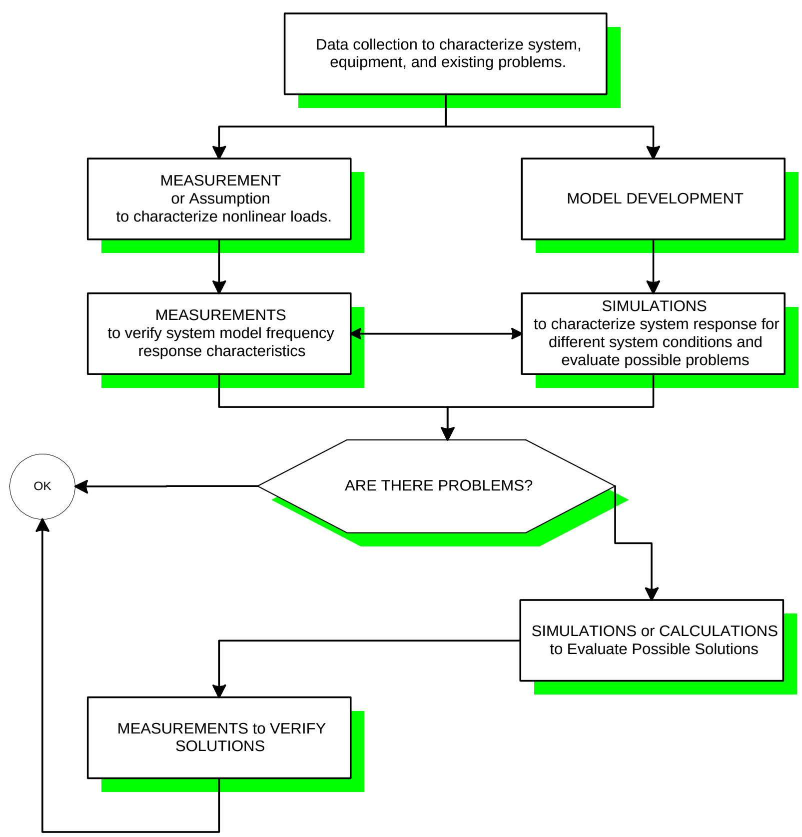


Figure 8-1
Harmonic Evaluation Flowchart

Evaluating Harmonics Caused by Arc Furnaces

The two most common types of electric arc furnaces are:

1. Three-phase AC arc furnaces, with three electrodes typically arranged in triangular configuration
2. DC arc furnaces, which employ a controlled rectifier to convert the AC power to a one- or two-electrode furnace

With respect to harmonic distortion, the behavior of AC arc furnaces can be understood by first considering a simple single-phase arc equivalent circuit as shown in Figure 8-2. The voltage across the arc is a function of the length of the arc and may be considered a voltage source of nearly a square waveform. The furnace transformer and secondary leads provide a reactance that limits the current in the arc. This equivalent circuit is also applicable to magnetically ballasted fluorescent lighting and other arc lamps.

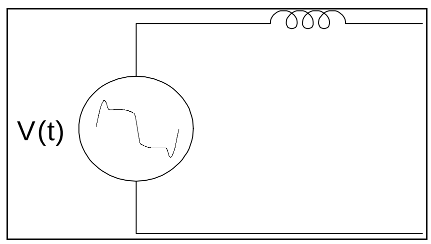


Figure 8-2
Simplified Equivalent Circuit for a Single-Phase Arc

A square-wave voltage decomposes into the 1/N harmonic series. That is, if the fundamental voltage magnitude is 1, then the 3rd harmonic magnitude is 1/3, the 5th harmonic is 1/5, and so on. When both the positive and negative half cycles of a waveform have identical shapes, the Fourier series contains only odd harmonics.

At maximum power, the peak magnitude of the voltage will be approximately half the system voltage. The amount of harmonic current that flows into the supply circuit for this single-phase circuit can be estimated by adding the impedance of the supply system to this simple circuit and solving at each harmonic. The supply voltage can usually be assumed to have negligible harmonic distortion and is modeled as being shorted at all harmonics other than the fundamental.

For a single-phase arc and typical values of arc-furnace impedance, the 3rd harmonic current will be the largest component and can easily be in the range of 25% to 35%. Therefore, a three-phase electric arc furnace is nearly always fed by a delta/delta or ungrounded-wye/delta transformer to block the flow of zero-sequence currents. This provides electrical isolation for the arc and helps reduce the amount of 3rd harmonic currents, which tend to be zero-sequence. However, this blocking of triplen harmonics occurs only during reasonably balanced operating conditions. As Figure 8-3 illustrates, when an arc exists between only two electrodes—which will happen frequently during the scrapping phase of an arc furnace operational cycle—the currents are the same as they would be for a single-phase arc. High 3rd harmonic currents will be observed in the furnace supply. When the arc stabilizes during the refining period of the cycle, the 3rd harmonic content of the supply current will decline because the delta winding will block the flow of the 3rd harmonic current as the three arcs become more balanced.

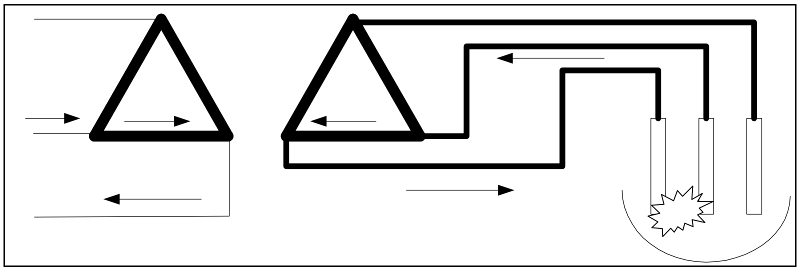


Figure 8-3
Configuration of a Three-Phase Arc Furnace Illustrating Current Flow When There Is an Arc Between Two Electrodes (Common in Early Stages of the Melt)

Thinking that third harmonics are synonymous with zero sequence, many engineers are surprised to find substantial third-harmonic current present in large magnitudes in the line current. However, they are not zero-sequence currents when the furnace is operating in the condition shown in Figure 8-3. The third-harmonic currents are equal amounts of positive- and negative-sequence currents.

In the electric arc furnace, the bulk of the current-limiting impedance, which is largely reactance, is contained in the furnace cable and leads. The contribution from the power system and furnace transformer itself makes up a minor part of the total impedances. Furnace designs for currents in excess of 60,000 amps are common.

The common practice in studies of arc furnace harmonics is to model the furnace as a source of harmonic currents. Table 8-1 shows values commonly assumed for the odd harmonics in these studies.

Table 8-1
Recommended Current Source Representation of Arc Furnaces for Harmonic Studies

Harmonic	Typical	High
1	100%	100%
3	18%	29%
5	5%	7.9%
7	2%	3.1%
9	1.2%	2.0%

While the typical study of harmonic currents produced by arc furnaces considers only the odd harmonics, there will be significant even harmonics during periods of erratic arcing, which happens when boring through scrap metal. The even harmonics occur when consecutive half-cycles of arcing do not look alike. Figure 8-4 shows an actual 3-second sample of arc furnace current during the scrapping phase of the melt cycle. This was measured on the transmission line via metering CTs.

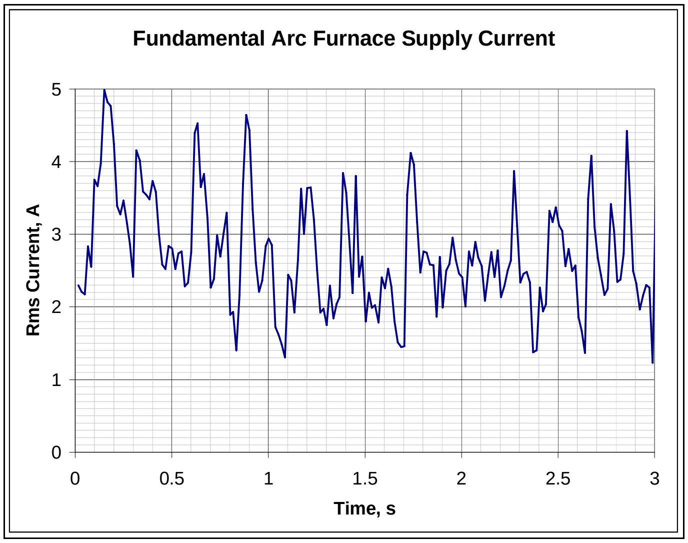


Figure 8-4
Example Variation in the Fundamental Frequency of an Arc-Furnace Current During Early Stages of Scrap Melting (Scale Is Line Amperes on the Transmission Supply System)

The 2nd, 3rd, and 5th harmonic currents for this same sample are shown in Figure 8-5. Much of the time, the 2nd harmonic is larger than either the 3rd or the 5th.

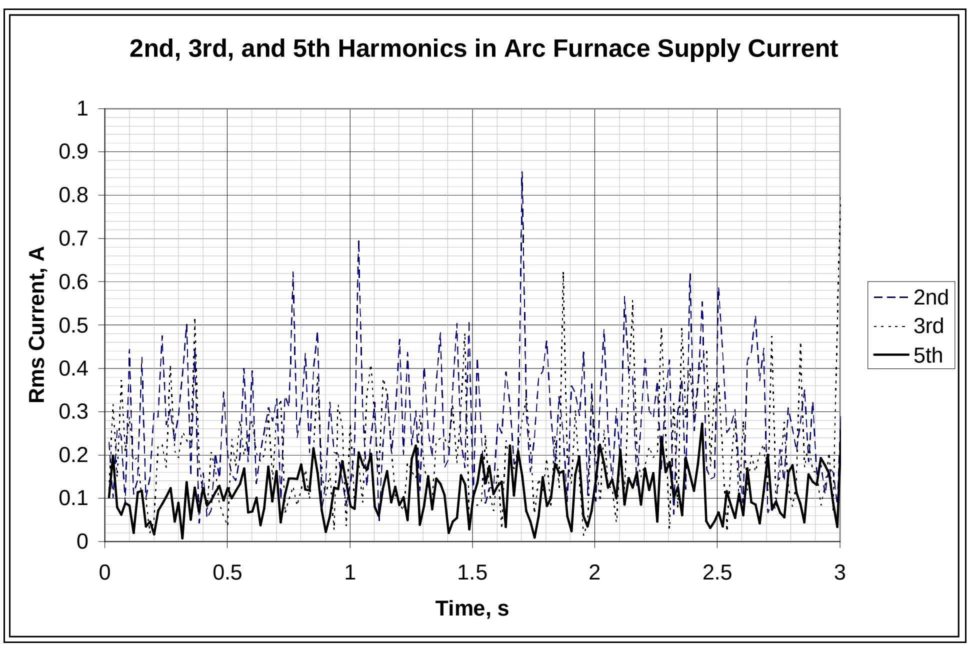


Figure 8-5
Variation of Individual Harmonic Components During the Sample from Figure 8-4

Even harmonics can be a problem if the furnace is in a system that is resonant near one of the even harmonics (especially the 4th). Normally, it would not be a problem for power-delivery systems to be tuned to these frequencies because typical nonlinear loads produce mostly odd harmonics; the presence of even harmonics would be a sign that something has failed. The presence of even harmonics in arc furnaces may require some special attention to filter design. Notch filters tuned to odd harmonics can create resonances near the even harmonics.

Filtering Harmonics from Arc Furnaces – C Filters

When an arc furnace that produces a wide spectrum of harmonics is placed in a power-delivery system that may have many switched capacitor banks and, therefore, many possible resonant frequencies, the application of conventional filters becomes difficult. One approach beyond a conventional filter is to apply a C filter like that shown in Figure 8-6. This filter provides filtering over a wide bandwidth without introducing the numerous resonances of a multi-stage filter than can prove troublesome in some situations, like the wide range of harmonic and interharmonic components that can be associated with an arc furnace.

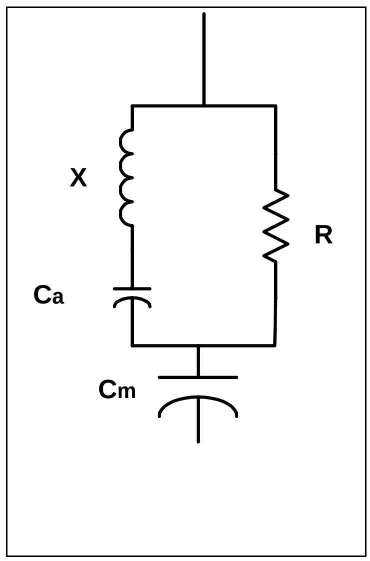


Figure 8-6
Configuration of a "C Filter" – The Resistor Provides Damping to Prevent Magnification of Other Frequencies That May Be Present

It is essentially a high-pass filter with the addition of a capacitor, Ca, that is intended to prevent fundamental-frequency current from flowing in the resistor, R. Thus, the losses are considerably lower than in a conventional single-stage high-pass filter. The branch of Ca and X is tuned to the fundamental frequency so that R is shorted at that frequency.

The impedance of the filter is defined by the following equations:

$$Z_f(h) = R_f(h) + jX_f(h)$$

Where,

$$R_f(h) = R\frac{X^2(h-1/h)^2}{D}$$

$$Xf(h) = R^2\frac{X(h-1/h)}{D} - \frac{X_{Cm}}{h}$$

$$D = R^2 + X^2(h-1/h)^2$$

These equations for a filter with R=29.5, X=1.383, and XCm=38.1 ohms are plotted in Figure 8-7. Assuming a source impedance of j1 ohms, the ratio of the *harmonic current out* compared to *harmonic current injected* from the harmonic-producing load is also plotted. This shows the high-pass effectiveness of the C filter in which the current going into the source is less than 40% of the current being injected by the load at frequencies above the tuned harmonic (the 5th). Note that there is a magnification of currents at frequencies slightly below the tuned frequency, as with notch filters.

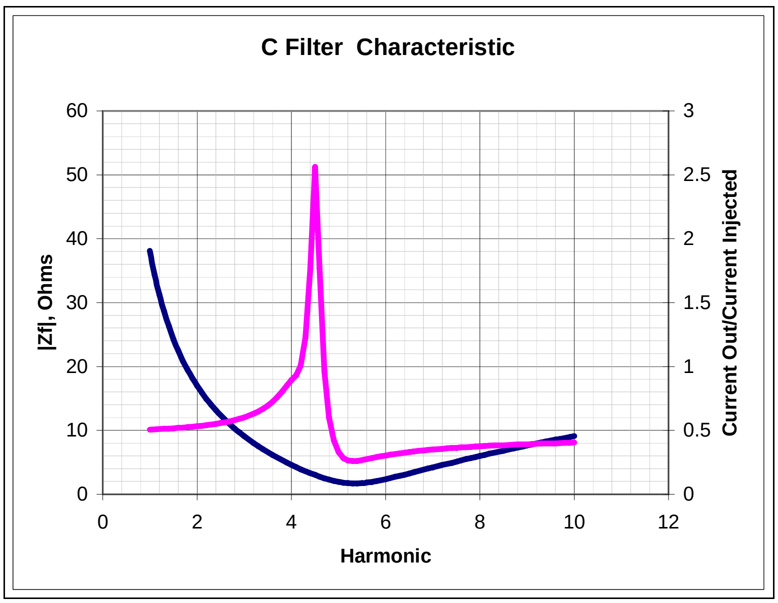


Figure 8-7
Frequency Response Characteristics of the C Filter Compared to a Conventional Notch Filter Tuned Near the Fifth Harmonic

The C filter is not a panacea for all harmonic problems. According to [7], using the C filter in an application where one would normally use a high-pass filter—that is, an application where one or more notch filters are tuned below the C filter—is not likely to be economical. The C filter does provide the savings associated with having no fundamental current in the resistor. However, the additional cost of the auxiliary capacitor is likely to outweigh the savings, especially because Ca becomes very large as the tuning frequency is increased. In cases where a single C filter could be sufficient to control harmonic levels, it may be an attractive option.

9
MODELING FOR DISTRIBUTION

Modeling Distribution Systems

General Modeling Guidelines

In computer modeling, distribution systems will usually be represented by full three-phase models. This is because there are typically many single-phase customers, and the resulting load unbalance can be critical for correctly simulating neutral and ground currents that can cause neutral-to-earth voltages and telephone interference. The full three-phase representation inherently models the positive- and zero-sequence networks correctly. Therefore, a single model can be used to study both triplen harmonics and non-triplen harmonic response of the system (whether these components are balanced or unbalanced).

Models of distribution systems will include the substation step-down transformers and typically an equivalent for the transmission system supply. Outgoing distribution circuits are modeled in detail. Nodes on the distribution system are selected based on the following considerations:

- Representation of all locations of capacitor banks (grounding configuration of capacitor banks should be represented correctly).
- Representation of important customer locations (large loads, harmonic-producing loads, and so on).
- Representations of important branches in the circuit.
- Underground cable circuits should be explicitly modeled (like capacitor banks).

Transformer representations should include their proper configurations (delta-wye grounded, and so on). Transformers having wye-delta configuration can act as sources of harmonics (predominantly 3rd) due to the magnetizing current. This effect can be included in the model by connecting a harmonic source at a transformer wye point, and the harmonic spectrum of the magnetizing current in the transformer can be used.

The distribution circuits will be represented by individual branches. Pi sections that represent the shunt capacitance characteristics of the sections as well as the series impedance are best.

Load representations distributed throughout the distribution system will be important to accurately represent the damping of resonances. The representation should include an estimate of the percentage of the load made up by motors and then a representation of the rest of the load with a combination of series and parallel equivalents. The transformer connection between the distribution system and the loads will influence the zero-sequence characteristics and should be modeled correctly.

Example 1 – Distribution System Resonance Magnifies Harmonic Distortion Levels

The first example illustrating harmonic issues on distribution systems is a typical case where a substation capacitor bank is causing the entire distribution system to exhibit resonance near a characteristic harmonic of typical nonlinear loads. The example system is illustrated in Figure 9-1. There is one capacitor bank in the distribution system (1,800 kVAr) and a large substation capacitor bank at the 23-kV substation bus (size can be in the range of 3,600 to 7,200 kVAr for this analysis). There were complaints of customers having their UPS switching to the backup mode. Also, there were instances of adjustable-speed motor drives tripping with an error code indicating variations in the input frequency. Measurements at the substation indicated voltage distortion levels of 10% and higher (see Figure 9-2), which was considered the most likely cause of these complaints.

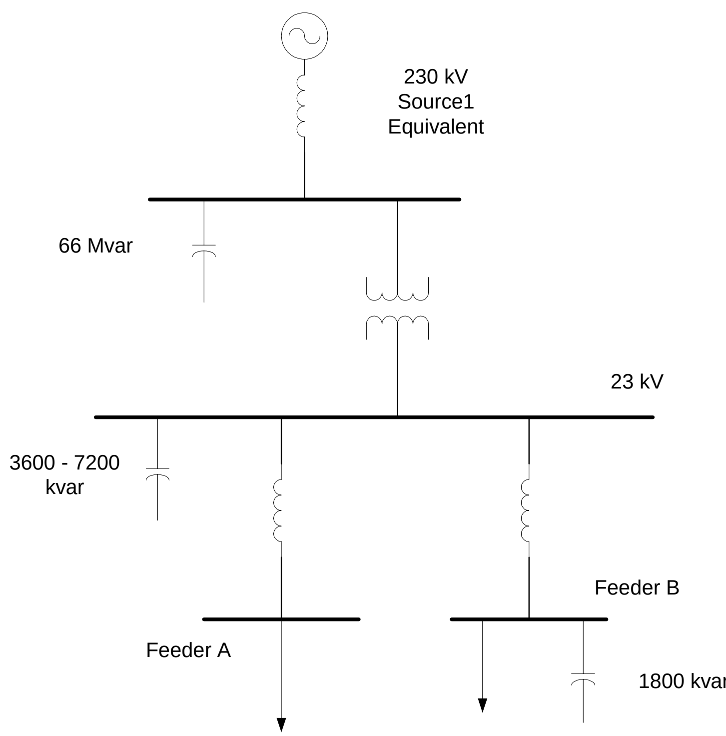


Figure 9-1
Single-Line Diagram of Distribution System for Harmonic Analysis

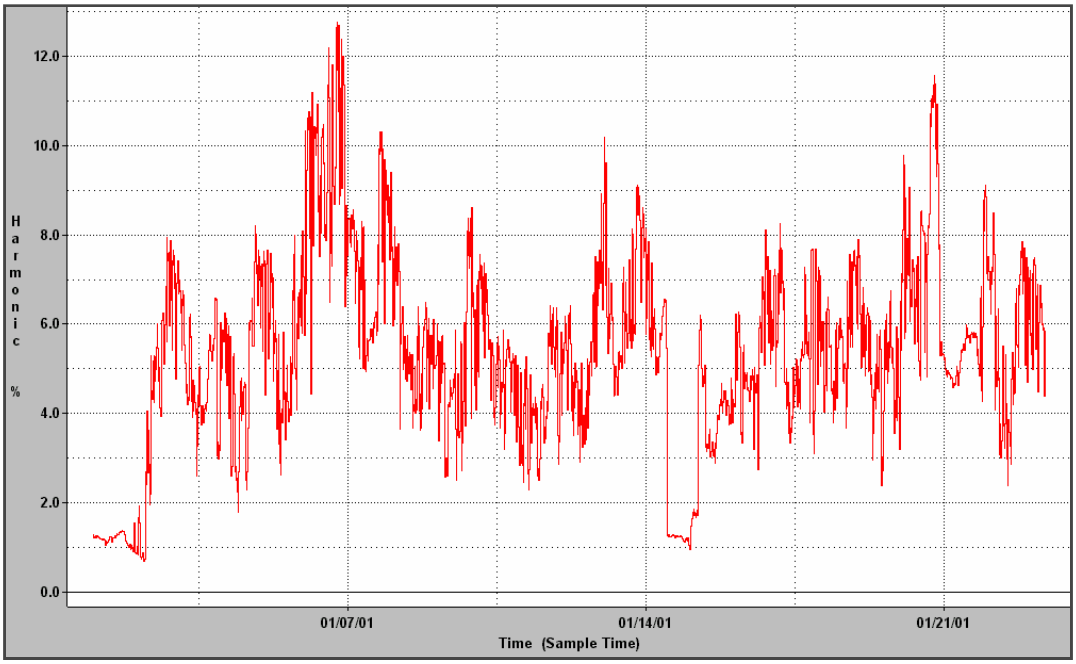


Figure 9-2
Trend of Voltage Distortion at the Substation for the Example System

Current distortion was measured in conjunction with the voltage distortion. Figure 9-3 shows the current distortion levels associated with one of the feeder circuits (the circuit with the most industrial load). Current distortion in the range of 3 to 9% is not considered excessive and indicates that there is probably not a single customer that is the cause of the voltage distortion.

Current distortion measurements in the secondary of the step-down transformer showed much higher distortion levels, ranging from 5 to 35% (Figure 9-4). These current distortion measurements indicate a resonance condition where the harmonic currents are getting magnified by the resonant circuit formed by the substation capacitor bank and the system source equivalent (see Figure 9-5 for illustration of the magnified current path).

A model of the system was developed to evaluate the frequency response characteristics. This model was used to evaluate the effect of the size of the substation capacitor bank on the system resonance. Figure 9-6 shows the frequency scan results for a number of different compensation levels. The parallel resonance can be close to the fifth harmonic, especially when the full 7,200 kVAr is in service.

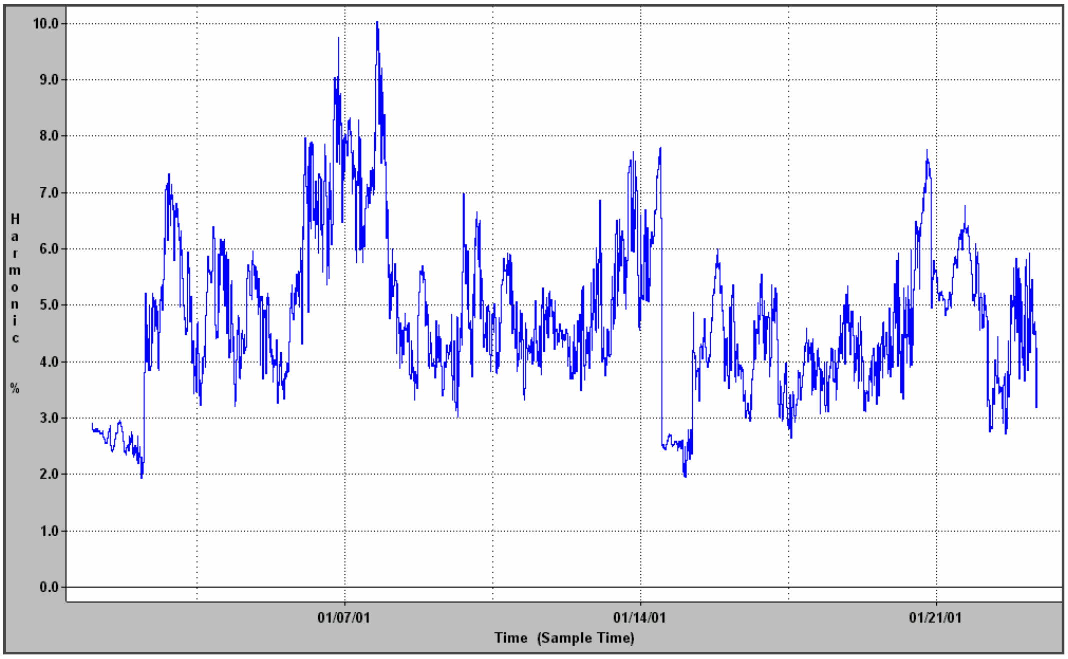


Figure 9-3
Measured Harmonic Current Distortion in the Feeder Circuit

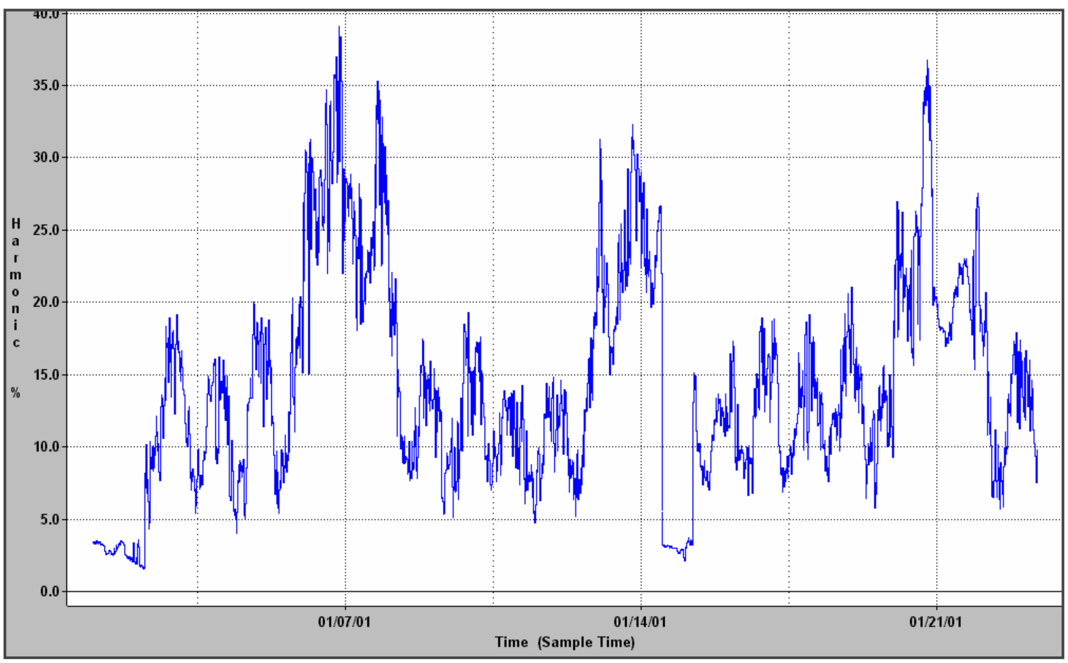


Figure 9-4
Measured Harmonic Current Distortion in the Secondary of the Step-Down Transformer at the Substation

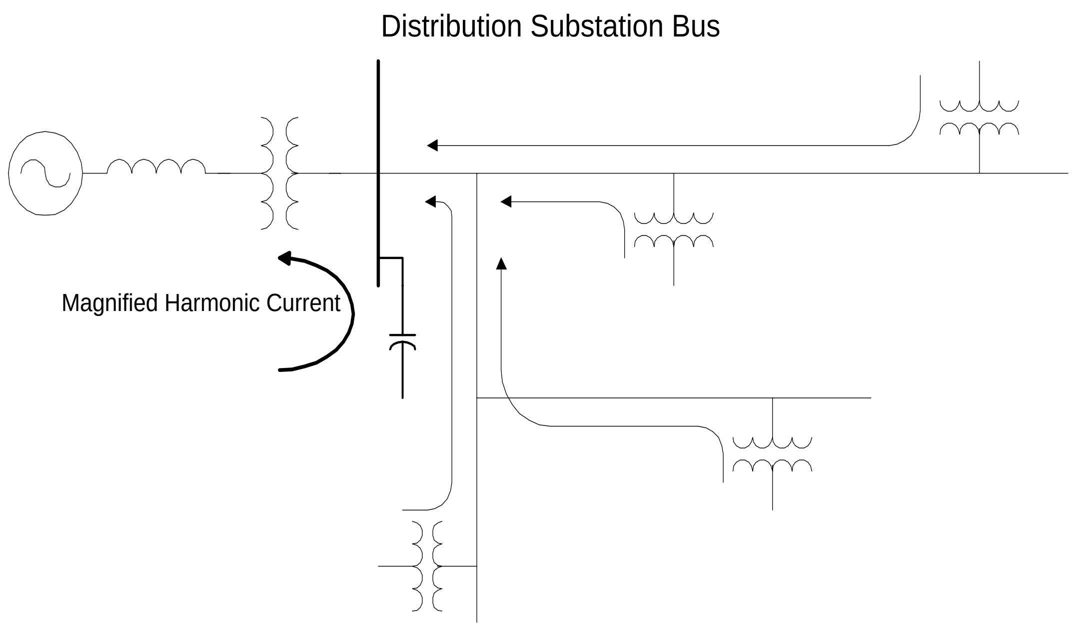


Figure 9-5
Illustration of General Case Where a Substation Capacitor Bank Can Result in Magnified Harmonic Currents in a Parallel-Resonance Condition

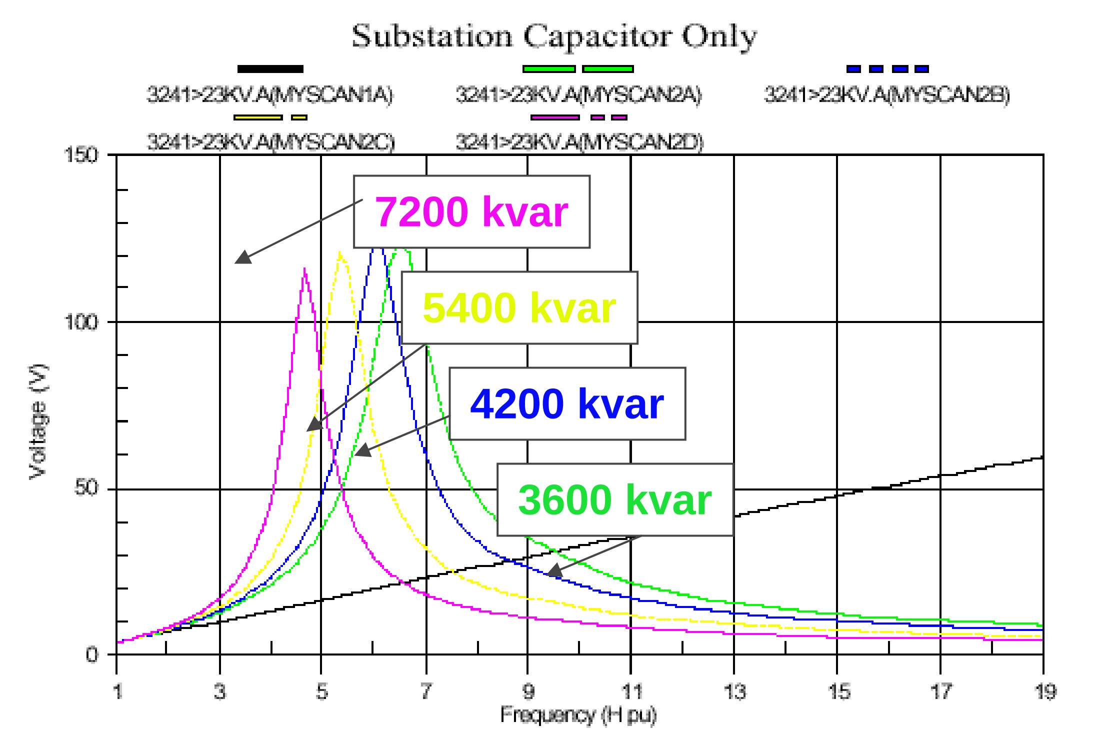


Figure 9-6
Frequency Scan Results – Effect of 23-kV Substation Capacitor Size on System Resonance

Because the problem of high voltage distortion was being caused by a system resonance rather than excessive harmonic generation from customers, the utility decided that it was their responsibility to solve the problem.

The problem could be solved by reducing the substation compensation. This was actually done as a temporary solution—capacitors were removed to make the bank a 3,600-kVAr bank. However, this compensation was needed for system support, and the smaller capacitor bank was not considered an acceptable long-term solution.

Therefore, a design was developed that converted the substation capacitor bank to a harmonic filter tuned to the 4.9th harmonic. The effect of the filter on the frequency response characteristics of the system are shown in Figure 9-7. It can be seen that the parallel resonance peak is shifted to well below the 5th harmonic, and the filter provides low impedance near the fifth harmonic.

The effectiveness of the solution is shown in Figure 9-8, which provides a trend of harmonic distortion levels showing the filter being switched in and the resulting harmonic distortion levels decreasing dramatically.

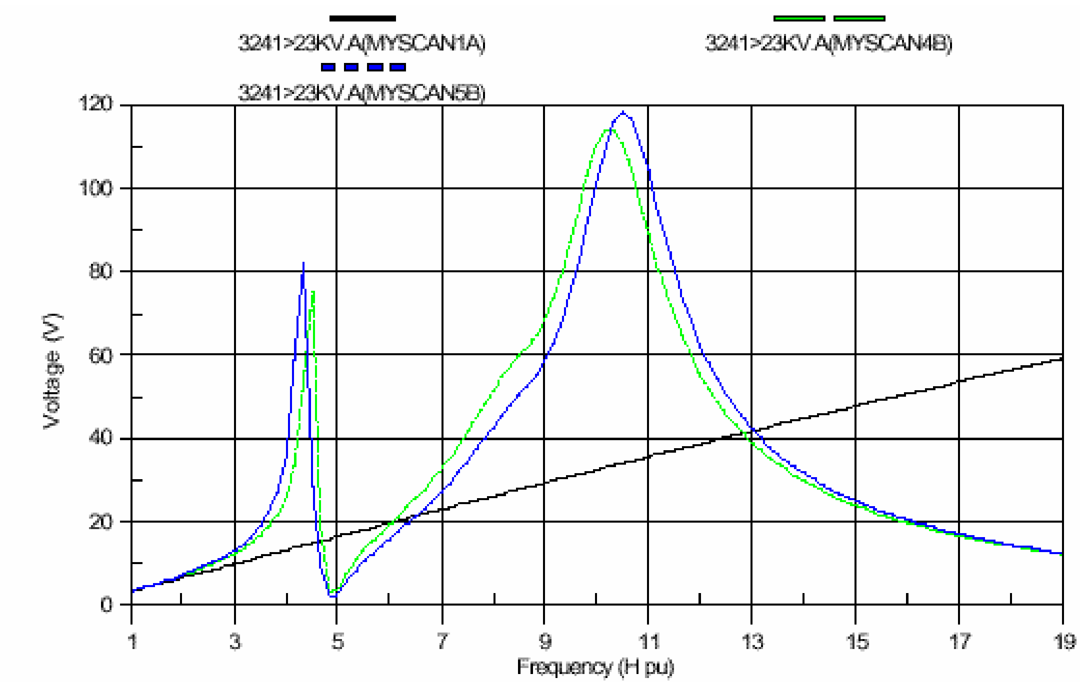


Figure 9-7
Impact of Substation Filter on Frequency Response

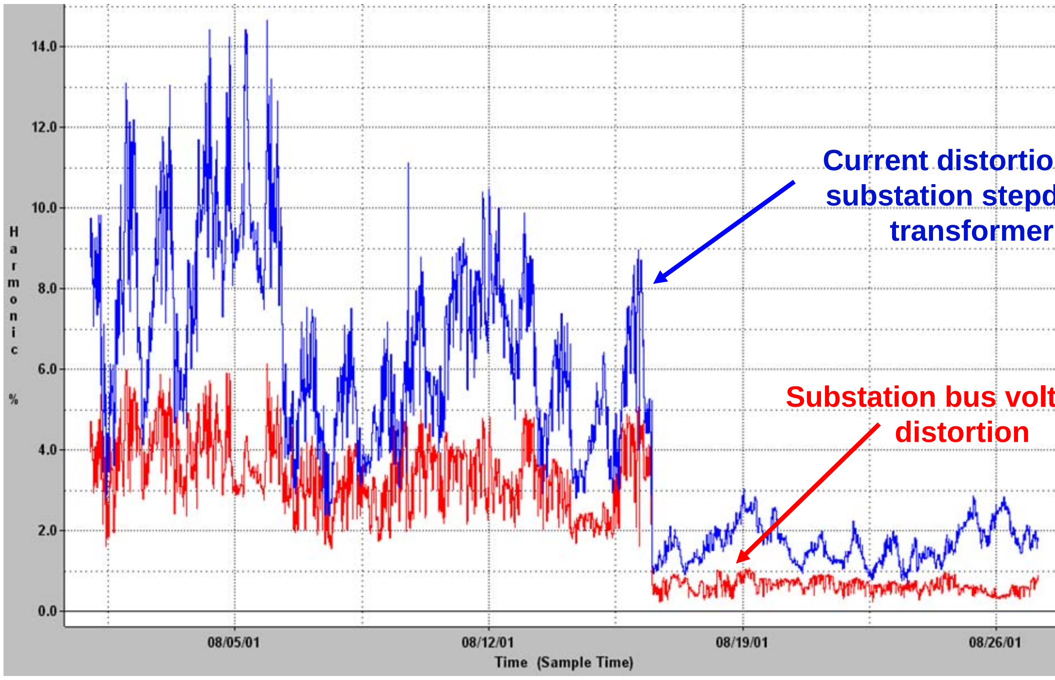


Figure 9-8
Trend of Harmonic Voltage Distortion at the Substation Showing the Harmonic Filter Being Switched into Service

Example 2 – Harmonic Interaction with Low-Voltage Power-Factor-Correction Capacitor Banks

This case study also deals with resonance conditions on the distribution system, but it also involves interaction with customer power-factor-correction capacitors. When customers install power-factor correction, the design should take into account the harmonic characteristics on the primary distribution system, or there is a possibility that the low-voltage capacitors will become overloaded due to harmonics from other customers or from interaction with the primary system. This case illustrates such a problem.

The system for Example 2 is shown in Figure 9-9. An industrial customer was expanding its operation with two new services. The customer process involved a plating operation with substantial rectifier load (waveforms shown in Figure 9-10). Therefore, they implemented power-factor correction as tuned capacitors. These were automatic systems that could range from 50 kVAr to 650 kVAr in 50-kVAr increments. Each step was tuned to the 4.8th harmonic. A picture of the low-voltage power-factor-correction system is shown in Figure 9-11.

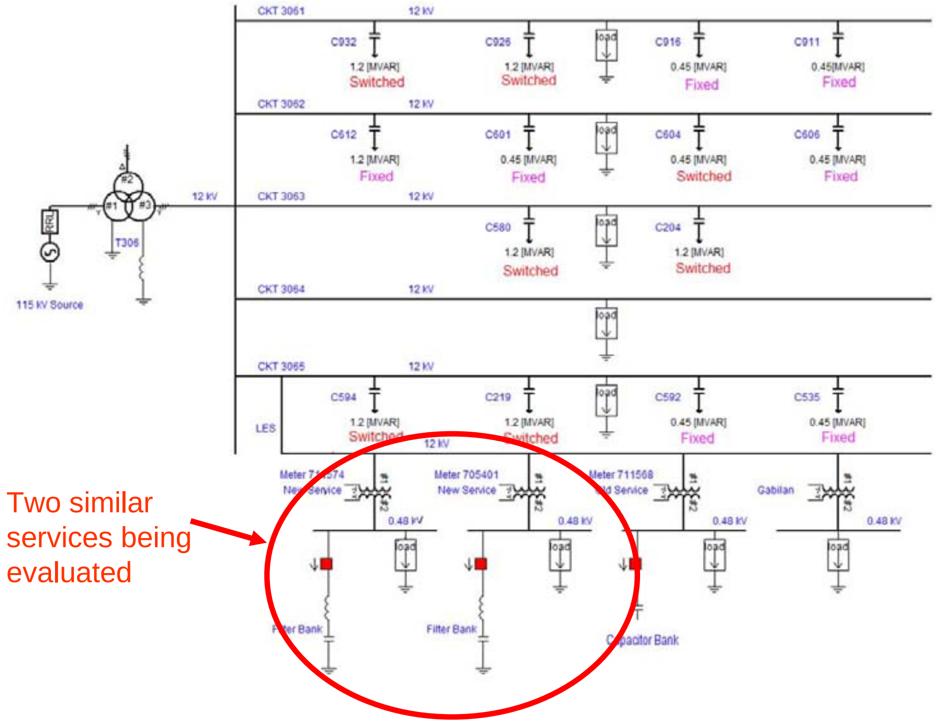


Figure 9-9
Single-Line Diagram of the System for Example 2 Showing the Distribution Circuits and the Industrial Customer with Low-Voltage Power-Factor-Correction Systems

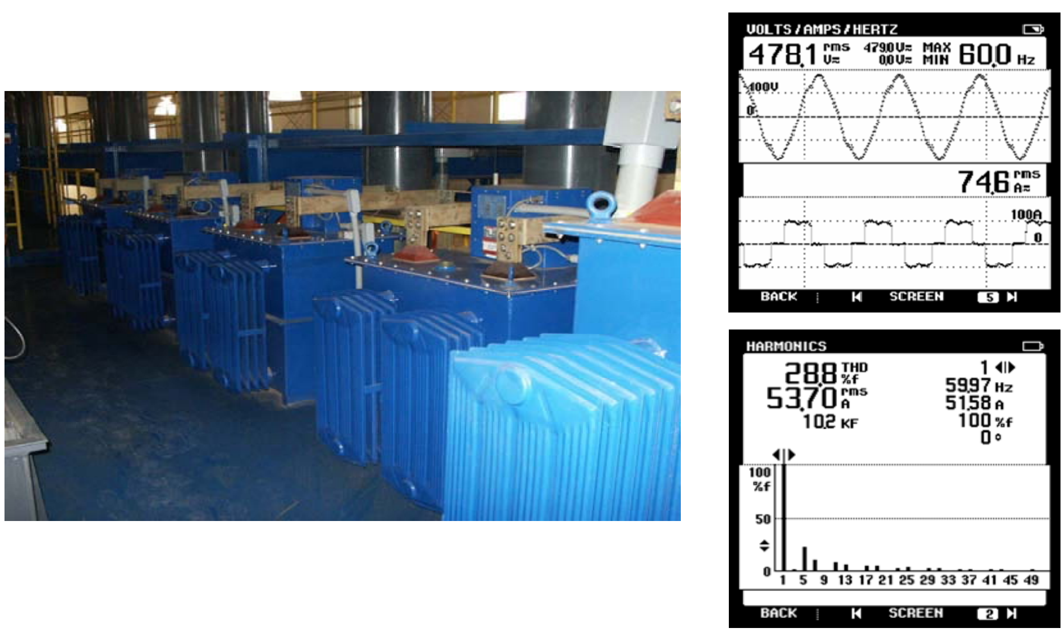


Figure 9-10
Waveform and Harmonic Characteristics for the Rectifier Loads in the Industrial Facility

Figure 9-11
Low-Voltage Power-Factor-Correction System Installed to Prevent Harmonic Resonance Problems by the Industrial Customer

When an engineer for the customer put the tuned power-factor-correction systems in service, he experienced fuse blowing in the individual steps of the power-factor-correction system. Various explanations were proposed, including possible magnification from a nearby industrial facility (also associated with the same customer) that did not have tuned capacitor banks for the power-factor correction.

The distribution system was modeled in detail to evaluate the potential for interaction between the customer system and the primary distribution system. As indicated in Figure 9-9, there are numerous capacitor banks on the distribution feeder circuits, resulting in resonance conditions that vary as capacitors are switched in and out of service. The model was verified for a particular capacitor-bank configuration; the results are shown in Table 9-1. However, other capacitor-bank configurations could result in substantially higher voltage and current distortion than this base case. Figure 9-12 gives a trend of the voltage distortion measured at the substation. This shows the effect of capacitors being switched in and out of service. It is clear that some capacitor configurations are resulting in higher voltage distortion levels and some magnification of harmonic components.

Table 9-1
Measured and Simulated Harmonic Voltage Distortion at the Substation for Model Verification

System Voltage	Magnitude (RMS)	%THD	%H3	%H5	%H7
Measured	7320	4.3	2.5	3.4	0.5
Simulated	7320	4.2	2.5	3.4	0.4

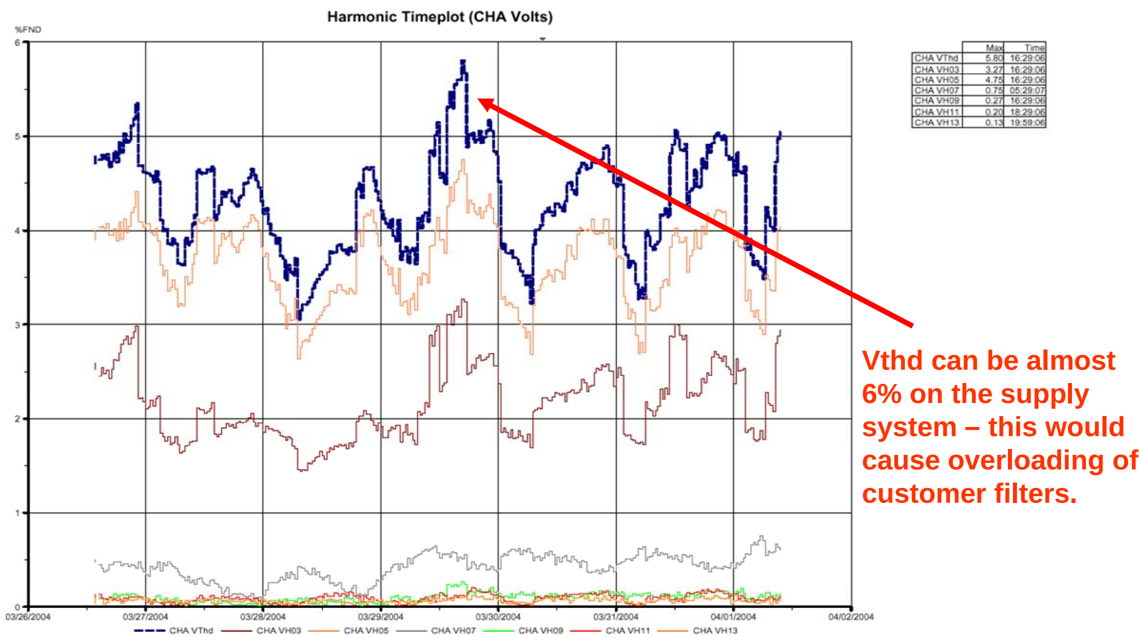


Figure 9-12
Trend of Harmonic Voltage Distortion at the Substation Illustrating the Effect of Switching Capacitor Banks in and out of Service

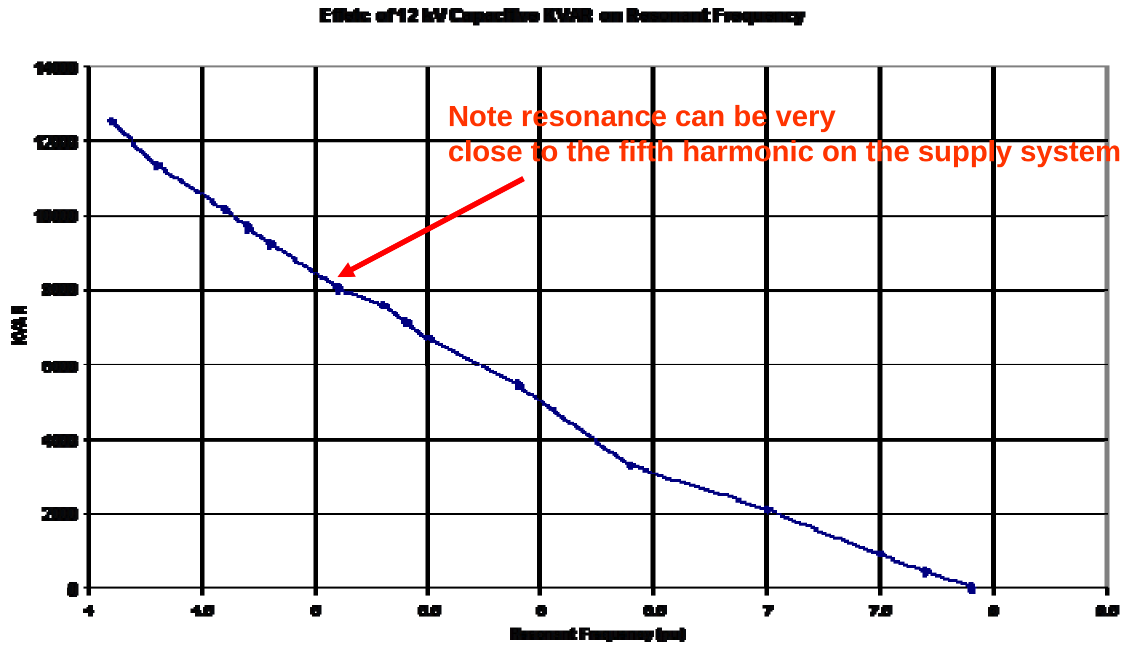


Figure 9-13
Illustration of the System Resonance as a Function of the Total Shunt Compensation on the Distribution System

Simulations illustrated the resonance condition more clearly. Figure 9-14 is an example of the frequency response characteristics showing the resonance for a few different capacitor-bank configurations that can result in resonance close to the fifth harmonic.

Even with a system resonance near the fifth harmonic, the harmonic voltage distortion levels were not excessive (less than 6%). However, these voltage distortion levels combined with the design of the customer power-factor-correction system resulted in overloading of the tuned banks. Basically, the customer power-factor correction was not designed to handle this level of loading from the supply system. If the tuned banks would have been tuned further away from the 5th harmonic or if they would have been designed for higher harmonic current levels, there would not have been a fuse-blowing problem.

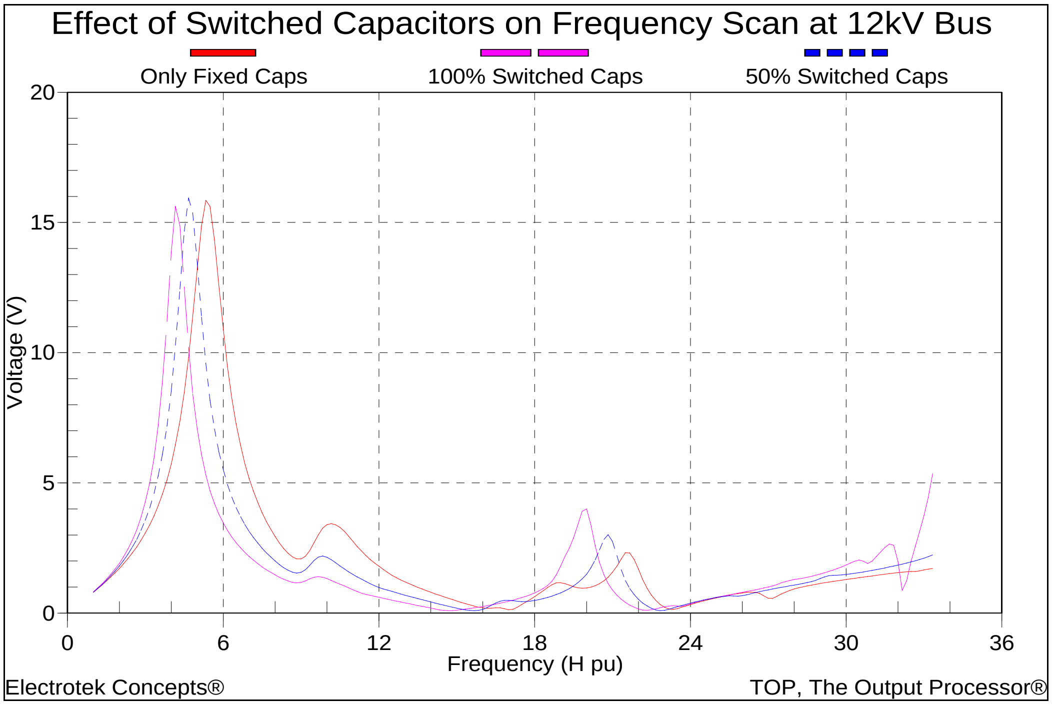


Figure 9-14
Frequency-Response Characteristics for Different Capacitor-Bank Configurations Illustrating Potential for Resonance Close to the Fifth Harmonic

The problem with this case study is finding the most economical way to allow the customer to operate its power-factor-correction system and maintain acceptable levels of voltage distortion on the distribution system.

Replacing the tuned power-factor-correction systems in the customer facilities with new units designed to handle the additional duty imposed from the primary distribution system was prohibitively expensive. Therefore, an alternative solution of designing a filter to avoid fifth-harmonic parallel-resonance conditions on the primary distribution system was developed.

The design involved converting a pole-mounted capacitor bank on the distribution system to a tuned filter. This prevents the fifth-harmonic resonance on the distribution system, regardless of the status of other capacitor banks on the system. The cost of the solution was less than 50% of the cost of replacing just one of the customer's power-factor-correction systems.

A bank close to the customer was used. The installation is shown in Figure 9-15. Voltage distortion levels were reduced to less than 4%, with the primary distortion occurring at the third harmonic after the filter was installed. Note that the higher third harmonic voltage distortion probably could have been avoided by designing the filter as an ungrounded bank so that it does not magnify the zero-sequence third-harmonic components. This is an issue that should be evaluated as part of distribution filter designs in general.

Figure 9-15
600-kVAr Tuned Capacitor Bank Installed on the Distribution System to Prevent Magnification of the Fifth-Harmonic Component

Modeling Underground Systems and Underground Networks

Urban distribution systems are often virtually 100% underground and may have networked secondaries. These systems have some special characteristics for harmonic evaluations.

Modeling Guidelines

As with modeling distribution systems in general, it is important to include all capacitive elements in the model. For underground systems, the capacitance of the underground circuits can be a very important part of the total distribution system capacitance. Therefore, representation of all the cable circuits is necessary.

Another important aspect of the underground network system is the load representation. The significant amount of load supplied from a single distribution substation means that there is much more damping than on most distribution systems. This can be beneficial in preventing significant magnification when the system has a resonance close to a characteristic harmonic. However, the harmonic-producing characteristics of the load can also be important, and concerns for overheating of secondary network cables, primary cable circuits, and network transformers can be important.

Important elements of the system model include:

- Source equivalent at the primary of substation transformers
- Substation transformers with connection information
- Neutral grounding reactors or resistors often used to limit fault currents (these are important in representing the zero-sequence system)
- Substation power-factor-correction capacitors (grounded or ungrounded)

- Primary distribution cable circuits
- Network transformers (may be aggregated to represent groups of transformers)
- Representation for coupling in the secondary network
- Load representation (aggregated)

Some of these considerations are illustrated with an example assessment of an underground network system frequency response and harmonic distortion evaluation.

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- Network transformers (may be aggregated to represent groups of transformers)
- Representation for coupling in the secondary network
- Load representation (aggregated)

Some of these considerations are illustrated with an example assessment of the frequency response of an underground network system and harmonic distortion evaluation.

Example 2 – Underground Network System Example

The system being studied is a 27-kV distribution system supplied with four parallel 50-MVA transformers that step down from a 132-kV transmission system. The distribution system consists of underground primary feeders that supply delta-wye grounded network transformers. A one-line diagram of the basic configuration is shown in Figure 9-16. There are three large 30-MVAr capacitor banks that provide additional voltage support and power-factor correction beyond all the charging capacitance of the cable circuits.

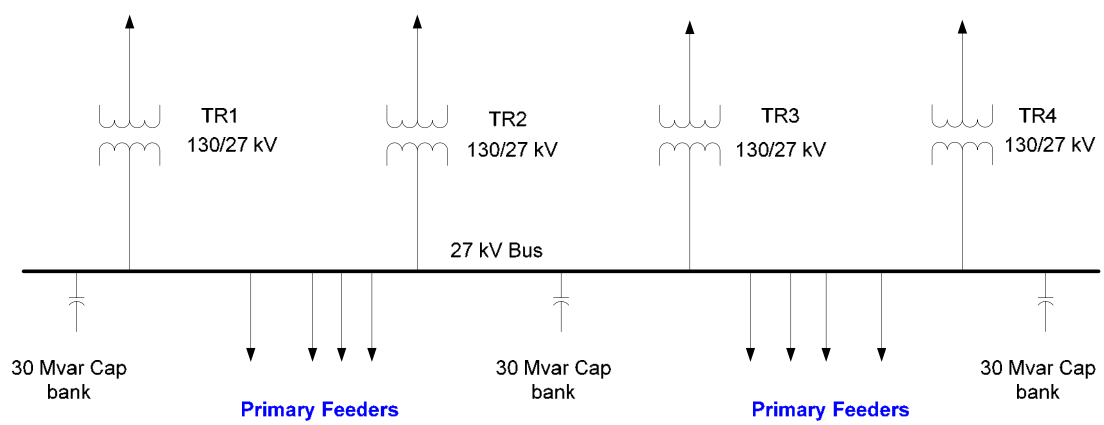


Figure 9-16
One-Line Diagram of Substation Configuration for Underground Network System Studied

Measurements provided information about actual voltage and current distortion levels on the system. The measurements are from the substation bus for the voltage and the substation transformer secondary for the current (current harmonics are expressed as a percent of the RMS current at this location that is exceeded 5% of the time). Statistical summaries of the measurement results are included in Figure 9-17 and Figure 9-18. Figure 9-19 gives a trend of the harmonic distortion levels that illustrates the variations over time.

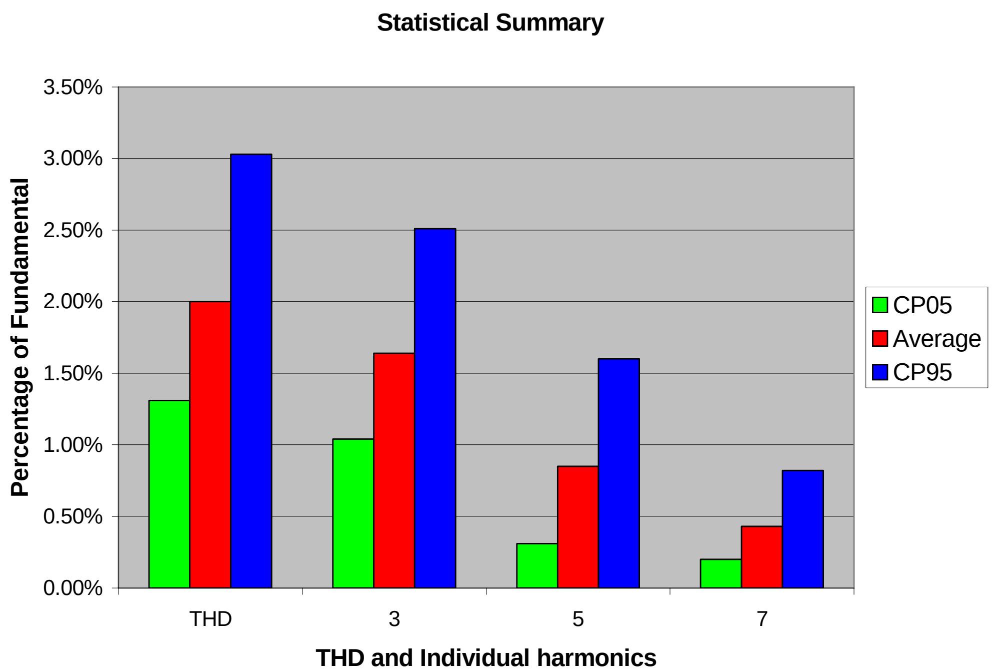


Figure 9-17
Statistical Summary of Voltage Distortion Levels at the Substation for the Underground Network System

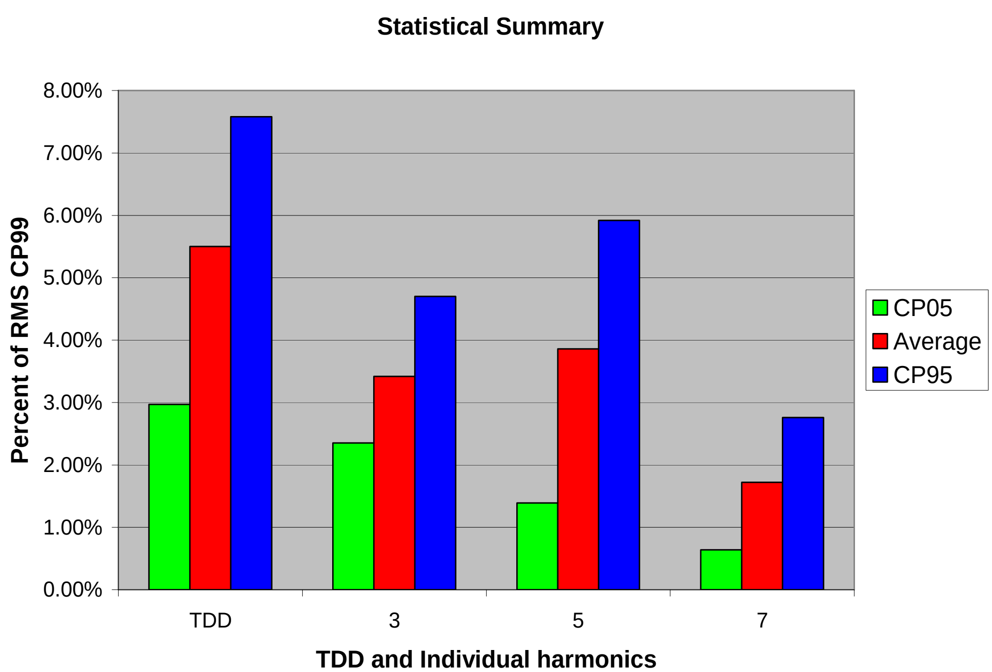


Figure 9-18
Statistical Summary of Current Distortion Levels at the Substation for the Underground Network System (Expressed in Percent of 95% Level RMS Current Values)

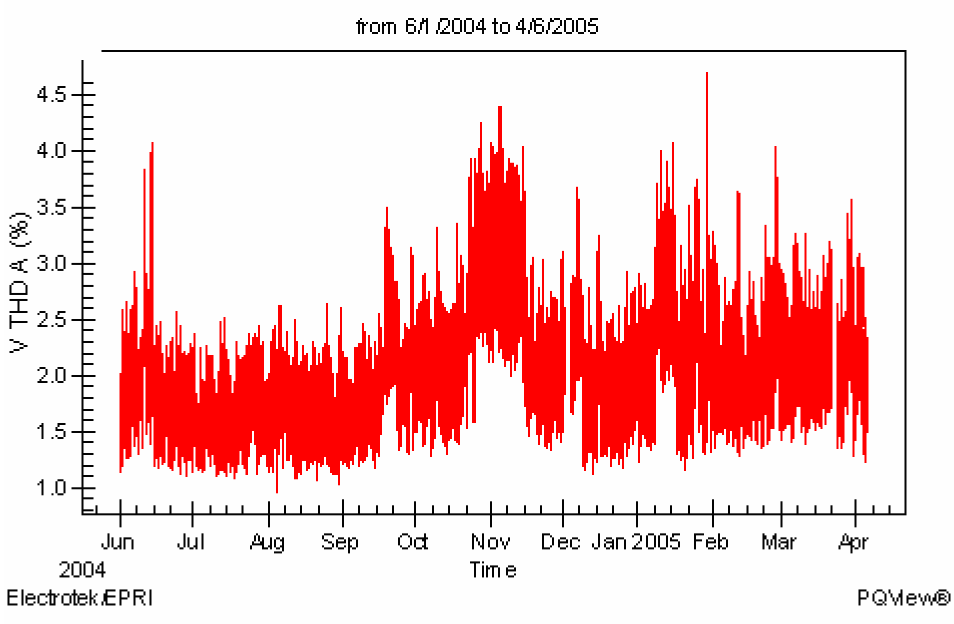


Figure 9-19
Trend of Harmonic Voltage Distortion Levels over Almost a One-Year Monitoring Period

The model of this system was developed by representing each primary feeder circuit with four main sections. The network transformers were aggregated at the nodes created between these sections, and load was represented on the secondaries of the network transformers. Both linear load and distributed harmonic-producing load were represented. Coupling between the network transformers was included to represent the secondary network system.

Harmonic distortion levels on the system are the result of harmonics produced by all of the customers combined. This is modeled with harmonic sources distributed throughout the system. A generic model for nonlinear loads was developed and used as a percentage of the total load. A typical harmonic spectrum was used to represent this distributed nonlinear load (in this case, the nonlinear load was assumed to be 15% of the total load). This resulted in a reasonable representation for the overall distortion levels on the distribution system, as indicated by the comparison with measurement results in Table 9-3.

Table 9-2
Assumed Harmonic Spectrum for the Nonlinear Portion of the Load Model

Harmonic	Magnitude (% of Fundamental)
3	15
5	10
7	8
9	3
11	2
13	1

Table 9-3
Comparison of Base-Case Simulation Results with Measurements as Verification of the Harmonic-Producing Load Representation

Parameter	Monitored (Average)	Simulated
27-kV Bus Voltage		
RMS Magnitude (V)	15,263	15,589
THD (%)	2.00	2.04
H3 (%)	1.63	1.51
H5 (%)	0.84	1.30
H7 (%)	0.43	0.44
Main Transformer Current		
RMS Magnitude (A)	926	956
THD RMS (%)	3.65	3.02
I3 (A)	9.62	13.9
I5 (A)	28.76	24.5
I7 (A)	8.04	5.9
Power at 27-kV Bus		
P (MW)	168	150
Q (Mvar)	12	8.5

Positive-Sequence Response Characteristics

There are a number of variables that can affect the frequency response-characteristics of the underground network distribution system. The most important variable is the status of the 30-MVAr capacitor banks. Due to their ungrounded configuration, the banks do not affect the zero-sequence resonance of the system. However, they have the most important impact on the positive-sequence resonance.

Without any capacitor banks in service, the positive-sequence resonance is close to the 8th harmonic. This is caused by the cable capacitance in parallel with the system source impedance. The switching in of the banks causes the positive-sequence resonance peak to shift downwards. For 30- and 60-MVAr compensation levels, the resonance peak appears in the vicinity of 5th harmonic. Fortunately, significant damping from system loads prevents high levels of magnification associated with this resonance. For 90-MVAr compensation level, the resonance peak shifts further down to the 4th harmonic and is less of a concern from a 5th-harmonic resonance point of view.

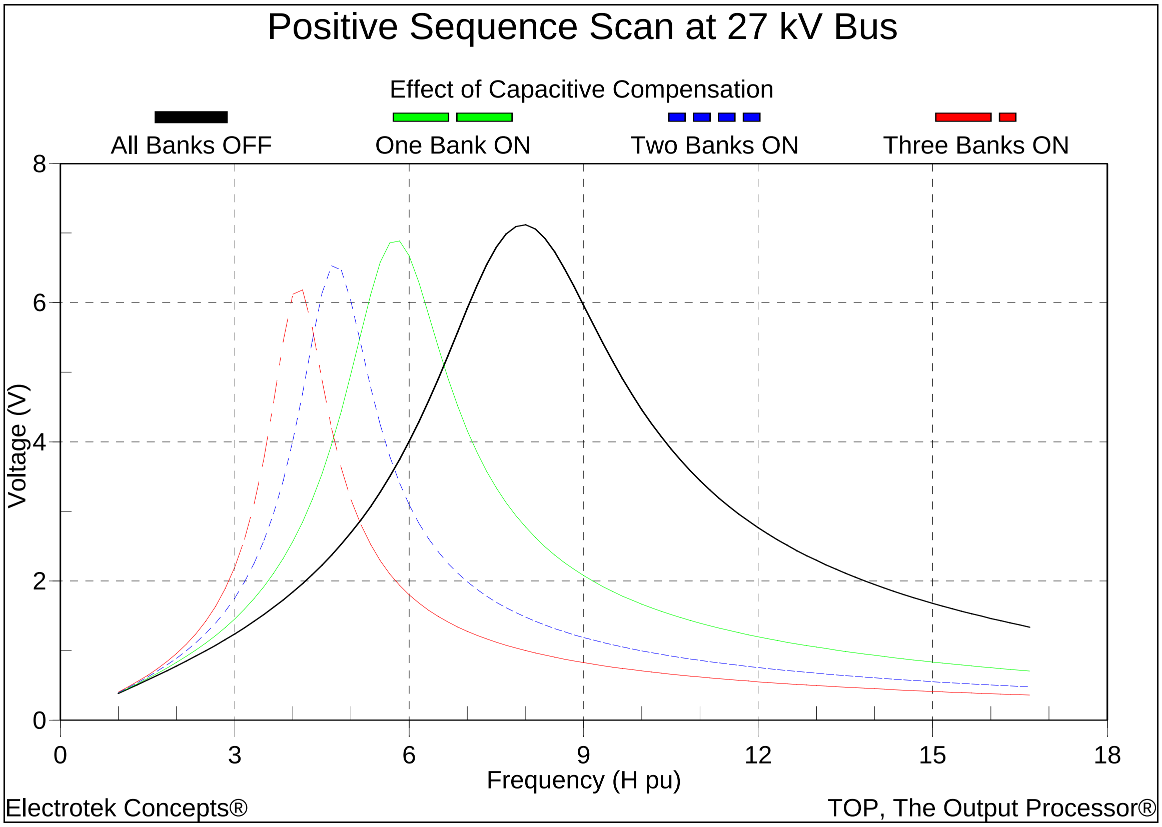


Figure 9-20
Positive-Sequence Frequency-Response Characteristics of the Underground Network System Showing the Effect of the 30-MVAr Substation Capacitor Banks

Zero-Sequence Response Characteristics

It is also useful to look at the resonance conditions in the zero-sequence circuit. The harmonic summary data from the measurements in Figure 9-17 shows that the highest harmonic component in the voltage distortion is actually the third harmonic. This can possibly be explained by the resonance conditions in the zero-sequence circuit.

The zero-sequence resonance is not affected by the 30-MVAr capacitor banks. However, it is affected by neutral grounding reactors used in the substation transformers to limit fault current during single line-to-ground faults. These reactors increase the zero-sequence source impedance and result in a lower resonant frequency. The capacitance affecting this resonance is the total cable capacitance of all the primary distribution cables (this capacitance appears in both the positive- and zero-sequence circuits).

The frequency-response characteristics of the zero-sequence circuit are shown in Figure 9-21. It is interesting to note that the zero-sequence resonance is in the vicinity of the third harmonic. The zig-zag transformers shift the resonance slightly. The overhead loop has a much more dramatic impact on the resonance in the damping provided by the load on the overhead loop. When the overhead loop is not connected, there is no load to provide damping in the zero-sequence circuit because it is isolated from the primary system by the delta-wye network transformers.

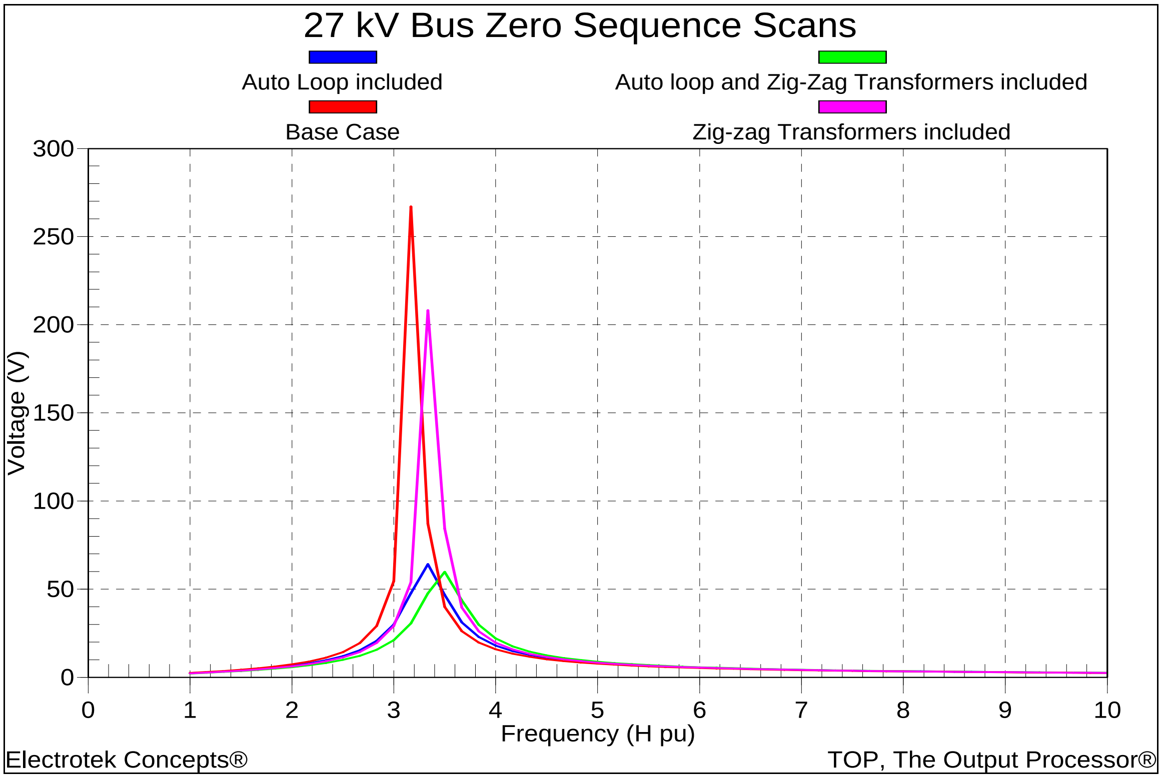


Figure 9-21
Frequency-Response Characteristics of the Zero-Sequence Circuit for the Underground Network System (Including the Effect of Backup Supply to Overhead Loops)

None of these conditions result in serious voltage distortion. Even though the resonance is close to the third harmonic in the zero-sequence circuit, there is very little generation of third harmonic because the zero-sequence load harmonics cannot pass through the delta-wye network transformers. When the overhead loop is connected, the amount of third-harmonic generation is more significant, but the damping of the load reduces the magnification so that the distortion levels are still acceptable.

The following are conclusions derived from this case study and other examples of underground network system characteristics:

- Positive-sequence frequency response primarily depends on the source strength and the capacitor banks. The positive-sequence resonance is likely to be in the vicinity of the 5th and 7th harmonics with at least one large capacitor bank in service. Maximum compensation levels may move the resonance below the fifth harmonic. The resonance in these circuits is well damped by the load on the circuits. This prevents serious magnification of harmonic components, even when there is a resonance close to the fifth harmonic.
- Zero-sequence resonance in most of these circuits will be determined by the total cable capacitance and the zero-sequence source equivalent, which is heavily influenced by the presence of neutral reactors in the substation transformer. This resonance can be as low as the

third harmonic but is more typically in the range of the 5th to 8th harmonic. Note that the zero-sequence resonance is very lightly damped in these circuits because the load does not appear in the zero-sequence circuit.

Underground networks that supply overhead loops have a different characteristic. The resonance is the same, but the damping is much greater. The overhead loop also results in much more harmonic injection in the zero sequence (third harmonic) due to single-phase customers. The result will generally be higher third-harmonic distortion levels due to the higher amounts of third-harmonic current injection.

10
TRANSMISSION-RELATED STUDY OBJECTIVES

Concerns for Adding Capacitors to Transmission Systems

When large capacitor banks are added at transmission voltages, the frequency response of the transmission system is significantly changed. The resulting resonances can magnify harmonics that are generated by large industrial customers or injected from distribution systems supplied from the transmission system. The result can be increased voltage distortion levels on the transmission system.

High voltage distortion levels on the transmission network can be a particular problem because these harmonics voltages can then affect many different distribution systems. The voltage distortion on the transmission system can excite local resonances at distribution voltages or within customer facilities, causing harmonic problems at lower voltages. This is the main reason that recommended voltage distortion limits are lower for transmission voltages.

In general, a transmission harmonic study has following objectives:

- Determine the system frequency-response characteristics with and without the addition of proposed transmission capacitor banks.
- Identify resonance concerns introduced or aggravated by the proposed capacitor banks.
- Estimate the impact of proposed capacitor banks on the system harmonic distortion levels.
- Evaluate solutions to control harmonic distortion levels.

These concerns are illustrated with an analysis of an example 138-kV system.

Example 1– 138-kV Transmission System with Large Capacitor Banks

Capacitor banks are being proposed for a 138-kV system for voltage support during heavy power-flow conditions. This system supplies a number of industrial customers, and there is a concern that the capacitor banks could result in resonance conditions that would magnify harmonics and create unacceptable levels of voltage distortion. Figure 10-1 is a one line-diagram illustrating this system along with both the existing and proposed capacitor banks. Besides the 138-kV system, 69-kV and 23-kV buses have to be represented due to the presence of large capacitor banks at these lower-voltage locations.

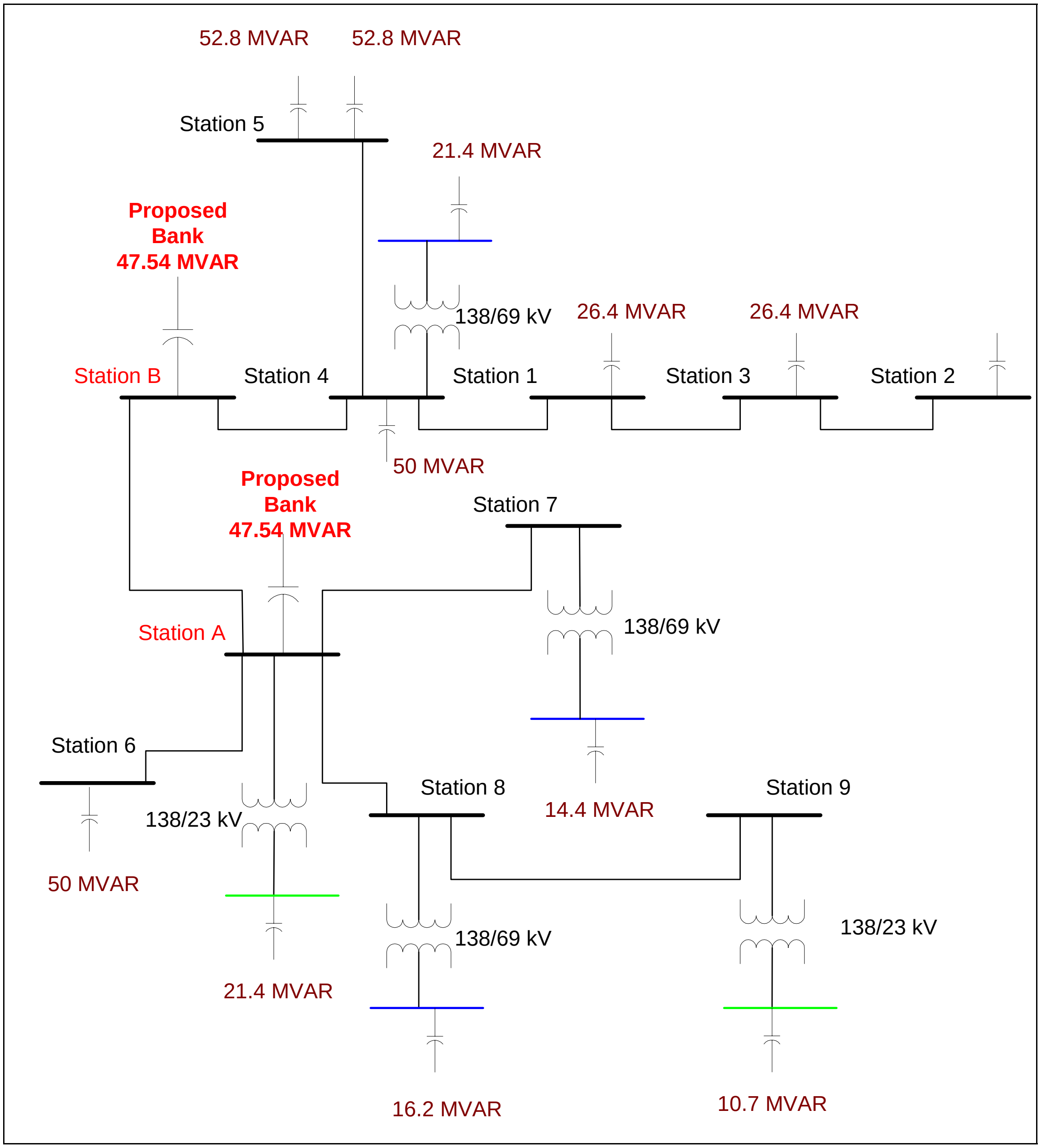


Figure 10-1
Single-Line Diagram of the Example Transmission System Representation for Harmonic Analysis

The model of this system included distributed loads that provide damping at resonance frequencies (linear portion) and are also the source of harmonic currents (nonlinear portion). A general harmonic spectrum for the nonlinear portion of the load was developed that could be distributed around the system. Because this was an industrial area, about 30% of the load was assumed to be nonlinear with a spectrum as indicated in Table 10-1.

Table 10-1
Assumed Harmonic Current Spectrum for the Nonlinear Portion of the Loads Supplied from the Transmission System

Harmonic	Magnitude (% of Fundamental)
3	1.5
5	20
7	4
9	2
11	1

The harmonic analysis consists of frequency scans to characterize the frequency-response characteristics of the system and the effect of the proposed capacitor banks. Next, a harmonic analysis is performed with the distributed harmonic generation from loads throughout the system to estimate actual levels of voltage distortion that might occur.

Important variables for the frequency-response analysis include:

- 138-kV capacitor banks
- Other capacitor banks in the system that also affect the resonance
- Loads that provide damping for the resonance
- Source conditions

Example frequency-response results from one of the proposed capacitor bank locations are illustrated in Figure 10-2, Figure 10-3, and Figure 10-4 for three different loading levels. At each successive increase in loading levels, it is assumed that more capacitor banks are needed on the system for support. At medium load levels, the resonances are starting to approach the fifth harmonic. At the maximum load levels, the first resonance is actually below the fifth harmonic.

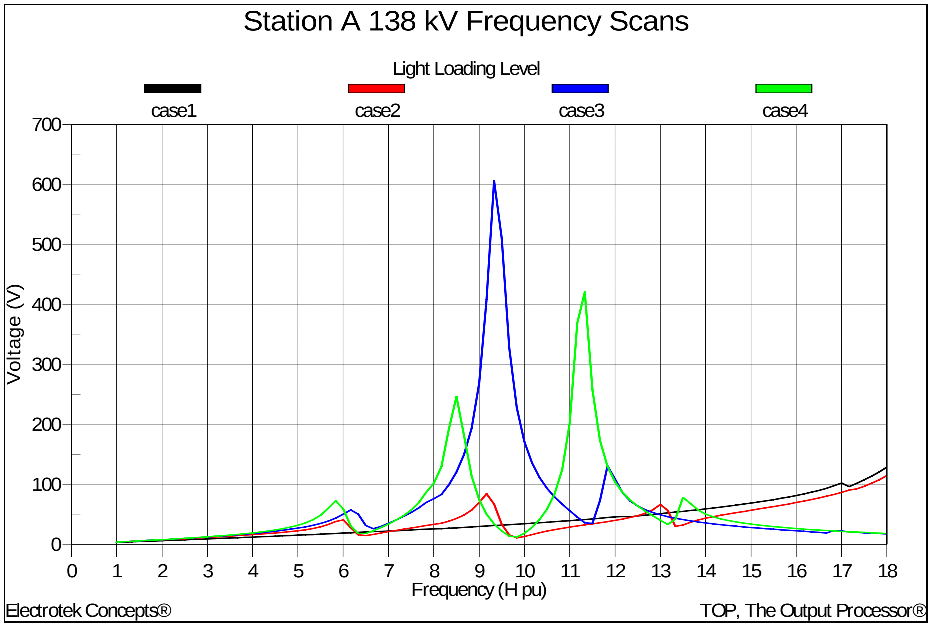


Figure 10-2
Frequency-Response Simulations for Light Loading Cases (Different Capacitor Bank Configurations)

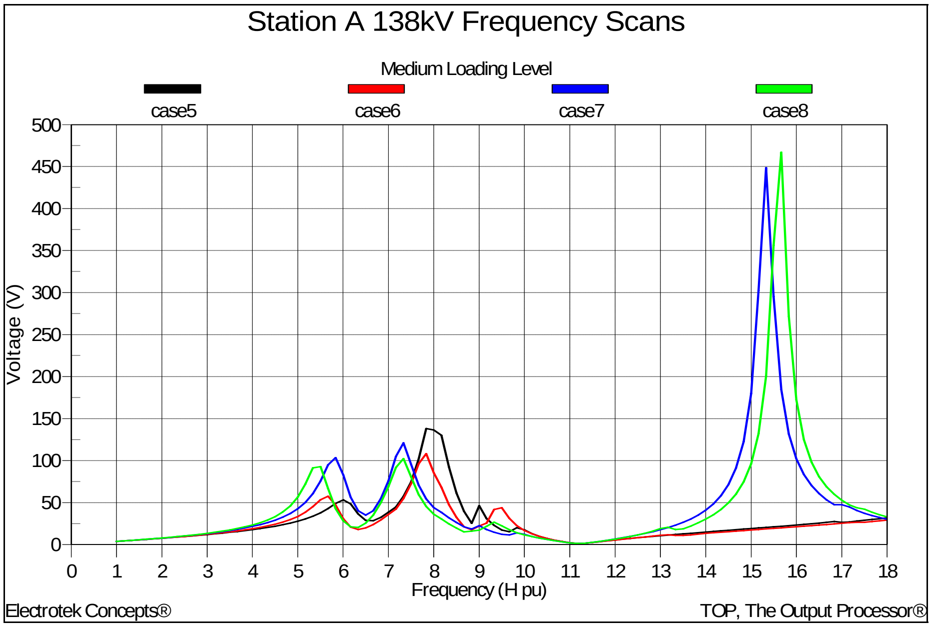


Figure 10-3
Frequency-Response Simulations for Medium Loading Cases (Different Capacitor Bank Configurations)

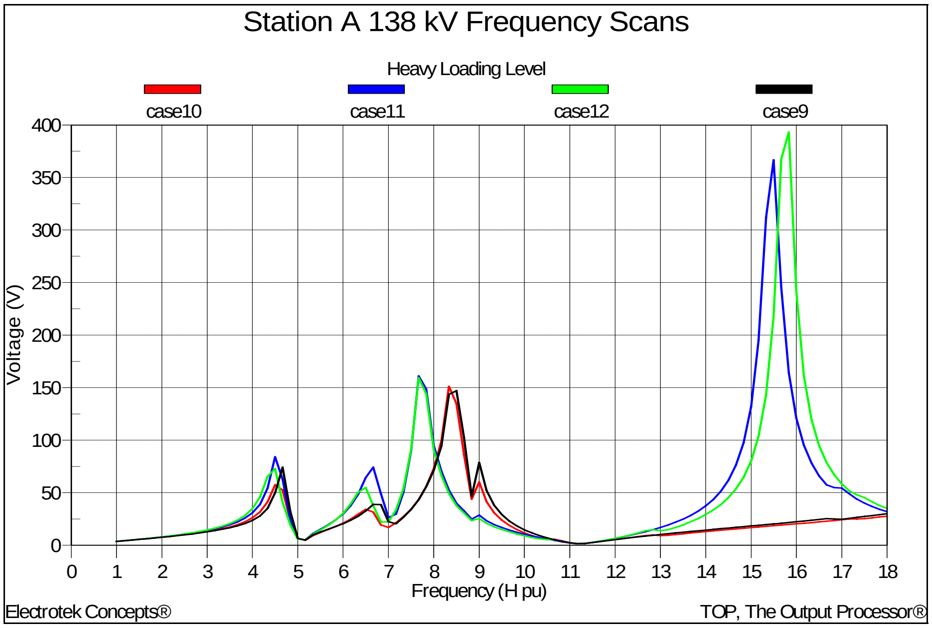


Figure 10-4
Frequency-Response Simulations for Heavy Loading Cases (Different Capacitor Bank Configurations)

Based on the frequency scan results described in the previous section, following conclusions can be drawn:

- For light load conditions, the resonance peaks are between 8th and 12th harmonic for different cases. There is also a damped resonance peak around 6th harmonic at both the substations. There is no resonance around 5th harmonic for any of the light loading cases.
- For medium loading, the peaks shift towards lower frequencies. This is expected because as reactive compensation increases (capacitance increases), the resonant frequency reduces. Note that the peak around 6th harmonic has shifted towards 5th. This indicates a potential resonant condition at the 5th harmonic. There are resonant peaks between the 7th and 10th harmonic, but they are not of concern from a harmonic standpoint.
- For heavy loading, the resonance peak has shifted below the 5th harmonic.

For medium and heavy loading conditions, it is evident that there is a potential for a resonance condition at the 5th harmonic. Additional scans were performed to investigate the possibility of obtaining a resonance peak even closer to the 5th harmonic. Various capacitor bank configurations create this possibility (although these are all conditions that should have significant system loading resulting in some damping of the resonance).

The frequency-response analysis illustrates the possibility of system resonances near the peak. Simulations to evaluate the response to distributed harmonic sources help to evaluate the impacts of this resonance. Measurements (Table 10-2) were performed for a specific capacitor bank configuration, and these measurements were used to calibrate the harmonic-generation characteristics in the model. Note that this case was a light loading case with very few capacitor banks in service, so the low levels of harmonic voltage distortion are not surprising.

Table 10-2
Harmonic Measurements at Station A That Are Used to Calibrate the Simulation Model

Harmonic	Phase A (%)	Phase B (%)	Phase C (%)
5th	1.1	1.1	1.1
THD	1.1	1.2	1.2

The simulations for the conditions corresponding to the measurements are shown in Table 10-3. The first row of the table represents the conditions that can be directly compared with the measurements, and the other rows are variations in the proposed capacitor banks. Note that the harmonic distortion levels are quite reasonable for all of these cases (although the distortion levels are increased significantly when both of the proposed capacitor banks are in service).

Table 10-3
Harmonic Simulation Results for Load Conditions and Capacitor Bank Conditions Corresponding to the Measurements (Base Case)

Case	Reactive Compensation (MVAr)			Capacitor Bank Status		% THD		% 5th	
	138 kV	69 kV	23 kV	Station A	Station B	Station A	Station B	Station A	Station B
1	0	21.4	10.7	0	0	1.03	1.2	0.94	1.11
1a	0	21.4	10.7	0	C	1.3	1.96	1.11	1.54
1b	0	21.4	10.7	C	0	1.49	1.42	1.23	1.26
1c	0	21.4	10.7	C	C	2.42	3.04	1.48	1.78

Capacitor Bank Status:
0 = Capacitor bank out of service
C = Capacitor bank in service

The frequency-response simulations indicated the potential for a fifth-harmonic resonance condition for higher load levels and additional compensation in service at the 138-kV level. These conditions were simulated, and the results are summarized in Table 10-4. Note the higher voltage distortion levels that may be possible for these conditions.

Table 10-4
Harmonic Simulation Results for Conditions That Result in a System Resonance in the Vicinity of the Fifth Harmonic

Case	Reactive Compensation (MVAr)			Capacitor Bank Status		% THD		% 5th	
	138 kV	69 kV	23 kV	Station A	Station B	Station A	Station B	Station A	Station B
1	226	30.6	10.7	0	0	2.87	4.08	2.69	**4.05**
1a	226	30.6	10.7	0	C	3.67	**6.08**	**3.39**	**5.91**
1b	226	30.6	10.7	C	0	4.23	4.91	**3.92**	**4.84**
1c	226	30.6	10.7	C	C	4.56	**6.46**	**4.48**	**6.41**

Capacitor Bank Status:
0 = Capacitor bank out of service
C = Capacitor bank in service

The simulation results illustrate the potential for magnified harmonics and voltage distortion that could exceed IEEE 519 guidelines significantly (the table indicates cases where the limits even for medium-voltage systems are exceeded—the limits for 138-kV systems are more strict).

- The table illustrates that the fifth-harmonic distortion levels can be quite high even without the new capacitor banks. This agrees with some evidence that previously there have been relatively high levels of voltage distortion on the 138-kV system.
- Adding the new capacitor banks can result in even higher levels of voltage distortion.

IEEE 519 limits at the 138-kV level are 1.5% for an individual harmonic and 2.5% for THD. These limits are likely to be exceeded for many conditions, but higher levels should still be acceptable.

The recommendation from the study is to monitor the harmonic levels closely to identify any potential problem conditions. Even levels of harmonic voltage distortion are considered to be unacceptable after the installation of the new capacitor banks; one or both of the capacitor banks can be converted into a harmonic filter. This is already standard practice for many transmission capacitor banks in Europe (Netherlands, UK).

Additional simulations were performed to illustrate the effectiveness of different filter options. An example filter configuration is provided here, and the effectiveness of applying this filter is summarized. The filter configuration is shown in Figure 10-5.

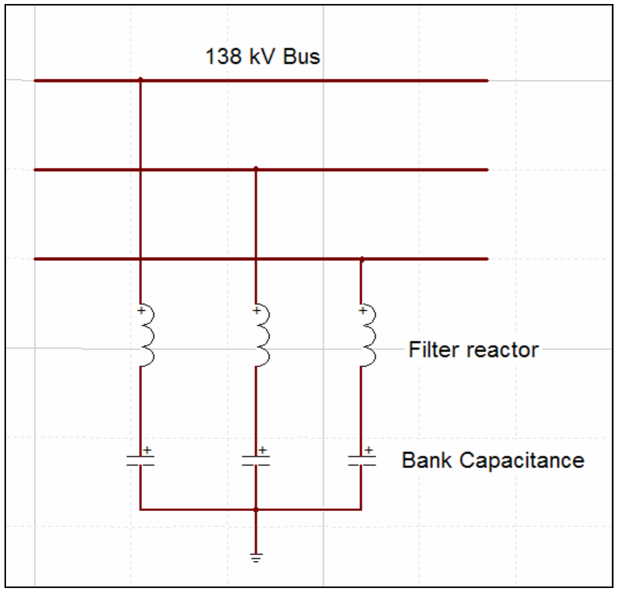


Figure 10-5
Configuration of a Standard Tuned Filter That Could Be Applied to the Transmission System

The filter inductance and capacitance can be calculated as follows.

$$X_c = \frac{(L-L\ Nomilal\ Bus Voltage)^2}{3-\phi Capacitor\ Bank\ Rating} \quad (1)$$

$$X_L = \frac{X_c}{h_r^{\ 2}} \quad (2)$$

Where,

h_r = Resonant harmonic frequency

For the 5th-harmonic filter evaluated, the design parameters are provided in Table 10-5.

Table 10-5
Example Design Specifications for a 5th-Harmonic Filter That Could Be Applied on the 138-kV System

Harmonic Filter Calculations — EPRI Solutions

Harmonic Filter Calculations: 5th Harmonic Filter

SYSTEM INFORMATION:

Filter Specification (e.g., 5):	5 th	Power System Frequency:	60 Hz
Three-Phase Capacitor Bank Rating:	51750 kVAr	Capacitor Voltage Rating:	144000 Volts
Rated Capacitor Bank Current:	207 Amps	Capacitor Frequency Rating:	60 Hz
Nominal Bus Voltage:	138000 Volts	Derated Capacitor Size:	47527 kVAr
Capacitor Bank Current (actual):	198.8 Amps	Total Harmonic Load:	2300 kVA
Filter Tuning Harmonic (e.g., 4.7):	4.8 th	Filter Tuning Frequency:	288 Hz
Capacitor Impedance (wye):	400.6957 Ω	Capacitor Rating (wye):	6.62 μF
Capacitor Impedance (delta):	1202.0870 Ω	Capacitor Rating (delta):	2.21 μF
Filter Reactor Impedance:	17.3913 Ω	Filter Reactor Rating:	46.1319 mH
Filter Full Load Current (actual):	207.9 Amps	Fundamental Frequency Compensation:	49684 kVAr
Filter Full Load Current (rated):	216.9 Amps		
Transformer Nameplate Rating:	50000 kVA	Utility Side Voltage Distortion (Vh):	2.00 %
Transformer Nameplate Impedance:	7.23 %	*(Utility Harmonic Voltage Source)*	
Load Harmonic Current:	20.00 % Fund	Load Harmonic Current:	1.9 Amps
Utility Harmonic Current:	11.0 Amps	Maximum Total Harmonic Current:	13.0 Amps

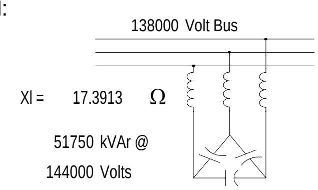
CAPACITOR DUTY CALCULATIONS:

Harmonic Filter RMS Current:	208.3 Amps	Fund. Freq. Capacitor Voltage:	144261.3 Volts
Harmonic Capacitor Voltage:	1799.6 Volts	Maximum Peak Voltage:	146060.9 Volts
RMS Capacitor Voltage:	144272.6 Volts	Maximum Peak Current:	220.8 Amps

CAPACITOR LIMITS: (IEEE Standard 18-2002)

	Limit	Contingency	Actual	Value
Peak Voltage:	100%	120%	101%	146061
RMS Current:	100%	135%	100%	208
KVAr:	100%	135%	101%	52043
RMS Voltage:	100%	110%	100%	144273

FILTER CONFIGURATION:



FILTER REACTOR DESIGN SPECIFICATIONS:

Reactor Impedance:	17.3913 Ω	Reactor Rating:	46.1319 mH
Fundamental Current:	207.9 Amps	Harmonic Current:	13.0 Amps
RMS Current Requirement:	208.3 Amps	Voltage Requirement:	79674.3 Volts

TOLERANCE EVALUATION:

	-	+	Tuning Range
Capacitor Tolerance:	0.00	10.00	4.52
Reactor Tolerance:	2.50	2.50	4.86

$$f_{tuned} = f_{nominal} \times \frac{1}{\sqrt{(1+t_r)(1+t_c)}}$$

The effectiveness of the filters is evaluated first by examining the frequency-response characteristics. If both of the proposed capacitor banks are installed as filters, then the fifth harmonic resonance conditions are completely avoided, as illustrated by the frequency-response characteristics in Figure 10-6.

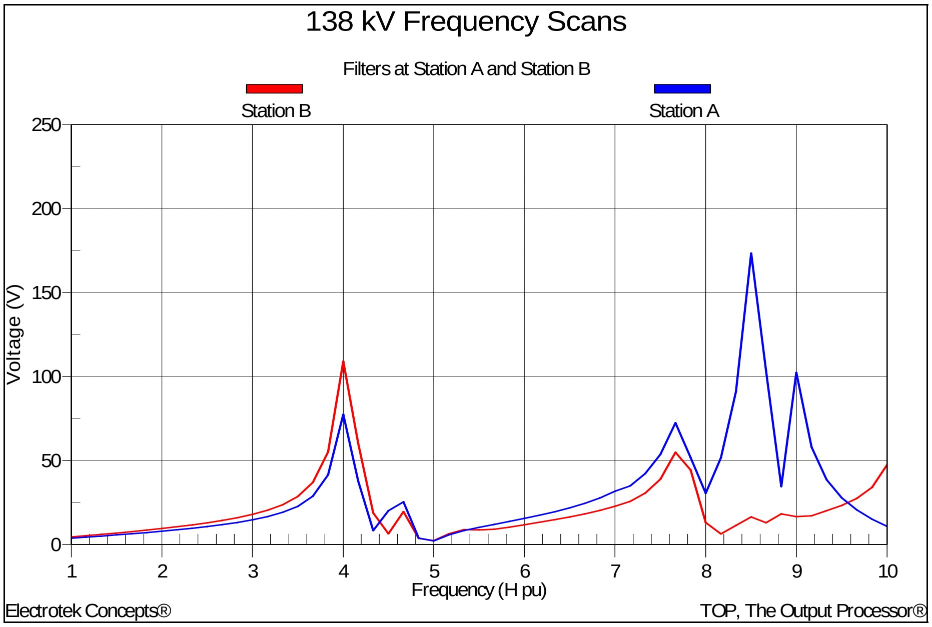


Figure 10-6
Frequency-Response Characteristics with Both Proposed Capacitor Banks Installed as Fifth-Harmonic Filters

If only one of the capacitors is installed as a filter, the effectiveness is not as clear. Figure 10-7 shows the case with a filter at Station A, and Figure 10-8 shows the case with the filter at Station B. In either case, the effectiveness is not as complete as with both banks installed as filters.

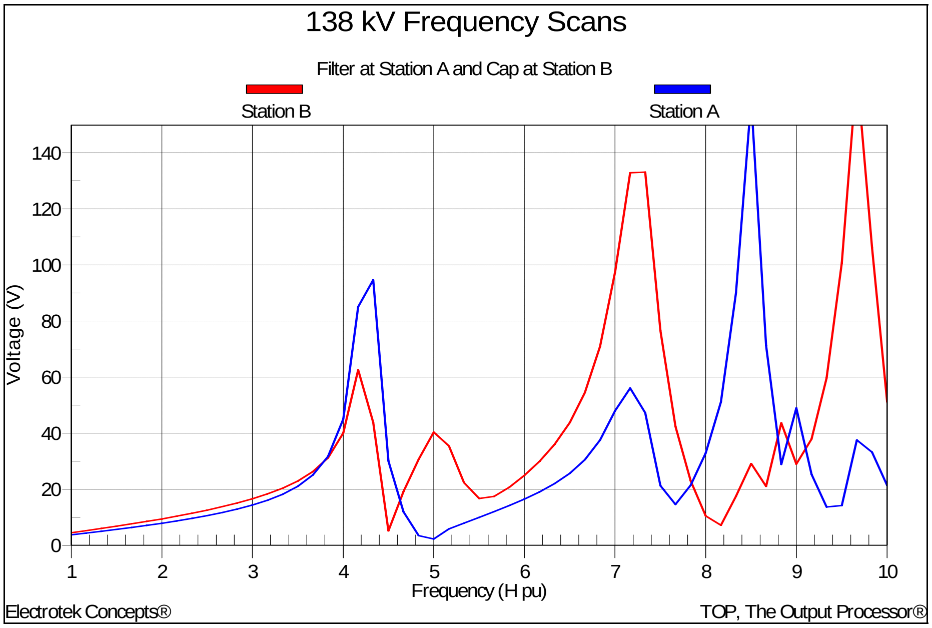


Figure 10-7
Frequency-Response Characteristics with a Filter at Station A and a Capacitor Bank at Station B

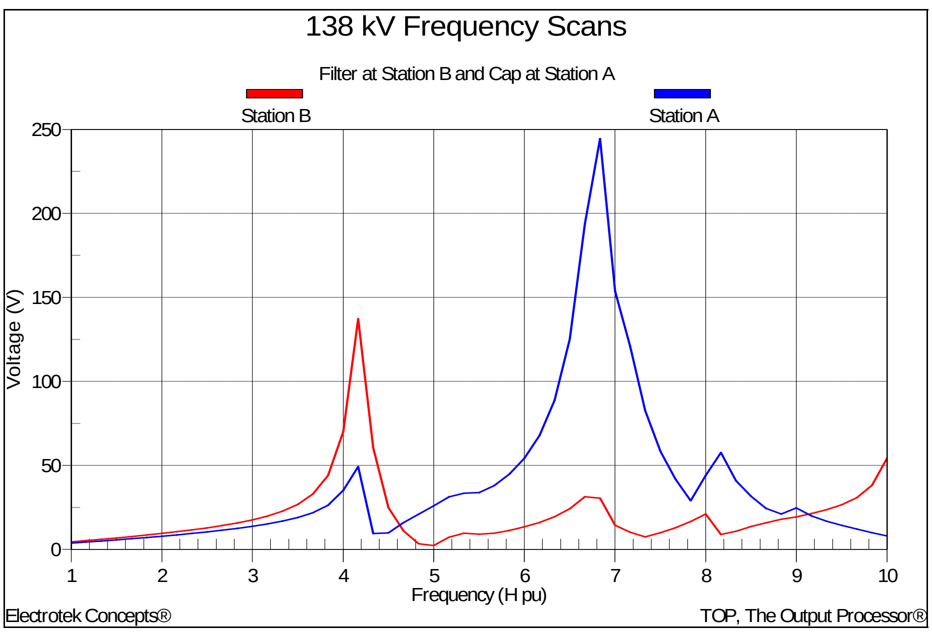


Figure 10-8
Frequency-Response Characteristics with a Filter at Station B and a Capacitor Bank at Station A

The effectiveness of the filters in reducing actual expected distortion levels is summarized in Table 10-6. Basically, installing either bank as a filter would be very beneficial for the expected distortion levels in the vicinity of these proposed banks. However, levels of voltage distortion that exceed the current IEEE 519 guidelines are still possible with only one bank installed as a filter (see Case 1d).

Table 10-6
Effectiveness of Different Capacitor and Filter Configurations in Reducing Expected 138-kV System Voltage Distortion

Case	Reactive Compensation (MVAr)			Capacitor Bank Status		%THD		%5th	
	138 kV	69 kV	23 kV	Station A	Station B	Station A	Station B	Station A	Station B
1	226	30.6	10.7	0	F	1.16	0.32	0.81	0.02
1a	226	30.6	10.7	F	0	0.44	2.09	0.02	2.08
1b	226	30.6	10.7	F	F	0.4	0.19	0.01	0.02
1c	226	30.6	10.7	C	F	2.38	0.76	1.06	0.02
1d	226	30.6	10.7	F	C	0.57	2.99	0.03	2.92

0 = No capacitor bank in service
C = Capacitor bank in service
F = Capacitor bank is implemented as 5th-harmonic filter

General Recommendations for Transmission Systems

Whenever a capacitor bank gets added to the transmission system, it is likely to have an impact on the frequency response in that part of the system. For certain system configurations, the addition of capacitor banks may result in unacceptable values of harmonic distortion. This situation was found to be the case in the Netherlands, and a general policy of installing filters instead of just capacitor banks was implemented for transmission applications.

Another solution is to design capacitor banks with some margin in the voltage rating so that they can be converted to a harmonic filter if necessary. Then the harmonic levels should be continuously monitored to identify possible conditions of concern. It may be possible to avoid very unusual conditions that cause high distortion levels.

General Approach for Dealing with Harmonic Issues

The continuous monitoring of the harmonic levels can help in identifying such conditions. If higher distortion levels are seen on a frequent basis under conditions that are not avoidable, it may be necessary to conduct a detailed harmonic analysis.

It is possible to perform a simplified analysis for distribution systems that are radial in nature. But, transmission systems—being more complex and highly interconnected in nature—require more detailed modeling. The extent of the model should include the nearby transmission capacitor banks as well as the capacitor banks in the LV systems. It is necessary because the range of possible frequencies at the proposed bank location is largely influenced by these banks.

Nearby transmission banks tend to drag the harmonic resonance lower towards the 5th harmonic. LV capacitor banks look like filters to the transmission system and therefore influence the frequency response by introducing the series resonance in the system.

Single-phase (positive sequence) modeling is sufficient for transmission systems. The measurements are very helpful because they help validate the models.

A detailed harmonic analysis (frequency scans and harmonic-distortion analysis) on the harmonic models of the system can be used to identify the capacitor banks that are contributing to the resonance concerns. Simulations can be done to identify the best locations for upgrading the banks into filters for reducing the harmonic levels.

11

PROCEDURE FOR INVESTIGATING TRANSMISSION-RELATED PROBLEMS

This chapter discusses a case study for performing harmonic analysis to exemplify the harmonic investigation procedure. The system under study is a 138-kV bulk transmission system in Ohio, part of the First Energy (FE) system. *EPRI would like to provide a special acknowledgment to First Energy for allowing these examples to be used in this document*. Specifically, concerns over harmonic distortion at two substations are considered: East Akron and BABB in Ohio. FE is planning to add a new capacitor bank at both the substations. The two substations are electrically close to each other. Therefore, they are considered in the same study. The area under study has 69-kV and 23-kV voltage levels in addition to 138 kV. There are capacitor banks at all three voltage levels. FE is concerned with excessive harmonic distortion due to newly proposed capacitor banks.

Model Development

The process of a harmonic-simulation study consists of first collecting the necessary data to represent the circuit to be modeled. There are two fundamental issues that need to be considered in developing a system model for harmonic-simulation studies. The first issue is the extent of the system model to be included in the simulation. The second issue is to decide whether the model should be represented as a single-phase equivalent or a full three-phase model.

Based on the guidelines developed, the model included:

- Three or four buses beyond East Akron and BABB
- Capacitor banks at 138-, 69-, and 23-kV levels around the vicinity of both the substations

The system was assumed to be balanced and positive sequence representation was used for the analysis.

The model was developed in SuperHarm, which is the commonly used software for performing harmonic studies. SuperHarm evaluates harmonics on electric power systems. SuperHarm enables you to develop a computer model of a power system to explore variations on system loads and configurations, along with the resulting impact on system frequency response and distortion levels. The data needed to develop the model was extracted from the PSS/E raw file and the CAPE impedance database of the FE 138-kV Ohio system. The overall procedure is shown in Figure 11-1 and is briefly described in the following sections.

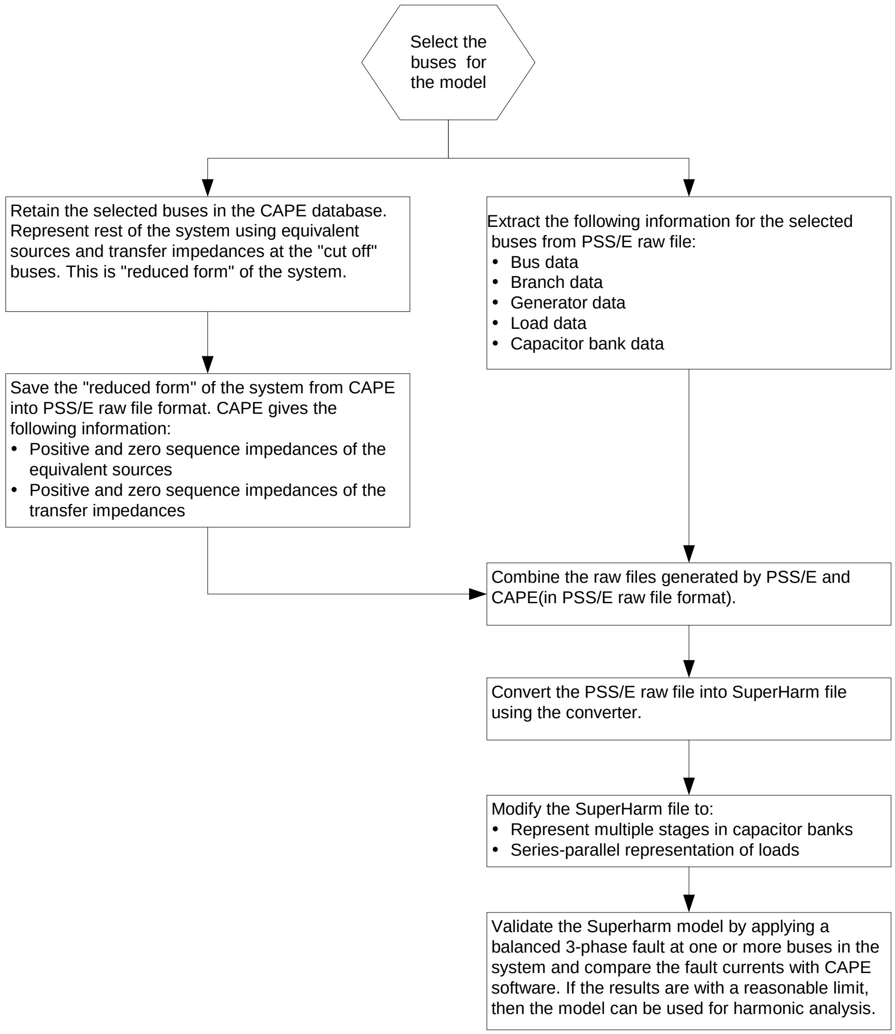


Figure 11-1
Model-Development Procedure

Selecting the Buses Required for the Model

As mentioned earlier, the harmonic model should include detail information about the selected buses and all the existing capacitor banks in the vicinity of the substations under study. The rest of the system must be represented by equivalent sources and impedances. The single-line diagram of the 138-kV system buses around East Akron and BABB substations that are included in the model is shown in Figure 11-2. The locations of the proposed 138-kV capacitor banks are also shown. The details of the existing capacitor banks are given in Table 11-1. The details of the proposed capacitor banks are given in Table 11-2.

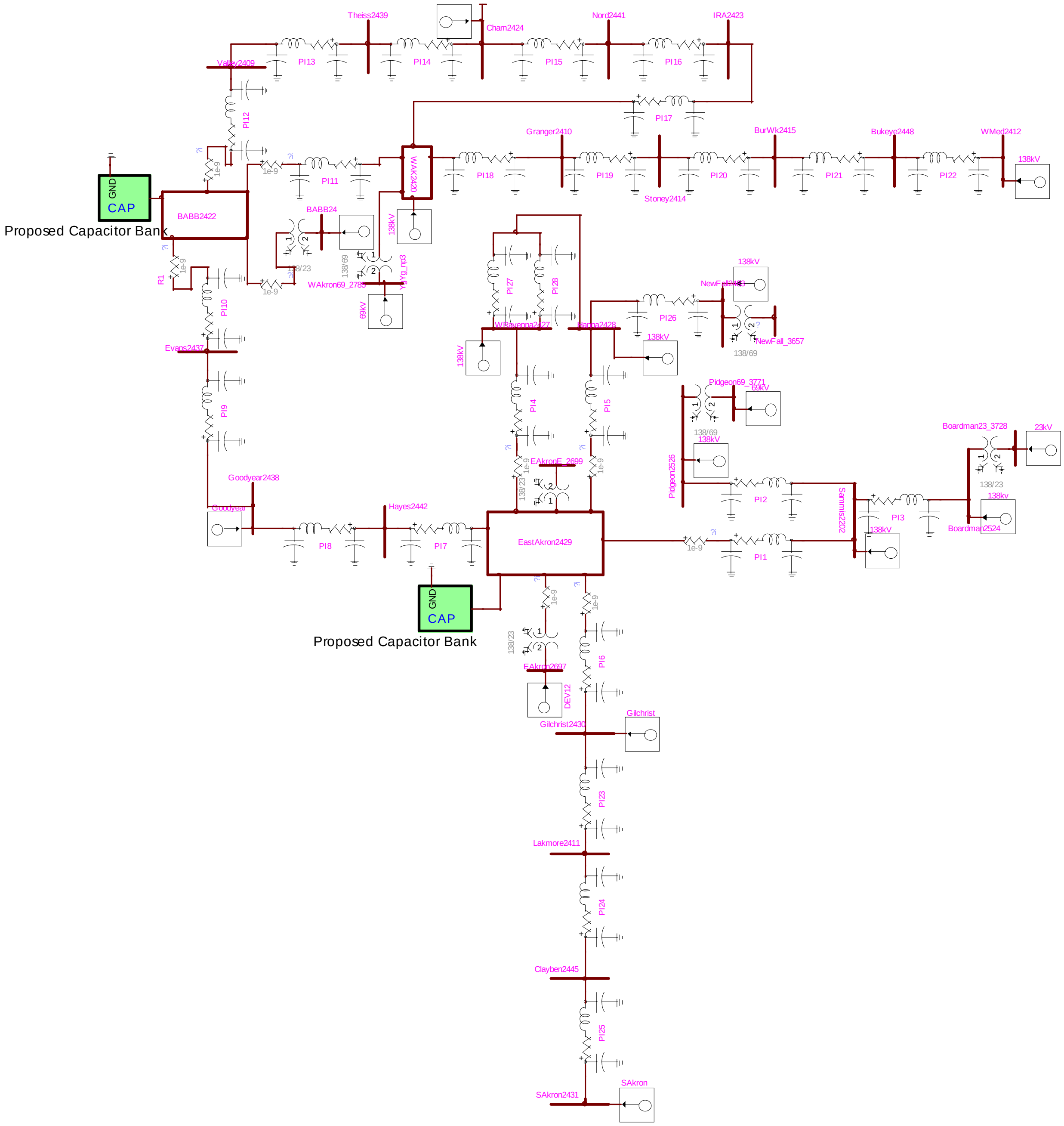


Figure 11-2
Single-Line Diagram

Table 11-1
Existing Capacitor Banks

Station Name	Voltage (kV)	MVAr Rating	Stages
Granger	138	26.4	1
West Medina	138	26.4	1
Brunswick	138	26.4	1
West Akron	138	50	1
Chamberlin	138	105.6	2 (52.8MVAR/stage)
Gilchrist	138	50	1
West Akron	69	21.4	1
Newton Falls	69	14.4	1
Pidgeon	69	16.2	1
East Akron E.	23	21.4	1
Boardman	23	10.7	1

Table 11-2
Proposed Capacitor Banks

Station Name	Voltage (kV)	MVAr Rating	Stages
East Akron	138	47.54	1
BABB	138	47.54	1

Extracting Information from PSS/E Raw File

FE provided a solved power-flow PSS/E case for the Ohio system. The raw file was used to extract the following information for the buses around East Akron and BABB:

1. Bus connectivity
2. Bus data
3. Branch data
4. Load real and reactive powers
5. Capacitor bank MVAr and number of stages
6. Source data

Reducing the System Using CAPE

The *Short Circuit Reduction* tool of the CAPE software was used to compute the source equivalents and the corresponding transfer impedances. The *Retain Set* function of the tool was used to extract the subsystem information in positive-, negative-, and zero-sequence components. The information is exported as PSS/E raw data and sequence data files. This procedure resulted in identification of the source, as shown Table 11-3. These sources, along with their transfer impedances, have been included in the model.

Table 11-3
Source Equivalents

Substation Name	Voltage (kV)	R1 (pu)	X1 (pu)
Boardman	138	0.00672	0.0568
Chamberlin	138	0.00095	0.035
Gilchrist	138	0.0571	1.07573
Goodyear	138	0.0421	0.12
Hanna	138	0.00042	0.02485
Newton Falls	138	0.01003	0.08918
Pidgeon	138	0.02053	0.12899
Sammis	138	0.00175	0.039
S. Akron	138	0.01474	0.07553
W. Akron	138	0.00556	0.03249
W. Ravenna	138	0.73298	1.58138
W. Medina	138	0.03204	0.26532
W. Akron (69 kV)	69	0.0959	0.31946
Pidgeon (69 kV)	69	0.16388	0.31185
BABB (24 kV)	23	0.127	1.08921
E. Akron (23 kV)	23	0.27053	2.18411
Boardman (23 kV)	23	0.32307	1.11825

Load Representation

The loading information for the retained buses was extracted from the PSSE raw data file of the system. The load was split into 70% linear and 30% nonlinear components. The linear load for the individual buses was modeled as having 50% series and 50% parallel representation. The assumed nonlinear load spectrum is shown in Table 11-4

Table 11-4
Harmonic Spectrum for the Simulation

Harmonic	Magnitude (% of Fundamental)
3	1.5
5	20
7	4
9	2
11	1

Analysis of Frequency Scan

1. Three different system loading levels were considered to evaluate the damping effect of loads on the frequency response: low (25% of total system load), medium (50% of total system load), and high (75% of total system load).
2. For each loading level, an approximate level of reactive compensation at each voltage level (23, 69, and 138 kV) was chosen.
3. For each load category and reactive compensation, frequency scans were obtained for the following scenarios with respect to the proposed capacitor banks:
    a. Both of the proposed banks are off.
    b. One of the banks is off while the other bank is on.
    c. Both of the banks are on.
4. The scans were obtained at East Akron as well as BABB substations.

The complete list of cases is shown in Table 11-5.

Table 11-5
Case List for Frequency Scans

Case	Reactive Compensation @ 138 kV(MVAr)	Reactive Compensation @ 69 kV (MVAr)	Reactive Compensation @ 23 kV(MVAr)	East Akron Bank	BABB Bank	System Loading(%)
1	100	16.2	0	Off	Off	25
2	100	16.2	0	Off	On	25
3	100	16.2	0	On	Off	25
4	100	16.2	0	On	On	25
5	200	30.6	10.7	Off	Off	50
6	200	30.6	10.7	Off	On	50
7	200	30.6	10.7	On	Off	50
8	200	30.6	10.7	On	On	50
9	285	52	32.1	Off	Off	75
10	285	52	32.1	Off	On	75
11	285	52	32.1	On	Off	75
12	285	52	32.1	On	On	75

Frequency-Response Results

The frequency scans for the twelve cases at East Akron substation are shown in Figure 11-3 through Figure 11-5.

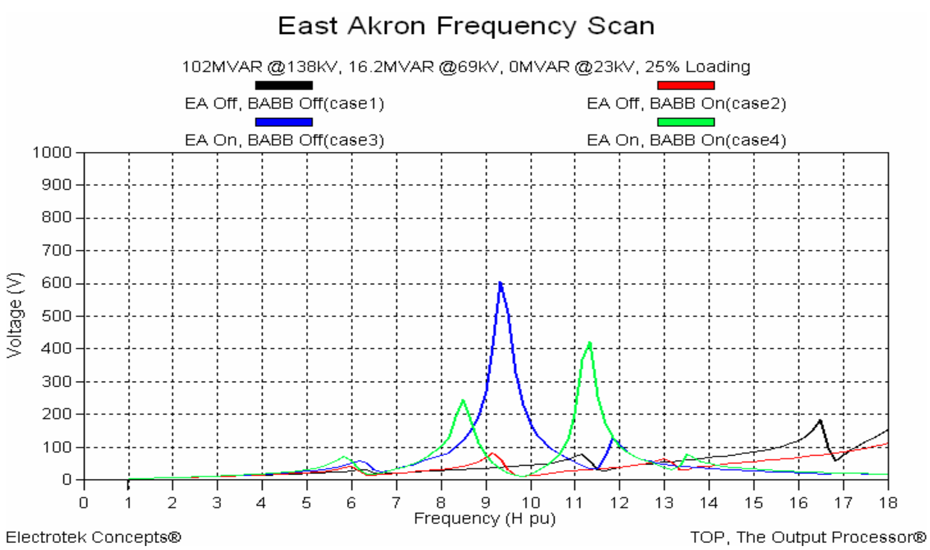


Figure 11-3
East Akron Scans for Light Loading Levels

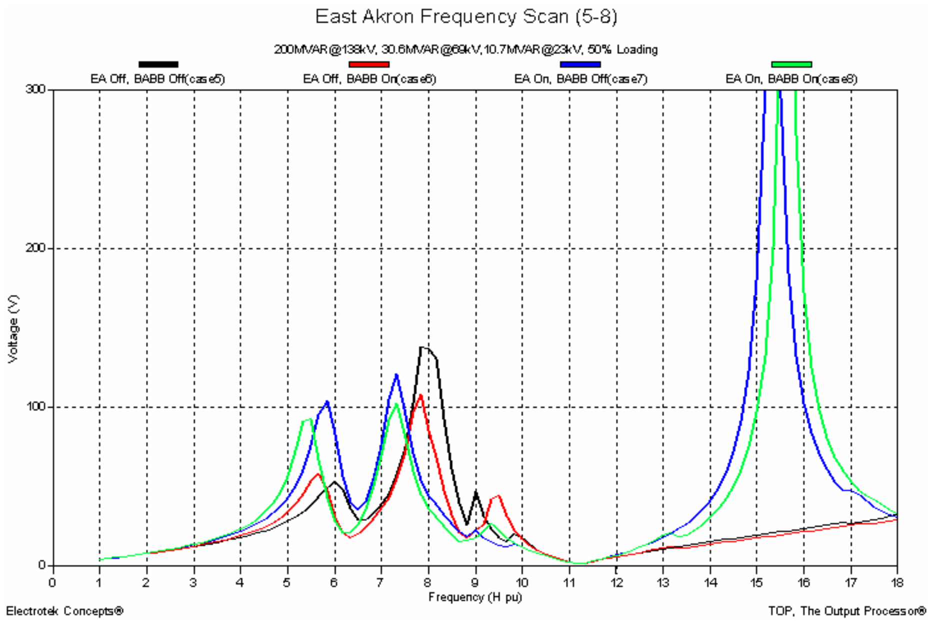


Figure 11-4
East Akron Scans for Medium Loading Levels

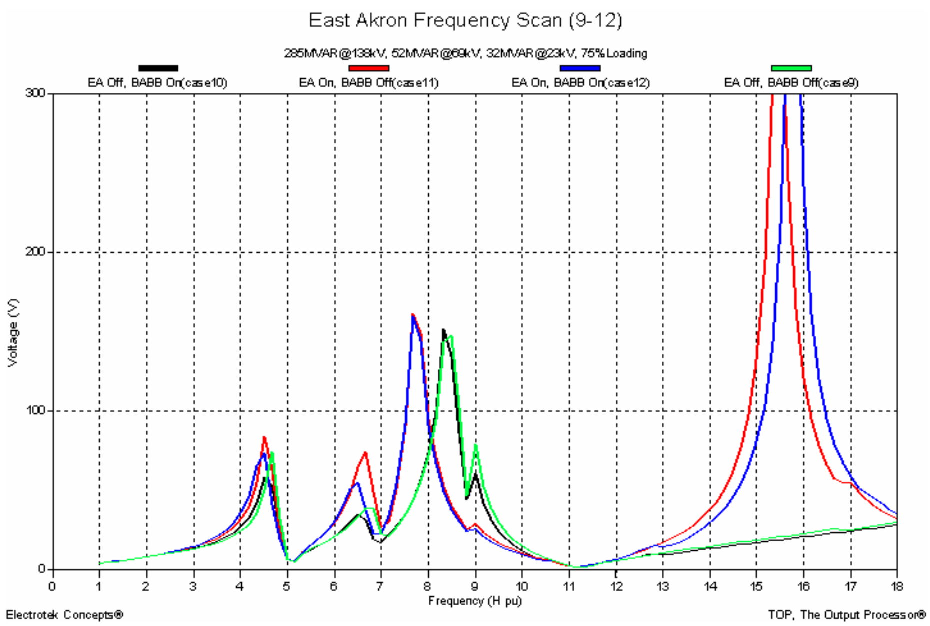


Figure 11-5
East Akron Scans for Heavy Loading Levels

The frequency scans for the twelve cases at BABB substation are shown in Figure 11-6 through Figure 11-8.

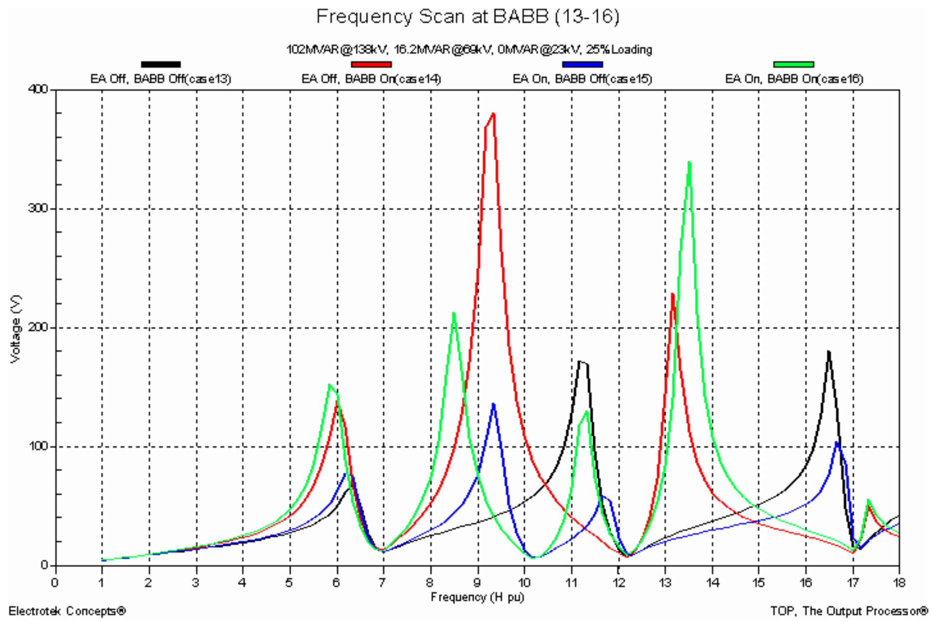


Figure 11-6
BABB Scans for Light Loading Levels

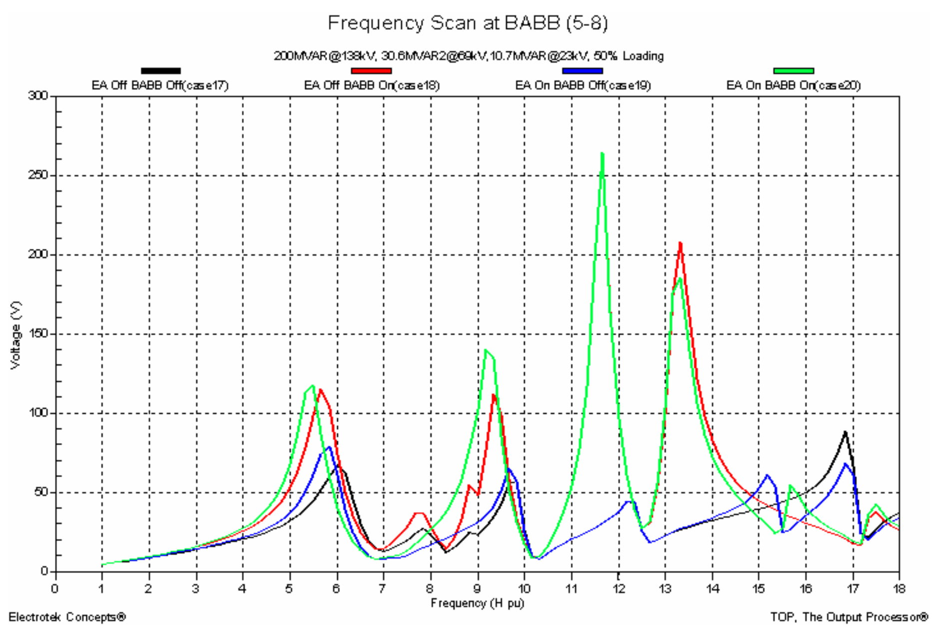


Figure 11-7
BABB Scans for Medium Loading Levels

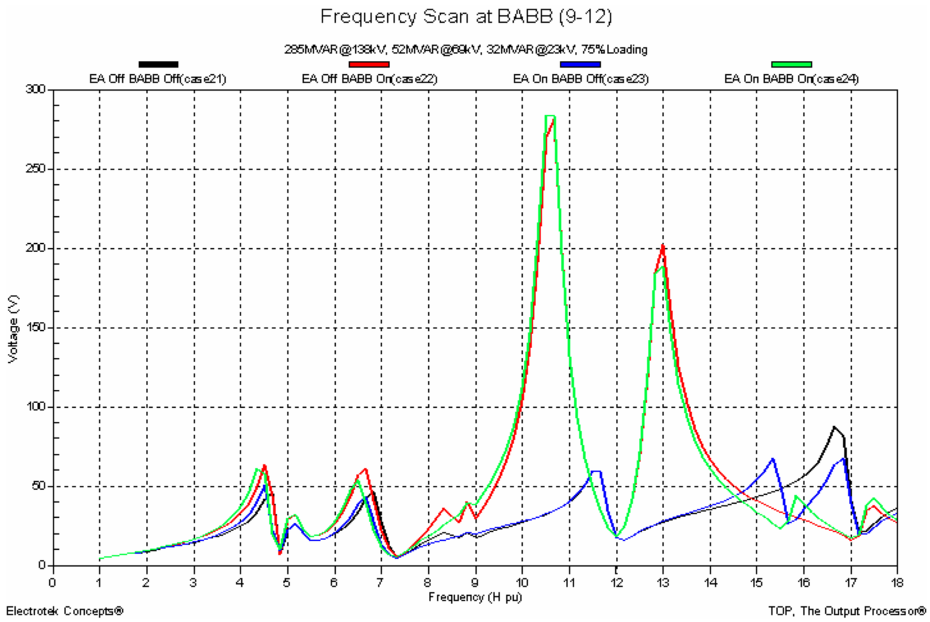


Figure 11-8
BABB Scans for Heavy Loading Levels

Conclusions from Frequency-Response Cases

Based on the results of the frequency scans described in the previous section, the following conclusions can be drawn:

- For light load conditions, the resonance peaks are between 8th and 12th harmonic for different cases. There is also a damped resonance peak around the 6th harmonic at both the substations. There is no resonance around the 5th harmonic for any of the light loading cases.
- For medium loading, the peaks shift towards lower frequencies. This is expected because as reactive compensation increases (capacitance increases), the resonant frequency decreases. Note that the peak around 6th harmonic has shifted towards 5th. This indicates a potential resonant condition at the 5th harmonic. There are resonant peaks between 7th and 10th harmonic, but they are not of concern from a harmonic standpoint.
- For heavy loading, the resonance peak has shifted below the 5th harmonic for East Akron. In the case of BABB, there is a damped peak at the 5th harmonic.

From medium and heavy loading conditions, it is evident that there is a potential for a resonance condition at the 5th harmonic. Additional scans were performed to investigate the possibility of obtaining a resonance peak exactly at the 5th harmonic. The loading conditions and reactive power compensation that results in a 5th-harmonic resonance at both substations are shown in Table 11-6.. The scans obtained for these conditions are shown in Figure 11-9.

Table 11-6
Loading Condition for the 5th Harmonic Resonance Condition

Case	Reactive Compensation @ 138 kV(MVAr)	Reactive Compen-sation @ 69 kV(MVAr)	Reactive Compen-sation @ 23 kV (MVAr)	East Akron Bank	BABB Bank	System Loading (%)
1	226	30.6	10.7	Off	Off	50

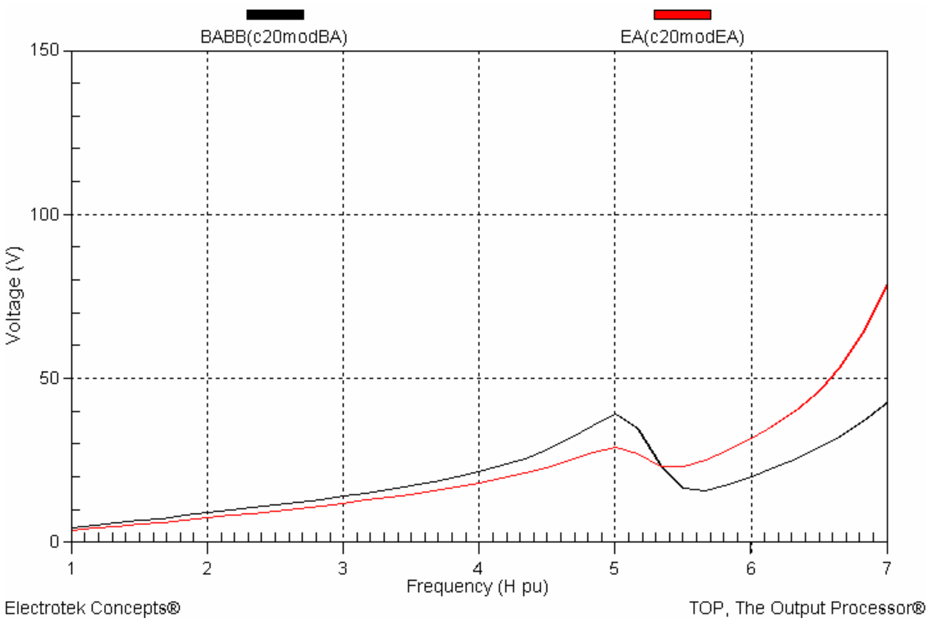


Figure 11-9
5th Harmonic Resonance at East Akron and BABB

The plot in Figure 11-9 shows a damped resonance peak at the 5th harmonic at both substations. This indicates a potential problem at the 5th harmonic. Note that the peaks are present even when the new capacitors are not in service (indicating that the 5th harmonic is already a problem at both substations).

Next, the frequency scans with only one of the two proposed capacitor banks on are shown in Figure 11-10 and Figure 11-11. The resonance peak is still at the 5th harmonic, indicating that the problem might persist when one of the new banks is in service.

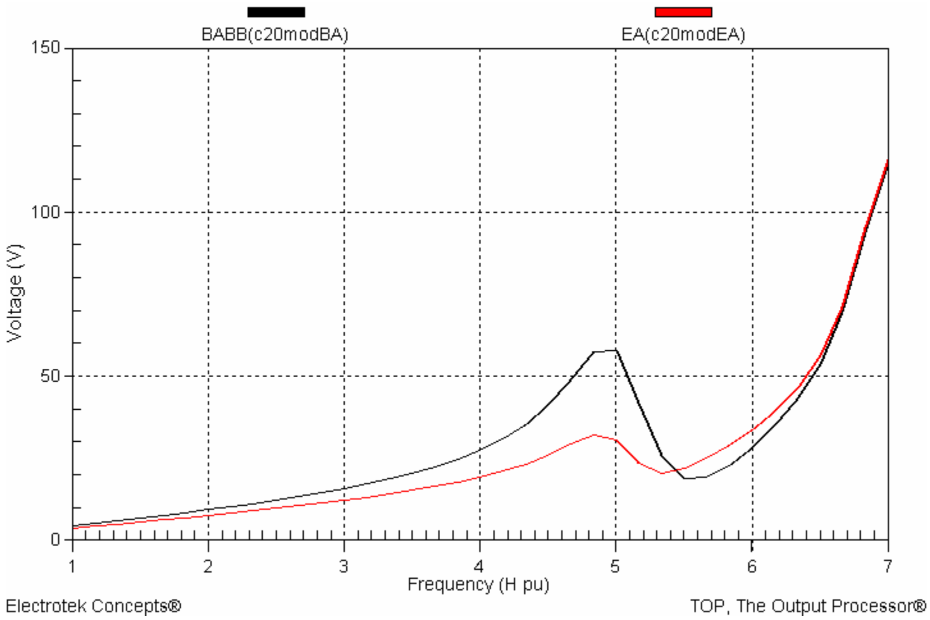


Figure 11-10
5th Harmonic Resonance at East Akron and BABB with Capacitor Bank in Service at BABB

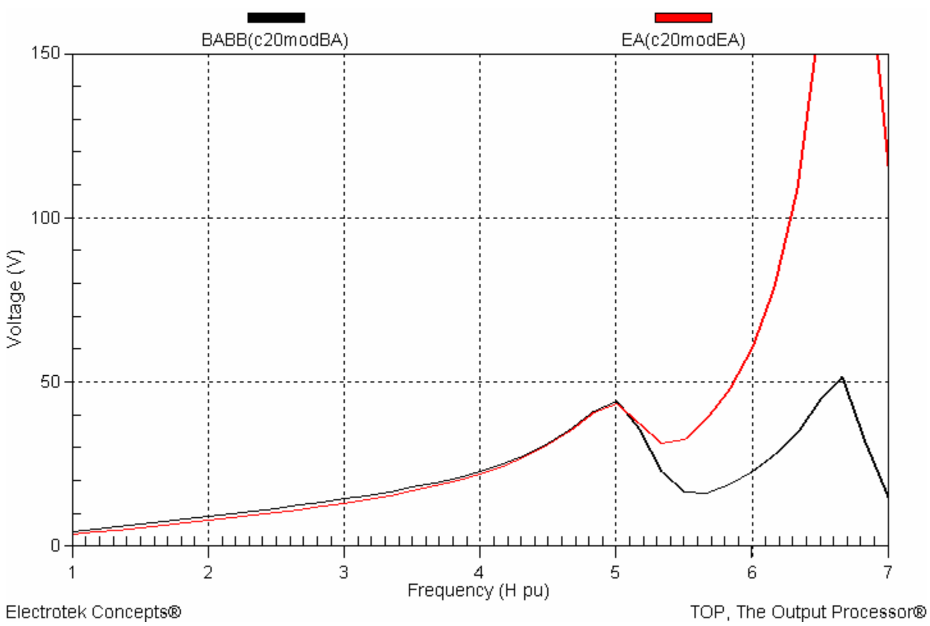


Figure 11-11
5th-Harmonic Resonance at East Akron and BABB with Capacitor Bank in Service at East Akron

The frequency scan when both the capacitor banks are on is shown in Figure 11-12. The resonance peak has in fact shifted slightly below the 5th harmonic.

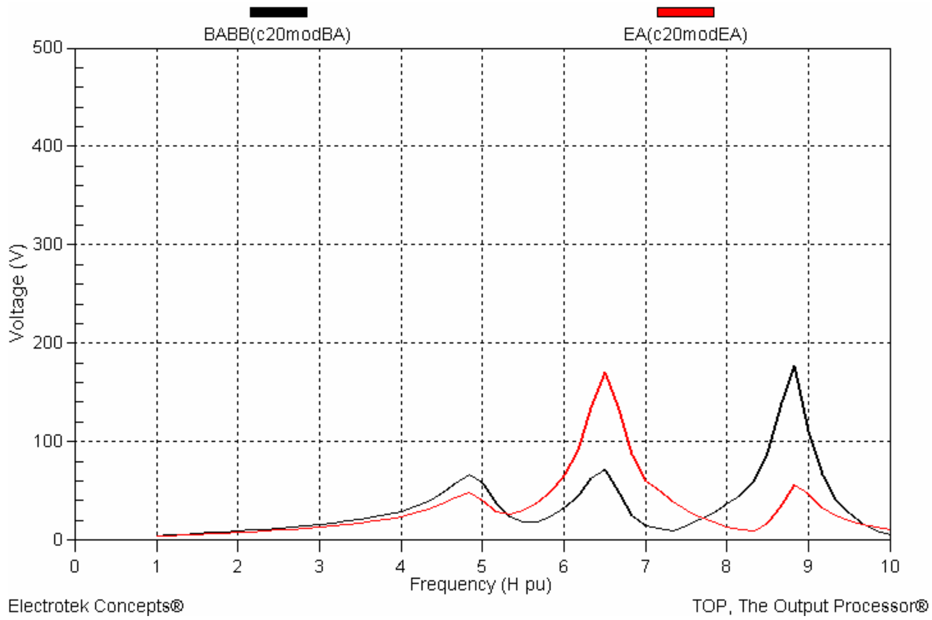


Figure 11-12
5th Harmonic Resonance at the EA site and BABB with Capacitor Banks in Service at EA and BABB

Conclusions from Analysis of Frequency Scans

In conclusion, the 5th harmonic can be a problem at both substations. Given the fact that the 5th harmonic is usually the most dominant harmonic component coming from system loads and lower-voltage systems, this resonance condition is a potential concern. To alleviate the problem, one solution is to design one or more of the capacitor banks as filters.

Analysis of Distortion Simulation

The analysis of the frequency scans indicated a potential resonance problem at the 5th harmonic. The next step is to evaluate the actual harmonic distortion levels in the system. A harmonic-injection approach is used for the purpose of analysis. In this approach, individual nonlinear loads act as sources of current harmonic injections into the system. Based on the frequency-response characteristic of the system, these current harmonics cause harmonic components to appear in the bus voltages all over the system.

Base Case

The harmonic measurements at East Akron are shown in. Measurements at BABB were not available.

Table 11-7
Measured 5th Harmonic and THD Levels at East Akron

Harmonic	Phase A (%)	Phase B (%)	Phase C (%)
5th	1.1%	1.1%	1.1%
THD	1.1	1.2	1.2

1. Because the 5th-harmonic resonance was obtained at medium load (50% of the rated load), the individual buses in the system were assumed to have medium loading levels too. Note that only a few buses are represented in the model, while rest of the system is modeled using equivalents. Harmonic injection must also be included for buses that are equivalized in the representation. As a result, sources of nonlinear current injection were added to some of the buses where equivalents were formed.
2. The individual loads were split into 70% linear and 30% nonlinear components. The nonlinear component of the load acts as the source of harmonic injections into the system. The spectrum assumed for the nonlinear loads is shown in Table 11-8.

Table 11-8
Harmonic Spectrum of Nonlinear Load

Harmonic	Magnitude (% of Fundamental)
3	1.5
5	20
7	4
9	2
11	1

3. The model developed was validated by simulating a balanced three-phase fault at East Akron and BABB buses and comparing the resultant fault currents with those obtained by creating similar faults in the CAPE software. The fault currents are compared in Table 11-9. The match between the currents is found to be satisfactory.

Table 11-9
Comparison of Current Levels during a Balanced Three-Phase Fault

Software Package	Fault Current (Amp)	
	East Akron	BABB
CAPE	21,210.4	18,734.9
Superharm Model	21,675.4	18,177.4

Results of Base Case

The impact of the existing and the proposed capacitor banks on the 5th harmonic voltage and overall THD levels is studied in this section. The base case (Case 1 in Table 11-10) was developed such that the 5th harmonic and %THD values are in agreement with the measurements. Note that no 138-kV capacitor banks were in service in the base case. Cases 1a through 1c in Table 11-10 indicate that switching in capacitor banks increase THD as well as the 5th harmonic contribution. In some cases, the levels are above the thresholds recommended in the IEEE 519 standard. This indicates that switching on one or both of the capacitor banks can increase harmonic distortion levels even when there are no 138-kV banks in service at the time.

Table 11-10
Harmonic Levels for Base-Case Variations

Case	Reactive Compen-sation @ 138 kV (MVAr)	Reactive Compen-sation @ 69 kV (MVAr)	Reactive Compen-sation @ 23 kV (MVAr)	EA Cap	BABB Cap	%THD EA	%THD BABB	%5th @EA	%5th @BABB
1	0	21.4	10.7	0	0	1.03	1.2	0.94	1.11
1a	0	21.4	10.7	0	B	1.3	1.96	1.11	1.54
1b	0	21.4	10.7	B	0	1.49	1.42	1.23	1.26
1c	0	21.4	10.7	B	B	2.42	3.04	1.48	1.78

0 = No capacitor bank in service
B = Capacitor bank in service

Variations in the Base Case

Frequency scans indicated resonance at the 5th harmonic. Therefore, the base case was changed to a case that gave resonance at the 5th harmonic in the frequency-scan analysis. The results are shown in Table 11-11. The % harmonic and THD values are higher than the values for the corresponding proposed capacitor bank configurations in Table 11-10. The 5th harmonic and %THD values are above the IEEE 519 limit.

Table 11-11
Harmonic Levels for the Test Case

Case	138 kV (MVAr)	69 kV (MVAr)	23 kV (MVAr)	EA Cap	BABB Cap	%TH DEA	%THD BABB	%5th @ EA	%5th @ BABB
1	226	30.6	10.7	0	0	2.87	4.08	2.69	4.05
1a	226	30.6	10.7	0	B	3.67	6.08	3.39	5.91
1b	226	30.6	10.7	B	0	4.23	4.91	3.92	4.84
1c	226	30.6	10.7	B	B	4.56	6.46	4.48	6.41

0 = No capacitor bank in service
B = Capacitor bank in service

Conclusions from the Harmonic Distortion Analysis

Based on the simulation results explained in the previous sections, the following conclusions can be drawn:

- The 5th harmonic voltage distortion could be significant even without the new capacitor banks.
- Adding the new banks has the potential to result in even higher levels of voltage distortion.

IEEE 519 limits at 138kV level are 1.5% for individual harmonic and 2.5% for THD. For the simulation cases in

Harmonic Filter Design

There are a number of options available to control harmonic distortion. One option is to design the capacitor banks as 5th harmonic notch filters. Design of 5th harmonic notch filters for our test case is discussed in this section.

C-filters are an alternative to 5th harmonic notch filters. C-filters can be designed as low-pass broadband filters to reduce multiple harmonic frequencies simultaneously. C-filter design is also discussed in this section.

Capacitor Bank Tuned to the Fifth Harmonic

The filters are designed as Y-grounded capacitor banks. Each phase of Y has an inductor in series with the capacitor. The filter schematic is shown in Figure 11-13.

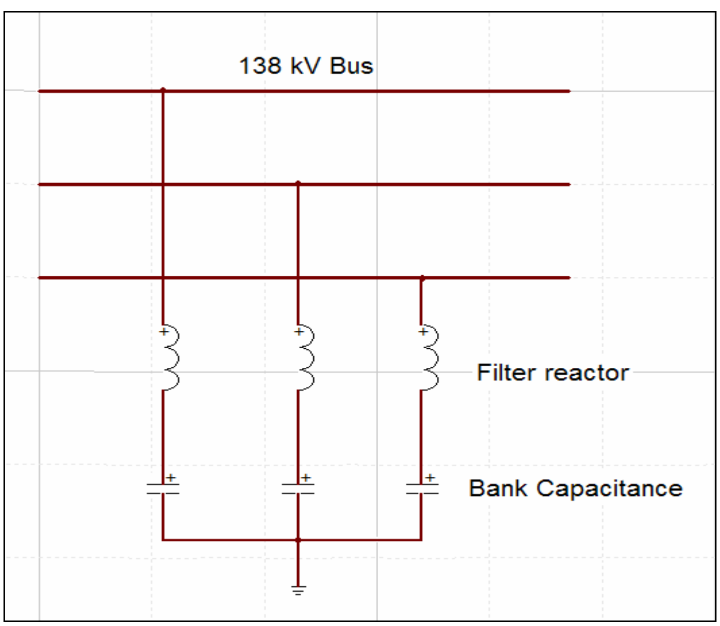


Figure 11-13
Schematic of 5th Harmonic Notch Filter

The filter inductance and capacitance can be calculated as follows.

$$X_c = \frac{L - L\ Nomilal\ Bus\ Voltage}{3 - \phi\ Capacitor\ Bank\ Rating} \tag{3}$$

$$X_L = \frac{X_c}{h_r^{\,2}} \tag{4}$$

Where,

h_r = Resonant harmonic frequency

For the 5th harmonic filter, the parameters are shown in Table 11-12.

Table 11-12
Parameters of a 5th Harmonic Notch Filter

h_r	Xc(Ω)	X_L(Ω)
5	400.59	16.02

The complete filter design specifications are given in Table 12-13.

Table 11-13
Filter Design Specifications

Low Voltage Filter Calculations: Falcon Foundry 2,300 volt Bus

Wade J. Eckler, Power Systems Engineer, Electrotek Concepts

SYSTEM INFORMATION:

Filter Specification:	5	th	**Power System Frequency:**	60	Hz
Capacitor Bank Rating:	47540	kVAr	**Capacitor Rating:**	144000	Volts
Rated Bank Current:	191	Amps		60	Hz
Nominal Bus Voltage:	138000	Volts	**Derated Capacitor:**	43661	kVAr
Capacitor Current (actual):	182.7	Amps	**Total Harmonic Load:**	2300	kVA
Filter Tuning Harmonic:	5	th	**Filter Tuning Frequency:**	300	Hz
Cap Impedance (wye equivalent):	436.1801	Ω	**Cap Value (wye equivalent):**	6.1	uF
Reactor Impedance:	17.4472	Ω	**Reactor Rating:**	46.2802	mH
Filter Full Load Current (actual):	190.3	Amps	**Supplied Compensation:**	45480	kVAr
Filter Full Load Current (rated):	198.5	Amps			
Transformer Nameplate:	50000	kVA	**Utility Side Vh:**	2.00	% THD
(Rating and Impedance)	7.16	%	*(Utility Harmonic Voltage Source)*		
Load Harmonic Current:	20.00	% Fund	**Load Harmonic Current:**	1.9	Amps
Utility Harmonic Current:	11.7	Amps	**Max Total Harm. Current:**	13.6	Amps

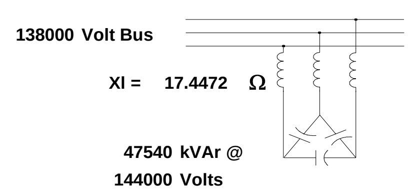
CAPACITOR DUTY CALCULATIONS:

Filter RMS Current:	190.8	Amps	**Fundamental Cap Voltage:**	143750.0	Volts
Harmonic Cap Voltage:	2058.6	Volts	**Maximum Peak Voltage:**	145808.6	Volts
RMS Capacitor Voltage:	143764.7	Volts	**Maximum Peak Current:**	203.9	Amps

CAPACITOR LIMITS: (IEEE Std 18-1980)

	Limit		Actual
Peak Voltage:	120%	←→	101%
Current:	180%	←→	100%
KVAr:	135%	←→	100%
RMS Voltage:	110%	←→	100%

FILTER CONFIGURATION:



FILTER REACTOR DESIGN SPECIFICATIONS:

Reactor Impedance:	17.4472	Ω	**Reactor Rating:**	46.2802	mH
Fundamental Current:	190.3	Amps	**Harmonic Current:**	13.6	Amps

C-Filter Design for the Capacitor Bank

The fifth-harmonic tuned notch-filter design discussed in the previous section permits a shift of the resonance to a lower acceptable frequency, but this resonance point may vary somewhat depending on the system conditions. The C-type filter design discussed in this section has damped characteristics resulting in no problematic resonance across the frequencies of interest. The configuration of a C filter is shown in Figure 11-14. The equivalent circuit is shown in Figure 11-15. A C filter possesses an auxiliary capacitor, Ca, in series with an inductor, Lm. The auxiliary capacitor is sized in such a way that its capacitive reactance cancels out Lm at the fundamental frequency, bypassing the damping resistance R. For this reason, the losses associated with R are practically eliminated, allowing a C filter to be tuned to a low frequency. At high-order harmonic frequencies, the reactance, Ca, is small, while that of Lm is large. Therefore, the impedance of the series Lm and Ca branch is dominated by the reactance of Lm.

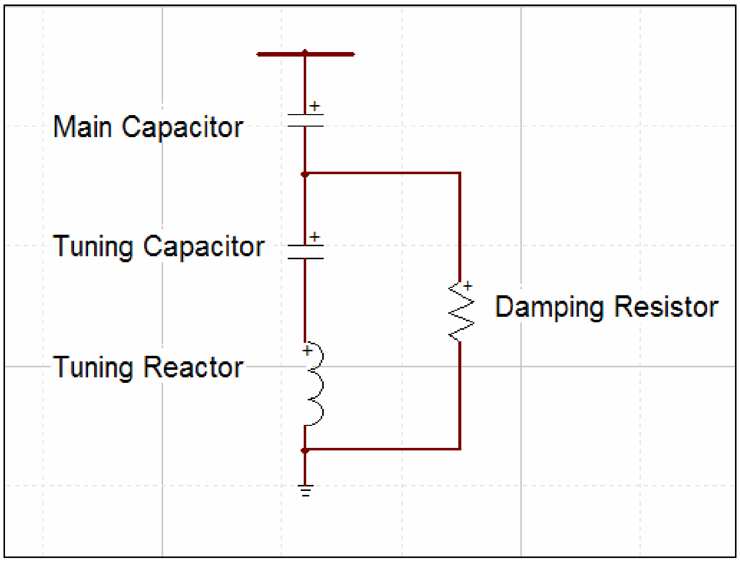


Figure 11-14
C-Filter Design

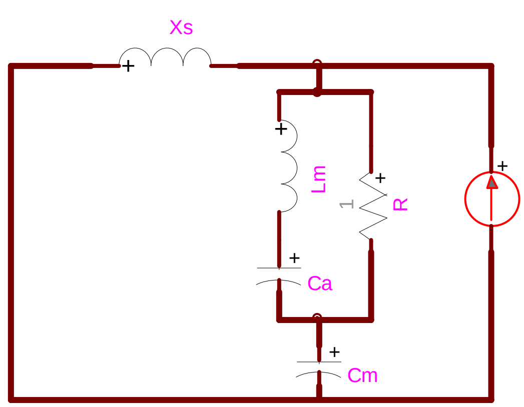


Figure 11-15
Equivalent Circuit for Deriving C-Filter Specifications

In designing a C filter, it is necessary to specify $I_{SF}(h_T)$, the maximum harmonic current allowed to flow into the system at h_T, the tuned harmonic frequency. It is also assumed that the requirement for the reactive power compensation be known, thus establishing the nominal size of capacitor Cm.

The short-circuit reactance of the source is denoted as X_s. Filter components can be computed as follows:

$$R_F = \frac{h_T X_s}{\sqrt{\dfrac{1}{I_{SF}(h_T)^2} - 1}} \tag{5}$$

$$R = \frac{R_F(h_T)^2 + \left(\dfrac{X_{Cm}}{h_T}\right)^2}{R_F(h_T)} \tag{6}$$

$$X_{Lm} = X_{Ca} = \frac{R_F(h_T)^2 + \left(\dfrac{X_{Cm}}{h_T}\right)^2}{\left(\dfrac{X_{Cm}}{h_T}\right)\left(h_T - \dfrac{1}{h_T}\right)} \tag{7}$$

Where:

X_S = short-circuit reactance at fundamental frequency

X_{Lm} = reactance of Lm at fundamental frequency

X_{Ca} = reactance of Ca at fundamental frequency

R = damping resistance

$I_{SF}(h_T)$ = Maximum current allowed to flow in the system at the tuned frequency h_T

C-Filter Design at BABB Substation

A C-filter application at BABB substation is illustrated in this section. Similar calculations can also be performed for East Akron substation. For this illustration, the C filter is designed at the 5th harmonic frequency. The design specifications are shown in Figure 11-14 and Table 11-14. The short-circuit reactance at the fundamental frequency is found to be 4.17 Ω.

Table 11-14
C-Filter Parameters for Different I_{SF}

$I_{SF}(h_T)$	R_F (Ω)	R (Ω)	$X_{Lm} = X_{Ca}$ (Ω)
0.1 (10%)	2.099	3,060.125	16.7
0.2 (20%)	4.263	1,509.93	16.73
0.3 (30%)	6.568	983.857	16.80

Effect of Filter on Frequency-Response Characteristics – Both Banks as 5th-Harmonic Filters

To evaluate the effect of filters, the simulation case that resulted in a 5th harmonic system resonance is used for analysis. The frequency scans were performed using filters (instead of capacitor banks) at the two substations. With both banks designed as filters, there is no parallel resonance at the 5th harmonic at either of the substations. The resonance has shifted to a lower frequency. This can be seen in Figure 11-16.

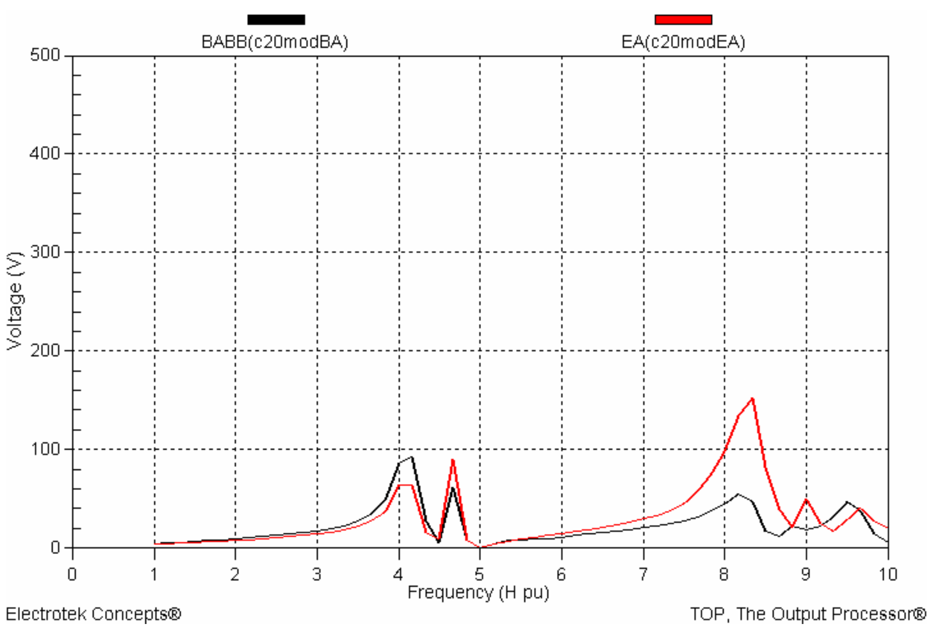


Figure 11-16
Frequency Scan: Both Capacitor Banks are Designed as Filters

Effect of a Single Filter on the Frequency-Response Characteristics

The frequency scan of capacitor bank at BABB and filter at East Akron is shown in Figure 11-17. There is no parallel resonance at the 5th harmonic at BABB. East Akron has a damped peak at the 5th harmonic. The scan in Figure 11-18 shows similar results, except now the filter is at East Akron (BABB has a bank).

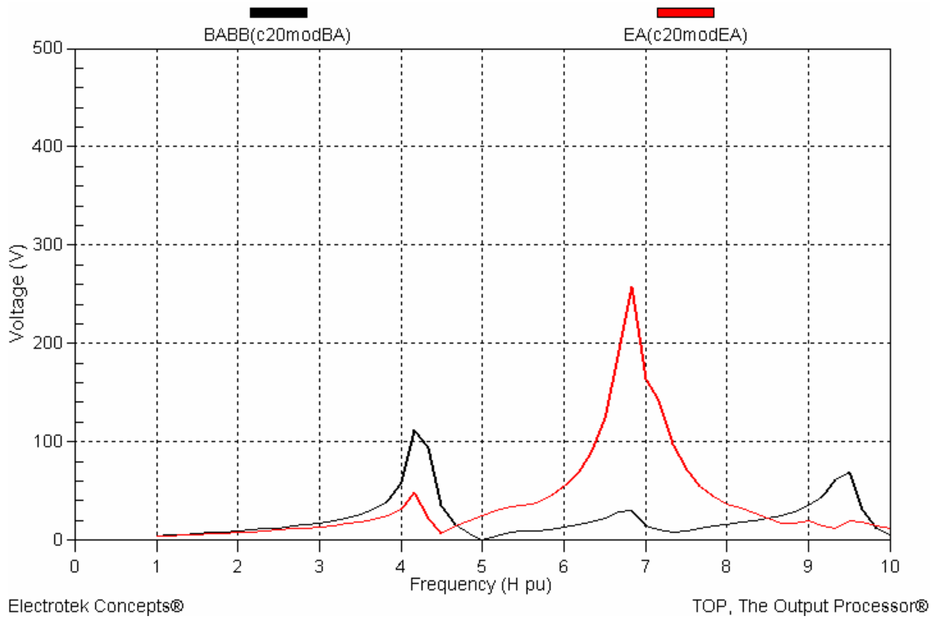


Figure 11-17
Frequency Scan: Capacitor Bank at BABB; Filter at East Akron

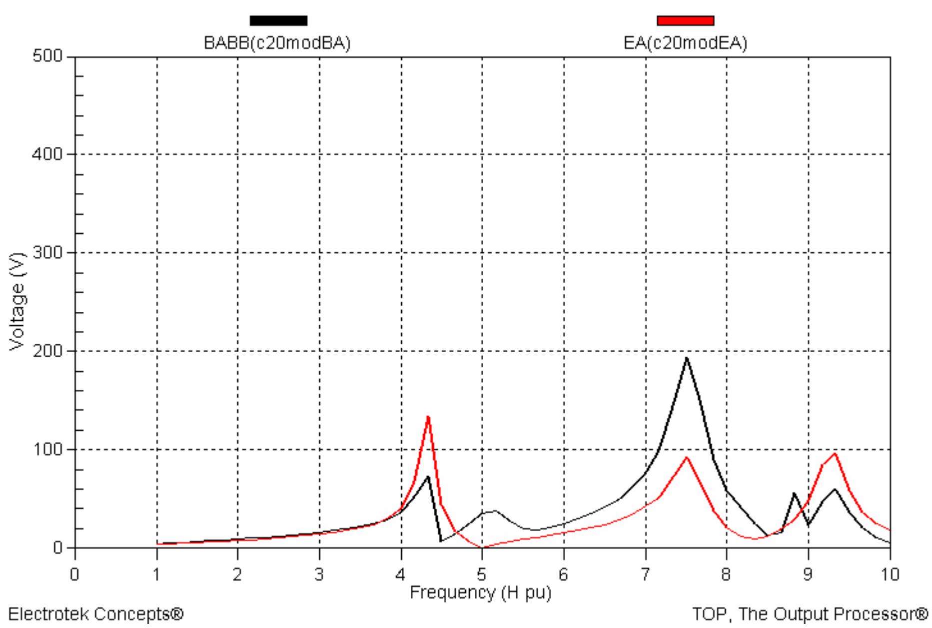


Figure 11-18
Frequency Scan: Capacitor Bank at East Akron; Filter at BABB

Effect of Filters on Expected Harmonic Distortion Levels

The effect of using filters at one or both locations on %THD and 5th harmonic voltage can be seen in Table 11-15. The base case for this table is the test case when the system has 5th-harmonic resonance at both substations.

Table 11-15
Harmonic Levels for the Test Case with Banks Designed as Filters

Case	138 kV (MVAr)	69 kV (MVAr)	23 kV (MVAr)	EA Cap	BABB Cap	%THD EA	%THD BABB	% 5th @ EA	% 5th @ BABB
1	226	30.6	10.7	0	F	1.16	0.32	0.81	0.02
1a	226	30.6	10.7	F	0	0.44	2.09	0.02	2.08
1b	**226**	**30.6**	**10.7**	**F**	**F**	**0.4**	**0.19**	**0.01**	**0.02**
1c	226	30.6	10.7	B	F	2.38	0.76	1.06	0.02
1d	226	30.6	10.7	F	B	0.57	2.99	0.03	2.92

0 = No capacitor bank in service
B = Capacitor bank in service
F = Capacitor bank is implemented as 5th-harmonic filter

The harmonic levels are the lowest when both the banks are designed as filters. Designing a filter at only one substation helps to solve the problem at that substation and reduces %THD at the other substation. However, implementing a filter at only one substation does not completely eliminate the problem at both substations. For example, in case 1d (filter at East Akron, bank at BABB), %THD at BABB is above the IEEE 519 limit.

Effect of Implementing C Filter on Frequency-Response Characteristics

An illustration of implementing a C filter is given in this section. The C filter is implemented at the BABB substation. For this example, I_{SF} is assumed to be 20% at the 5th harmonic. The frequency scans for the base case (when the system has resonance at the 5th harmonic), 5th-harmonic notch filter, and C filter are shown in Figure 11-19 . The C-filter performance is comparable to the notch filter.

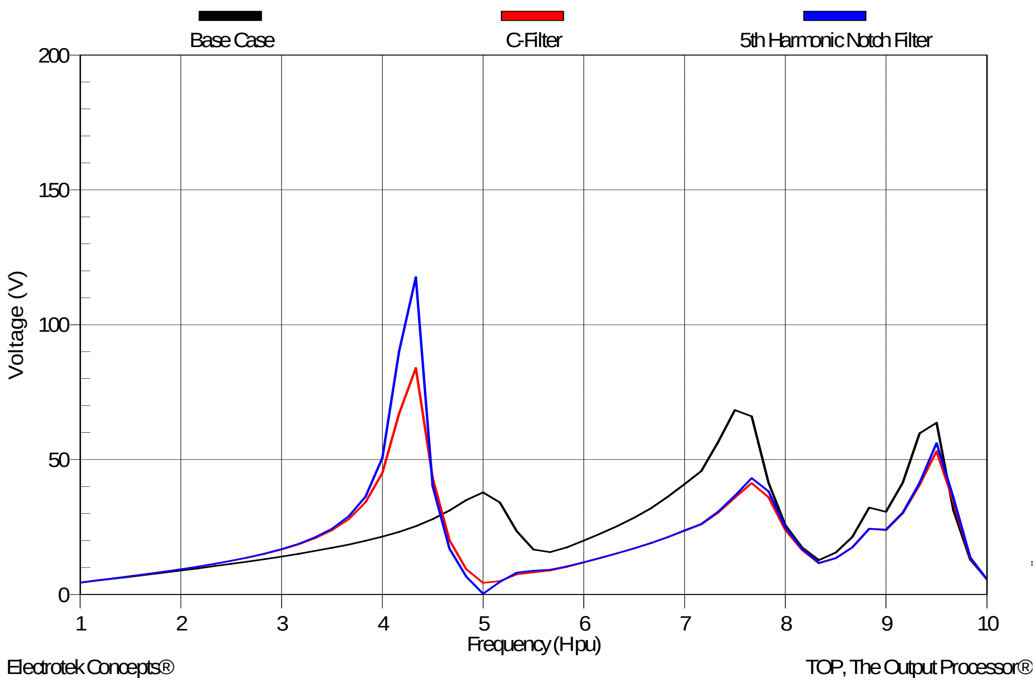


Figure 11-19
Frequency Scan: Base Case, 5th-Harmonic Notch Filter, and the C Filter

Table 11-16
Harmonic Levels for the Test Case with BABB Bank Designed as C Filter

Case	138 kV (MVAr)	69 kV (MVAr)	23 kV (MVAr)	EA Cap	BABB Cap	%THD EA	%THD BABB	% 5th @ EA	% 5th @ BABB
1	226	30.6	10.7	B	C-F	1.73	0.709	0.85	0.48

B = Capacitor bank in service
C-F = Capacitor bank is implemented as a C filter

Conclusions from the Filter Cases

The following conclusions can be drawn from the filter studies:

1. Overall, implementing the capacitor banks as filters would significantly reduce the harmonic distortion.
2. Implementing a filter bank at one location and a capacitor bank at the other location has mixed results. This scheme would substantially reduce distortion at the filter location and provide some reduction at the other location. However, one filter may not completely eliminate resonance concerns at both locations.
3. Implementing one of the capacitor banks as a C filter also gives satisfactory results. However, implementing a C filter may not be an economically feasible option.

Filter Location

From Table 11-15 it is clear that implementing both the capacitor banks as 5th-harmonic notch filters is the best solution (case 1b). However, this may not be economically feasible. The other option is to implement only one capacitor bank as filter. In this case, a choice has to be made between East Akron and BABB substations. Simulation results (cases 1c and 1d in Table 11-15) indicate that applying the filter at East Akron may not alleviate the problem at BABB. The 5th-harmonic and %THD limits at BABB were found to be above IEEE 519 limits in the simulation with a filter at East Akron. However, implementing the filter at BABB may keep the harmonic levels at East Akron within the limits. Therefore, BABB may be a more appropriate location to install the filter. Note that the conclusions are based on the simulation results. Both substations should be monitored for a sufficient time before making a decision about filter application.

Conclusions

Frequency scans at the East Akron and BABB 138-kV buses show that parallel resonance occurs in the vicinity of the 5th harmonic for the current system conditions. For certain system configurations, there is a chance of resonance occurring right at the 5th harmonic itself, a concern from a harmonic-distortion point of view.

The addition of the proposed capacitor banks is found to cause just a slight shift in the resonant frequency. The resonant peak will still remain in the vicinity of the 5th harmonic and is therefore still a concern.

Modification of the proposed bank(s) into a 5th-harmonic tuned filter serves to shift the resonance peak to a safer frequency away from the 5th harmonic. This option was found to be effective in reducing the individual and overall harmonic distortion to acceptable levels for a wide variety of the system configurations that may be expected. As expected, a C-type filter was also found to result in a comparable frequency response.

Recommendations

Based on the harmonic analysis conducted on, following recommendations are being made –

- The proposed banks tuned as 5th-harmonic filters would be beneficial for harmonic distortion levels.
- Given a choice between East Akron and BABB, implementing the filter bank at BABB may be enough to keep the harmonics within limits for all the conditions.
- If it is decided against implementing the filters, the capacitor bank should be designed so that it can be configured as a filter later.
- Although expected to be more effective, C-type filters may not be feasible because of the high costs involved.

12
MODELING FOR TRANSMISSION

Modeling Transmission Systems

Transmission systems require a much more complex model than distribution systems in order to accurately determine frequency-response characteristics. This is because of the many paths available for the harmonic currents to flow.

General Modeling Guidelines

There are two fundamental issues that need to be considered in developing a system model for harmonic simulation studies. The first issue is the extent of the system model to be included in the simulation. The second issue is to decide whether the model should be represented as a single-phase equivalent (or positive-sequence) or a full three-phase model.

Extent of System Model

It is impractical to model the entire transmission system under study. The following approach may be adopted in developing a model for a transmission system:

1. Model the system three or four buses away from the bus of interest and include everything in between.
2. For the buses represented in the model, include all the capacitor banks at transmission as well as sub-transmission voltage levels.
3. The rest of the system should be represented by a short-circuit equivalent network that can be obtained by reducing the system. Note that the reduction process creates additional sources, buses, and branches that are not present in the actual system. Also, reduction of the network tends to produce a large number of high-impedance equivalent branches. Using sparsity-enhanced reduction techniques tends to avoid this problem.

System Model

For transmission-system studies, a positive-sequence (or single-phase) model is often sufficient. Neglecting the effects of mutual coupling and phase imbalance in transmission systems has not been found to have a significant impact on harmonic analysis. Due to the need of including a relatively large portion of the system in the model, single-phase modeling helps to keep the model relatively simple and it is quicker to arrive at the solution.

The connection of transformers between the end-user loads and the transmission system prevent the injection of zero-sequence harmonic components from lower voltages. Although zero-sequence harmonics can be generated by wye-grounded transformer winding connections on the transmission system, these harmonics are small compared to the harmonics from loads. Note that the positive-sequence model is still appropriate for evaluating the system response to unbalanced third-harmonic components that may flow onto the transmission system from lower voltages. There are some situations when a three-phase model is required. These situations include interference with communication systems, presence of single-phase capacitor banks, single-phase or unbalanced harmonic sources, and presence of balanced triplen harmonic voltage sources. These situations are more likely to occur in distribution systems than transmission systems.

Example Model of Transmission System

System-Frequency Response and Harmonic Injection

If a relatively large capacitor is added to an existing network, the frequency response of the network will be affected. Usually, capacitor banks for transmission systems are large enough to cause significant change to the overall system frequency-response characteristics. For a system with some special kinds of harmonic-injection types of loads (adjustable-speed drives, process rectifiers, arc furnaces, and so on), changes in harmonic flows (illustrated in Figure 12-1) due to the added capacitor banks can be a concern. The added capacitance will provide a low-impedance path for the high-frequency components. Therefore, adding capacitor banks can reduce the magnitudes of high-order harmonics. However, the capacitors can result in system resonances that magnify voltage levels at low-order harmonics (such as 5th, 7th, 11th, 13th). Figure 12-2 illustrates an example of frequency-response characteristic.

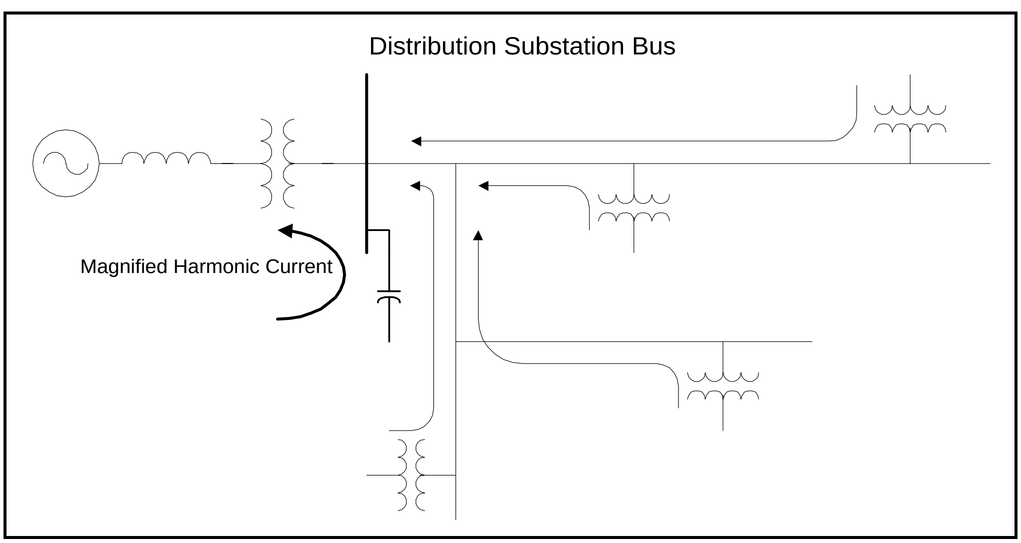


Figure 12-1
Impact of Capacitor Installation on Harmonic Current Flow

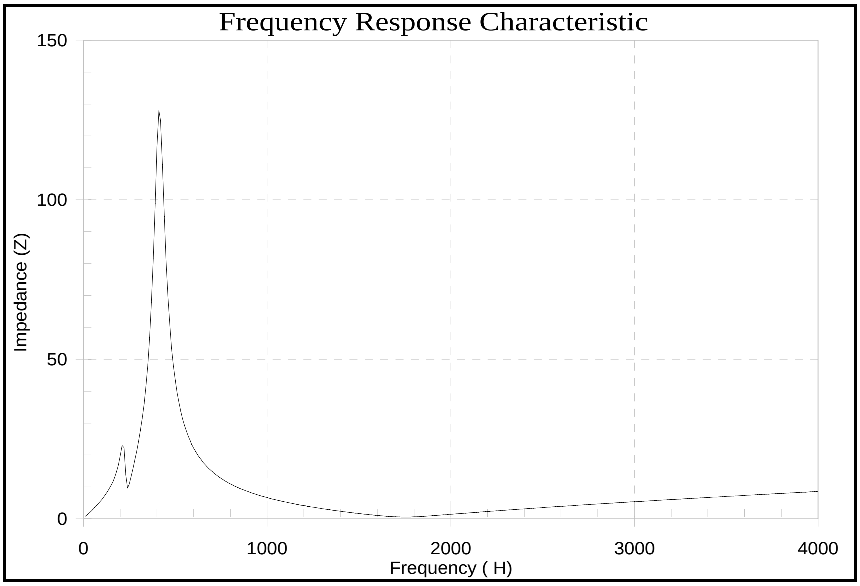


Figure 12-2
Example Frequency-Response Characteristic

In general, a harmonic study has the following objectives:

1. Determine system frequency-response characteristics with and without the addition of proposed transmission capacitor banks.
2. Identify resonance concerns introduced or aggravated by the proposed capacitor banks.
3. Estimate the impact of proposed capacitor banks on the system harmonic distortion levels.
4. Evaluate solutions to control harmonic distortion levels.

Procedure for Conducting a Harmonic Study

The general steps for performing a power-system harmonic study are laid out in the flowchart shown in Figure 12-3 as detailed in [9].

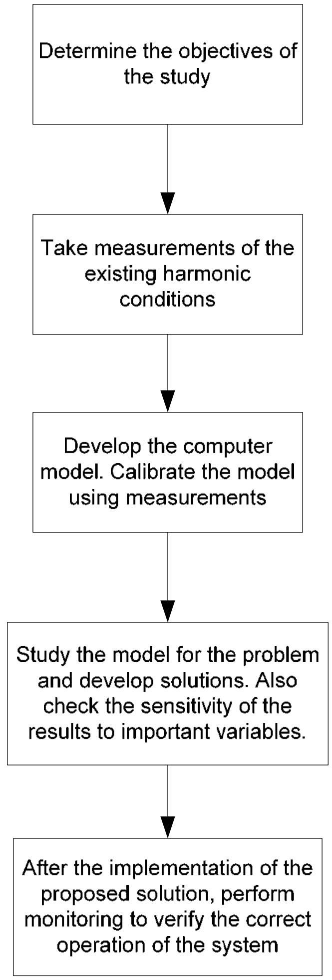


Figure 12-3
Steps in Harmonic-Study Procedure

The first step is to identify the objective of the study. One objective might be to identify the cause of the existing harmonic problem. Another objective might be to determine whether a new expansion is likely to cause or suffer from problems. For our study, the objective is to assess whether adding new capacitor banks is going to cause excessive levels of harmonic distortion. If possible, measurements of existing harmonic conditions should be made. This will give an indication of the existing conditions that can be used to calibrate the model. If the model is satisfactory, it can be used to develop solutions for the problem or predict the performance of altering the system. Finally, the system should be monitored after the system modification to verify the correct operation.

Model Development

As previously mentioned, transmission systems require a much more complex model than distribution systems in order to accurately determine frequency-response characteristics. This is because of the many paths available for the harmonic currents to flow. There are two fundamental issues that need to be considered in developing a system model for harmonic simulation studies. The first issue is the extent of the system model to be included in the simulation. The second issue is to decide whether the model should be represented as a single-phase equivalent (or positive-sequence) or a full three-phase model.

Extent of System Model

It is impractical to model the entire transmission system under study. Therefore, the following approach was adopted in developing a model for the subject systems:

1. Model a system three or four buses back from the bus of interest and include everything in between.
2. For the buses represented in the model, include all the capacitor banks at transmission as well as sub-transmission voltage levels.
3. The rest of the system should be represented by a short-circuit equivalent network.

In case of FE, new capacitor banks were proposed at 230- and 138-kV levels. In addition, capacitor banks are present at sub-transmission level (69 kV), and distribution levels (35 and 12.5 kV).

System Model

For transmission-system studies, balanced three-phase conditions are assumed, and a positive-sequence (or single-phase) model is often sufficient. The connection of transformers between the end-user loads and the transmission system prevent the injection of zero-sequence harmonic components from lower voltages. Although zero-sequence harmonics can be generated by wye-grounded transformer winding connections on the transmission system, these harmonics are small compared to the harmonics from loads. Note that the positive-sequence model is still appropriate for evaluating the system response to unbalanced third-harmonic components that may flow onto the transmission system from lower voltages. There are some situations when a three-phase model is required. These situations include interference with communication systems, presence of single-phase capacitor banks, presence of single-phase or unbalanced harmonic sources, and presence of triplen harmonic voltage sources [4]. These situations are more likely to occur in distribution systems than transmission systems. For the FE study, positive-sequence models were used.

Data for Model Development

Once the buses required for the harmonic study are selected, the following data is typically required:

1. System equivalents at the cutoff points
2. Utility source data at 60 Hz
3. Transformer impedances at 60 Hz
4. Transmission line modeling

5. Linear load impedances at 60 Hz
6. The harmonic spectrum of the nonlinear loads in the study
7. Information about existing and proposed capacitor banks (MVAr rating or impedance at 60 Hz)

System Equivalents

It is not practical to include the entire transmission-system model in a harmonic study. As mentioned earlier, the harmonic model should include detailed information about all the existing capacitor banks in the vicinity of the substations under study. The rest of the system must be represented by a short-circuit equivalent. Note that the reduction process creates additional sources, buses and branches that are not present in the actual system. Also, reduction of the network tends to produce a large number of high-impedance equivalent branches. Using sparsity-enhanced reduction techniques tends to avoid this problem [10]. Commercial software like CAPE has the capability to perform network reduction using conventional as well as sparsity-enhanced methods.

Utility Source Data

The data required for modeling the utility source is shown in Table 12-1.

Table 12-1
Data Required for Modeling the Utility Source

Positive-sequence voltage magnitude
Positive-sequence voltage angle
Positive-sequence resistance
Positive-sequence reactance

Note that representing the circuit by an equivalent would introduce new sources that should be used in the development of the harmonic model. Most of harmonic-analysis software is capable of performing power flow at the fundamental frequency to calculate phasor quantities for voltages and currents in the system.

Transformer Data at 60 Hz

Transformer data required for the harmonic study is given in Table 12-2.

Table 12-2
Data Required for Modeling Transformers

High-side voltage
Low-side voltage
%R
%X

Typically, a magnetizing branch is not represented in the harmonic studies but can be easily incorporated in any software. Skin effect may or may not be represented in the studies. If represented, transformer losses are assumed to increase linearly with frequency (that is, transformer X/R ratio is constant). Note that because we are dealing with only a positive-sequence network, we do not have to worry about transformer neutral connections. Note that transmission- and sub-transmission-level transformers will have a high X/R ratio (~ 20).

Modeling the Transmission Line

There are many ways to model a transmission line for harmonic studies. Short transmission lines (less than 80 km long) can be represented by series resistance and inductance as shown in Figure 12-4. However, this model neglects shunt capacitance and is therefore not suitable for harmonic studies (even for short lines).

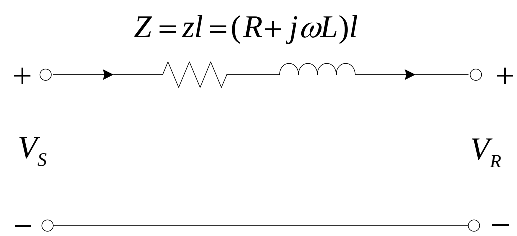


Figure 12-4
Model for Short Transmission Line

A nominal-pi model is another way of modeling a transmission line. This model lumps half of the total shunt capacitance at each end of the line (Figure 12-5). This model is used to represent medium-length transmission lines (80 to 250 km) at 60 Hz.

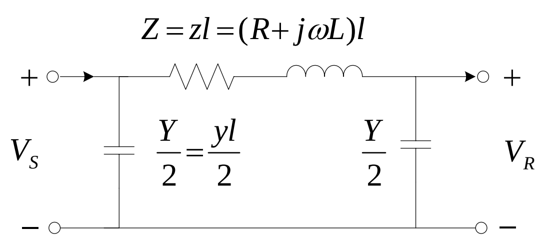


Figure 12-5
Model of a Nominal-Pi Transmission Line

Notation:

z = R + jωL Ω/m, series impedance per unit length

y = G + jωC S/m, shunt admittance per unit length

Z = zl Ω, total series impedance

Y = yl S, total shunt admittance

l = line length in meters

In reality, parameters of a transmission line are distributed over the entire length of the line. Lumping the parameters does not capture the distributed nature of the parameters of a transmission line. An equivalent-pi model is used to represent the distributed nature of transmission lines. This model is shown in Figure 12-6. Although this representation is identical to a nominal-pi representation, the admittance and reactance values have hyperbolic functions.

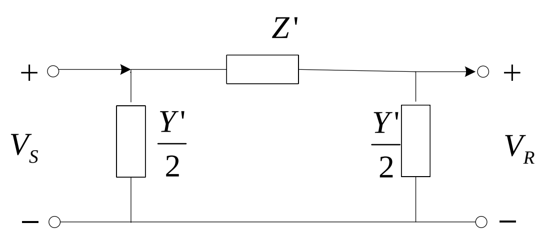


Figure 12-6
Equivalent-pi Transmission Line Model

Notation:

Z_c = Characteristics impedance of line in Ω

γ = Propagation constant of line

Z' = $Z_c \sinh(\ l)$

$$\frac{Y'}{2} = \frac{\tanh(\lambda l/2)}{Z_c}$$

l = line length in meters

Linear Load impedances at 60 Hz

A linear load is that part of any load that does not create harmonics. Data needed for representation of linear loads is given in Table 12-3. The series and parallel representations of the load are shown in Figure 12-7.

Table 12-3
Data Required for Modeling Linear Load

kVA
kV
Displacement power factor
%Series and %parallel split

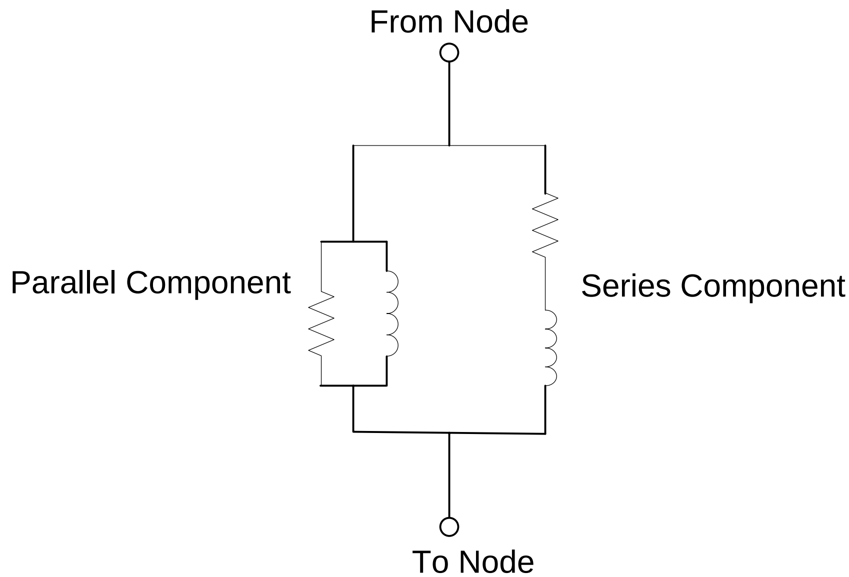


Figure 12-7
Representation of a Linear Load

As listed in Table 12-3, %parallel and %series selection depends entirely on the load to be modeled. Note that representing a load as 100% series would effectively remove damping at high frequencies. A recommended practice is to use 50% parallel and 50% series load.

Nonlinear Loads

At distribution level of a typical spectrum produced by a nonlinear device such as drives can be obtained from the manufacturer. At the transmission level, there is no single source of harmonics. Therefore, a harmonic spectrum of the nonlinear load can be estimated by experience or measured directly at the point of interest. The nonlinear loads are represented as harmonic current sources. The data required for modeling nonlinear loads is given in Table 12-4.

Table 12-4
Data Required for Modeling Nonlinear Load

Harmonic number
Current magnitude at each harmonic
Angle at each harmonic (in degree)

Current magnitude can be in actual ampere or as a percentage of the fundamental-frequency current. If the harmonic spectrum is coming from the actual measurements, special attention must be paid to scaling of angles in the model. This is because power quality monitors measure phase-angle spectra with respect to the fundamental component of the voltage at the measurement point (which is assumed to be 0°). However, in the actual circuit, this angle will not be zero and will be determined by the fundamental-frequency power-flow calculations. Therefore, the measured phase angles should be corrected by using the following relationship:

$$\theta_h = \theta_{h,\,Measured} + h \times \theta_{V1} \quad \textbf{(8)}$$

Where,

θ_h = Corrected harmonic angles

$\theta_{h,\,Measured}$ = Harmonic angles measured

h = Harmonic number

θ_{V1} = Angle of fundamental voltage

Usually, a harmonic software package can make this correction automatically.

Capacitor Banks

Capacitor banks are present at all voltage levels. At transmission and sub-transmission levels, the banks are used for reactive power compensation and voltage stability. The data required for representing capacitors is given in Table 12-5.

Table 12-5
Data Required for Modeling Capacitor Bank

Capacitor MVAr or value in microfarad
Voltage across the capacitor
Inrush current limiting reactor

The inrush current limiting reactor is designed so that there is sufficient impedance to adequately reduce the inrush current magnitude and frequency. IEEE Standard C37.06 (Table 3A) should be used to calculate the reactor size.

Harmonic Simulation

There are two types of harmonic simulations that are usually performed:

1. Frequency scans
2. Harmonic current injection

Frequency Scans

Frequency scans give general information about frequency-response characteristics. Frequency-response characteristics are useful in gaining general information about the system and tell about resonance conditions in the system.

Usually, the term "frequency scan" implies current scans. For current scans, all voltage sources are shorted, and all current and nonlinear sources are open-circuited. Unity ampere current is injected at different frequencies at the bus under investigation. All of these steps are performed automatically in all the harmonic study software.

Results of frequency scans depend on the amount of linear loading (damping) and capacitive compensation assumed in the analysis. It is impractical to plot frequency scans for all of the possible loading and compensation levels in the actual system. Therefore, some representative loading levels must be used to simulate loading conditions. The following general guidelines can be used for deciding the test cases for frequency scans:

1. Choose at least three loading levels: low (25%), medium (50%), and high (75%).
2. Capacitor banks are present at different voltage levels. Use engineering judgment to select reactive compensation at each voltage level.
3. The frequency scans should be repeated with and without the proposed capacitor banks.

Frequency scans help to identify potential resonance conditions. For example, some scans may indicate the presence of a resonance peak between around the 5th and 7th harmonic. If such conditions exist, then further analysis is necessary as follows:

4. Adjust the reactive compensation and/or loading such that the resonance peak is exactly at either the 5th or other harmonic of interest. This adjustment is "fine tuning" of the model to get resonant peaks at the worst harmonics (particularly the 5th).
5. With the modified conditions, the frequency scans should be repeated with and without the proposed capacitor banks.

Harmonic Current Injection

Harmonic current injection gives information about the actual harmonic content at the point of interest. This study is necessary to determine whether the system is in compliance with harmonic limits before and after the capacitor banks are installed.

Base Case

The starting point of distortion-simulation analysis is to come up with a base case that will simulate the background harmonic levels existing in the system. Proposed capacitor banks or filter banks should not be included in the base case. The different steps in building and validating the base-case model are shown in Figure 12-8.

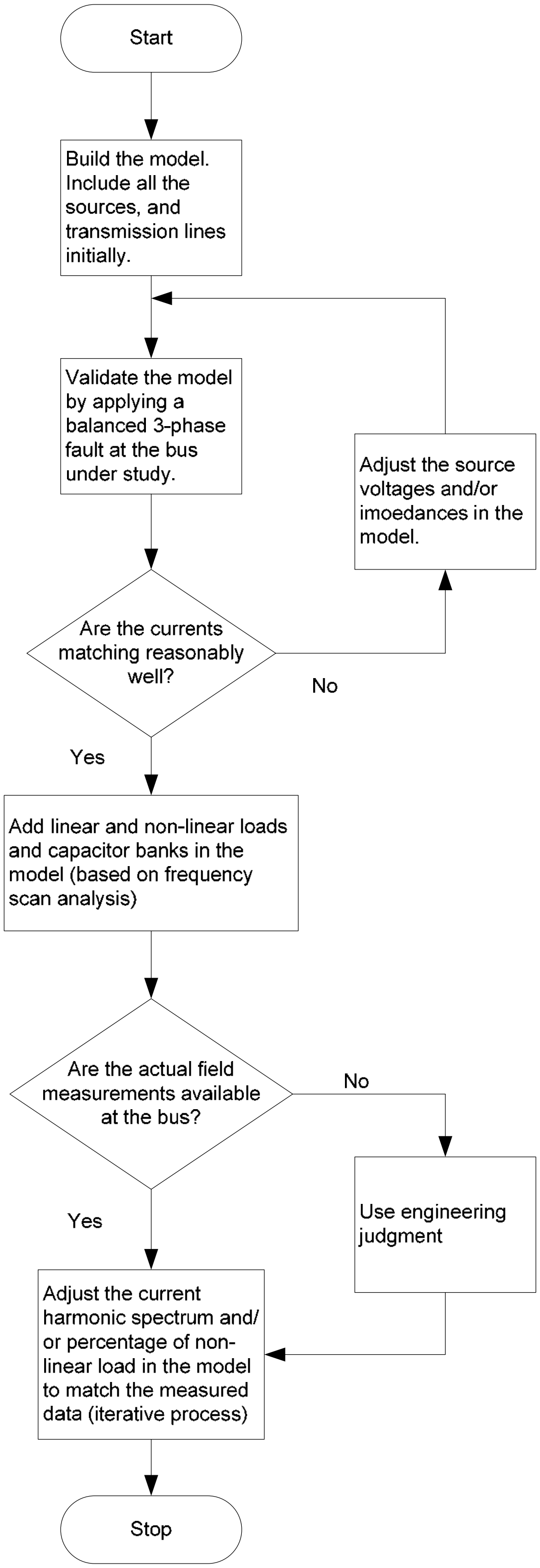


Figure 12-8
Flowchart for Building Base Case for Harmonic Distortion Studies

Model Validation at 60 Hz

The first step in the harmonic simulation study is to validate the model at 60 Hz by comparing simulated magnitudes of fault current with the values provided by the utility. In some cases, a short-circuit simulator program (such as CAPE, ASPEN) can be used to calculate the magnitudes of fault current. Note that only balanced three-phase faults are necessary because of the balanced conditions assumed. Loads and capacitor banks are not considered in the calculation of fault current. Therefore, it is not necessary to include them for 60-Hz model validation.

Nonlinear Loads and Harmonic Spectrum

Nonlinear loads are the sources of harmonics in the system. It is almost impossible to obtain exact percentage of nonlinear loads and their harmonic spectrum at the transmission level. If possible, harmonic measurements should be taken at the bus under study and compared with the simulation result. Matching the individual harmonic values and %THD for the base case with the measured data is an iterative process.

If the measured data is not available, then engineering judgment should be used. For the utilities in the United States, values of harmonics and %THD can be assumed for background harmonics at buses that do not have harmonic problems, as shown in Table 12-6.

Table 12-6
Assumed Values of THD and Individual Harmonics for Base Case

THD (%)	3rd (%)	5th (%)	7th (%)
1.1% to 1.5%	Negligible	1 to 1.1	0.2 to 0.3

Base-Case Variations

Once the base case is set up to measure the background harmonics, the following cases should be analyzed:

1. Run the base case with the new capacitor bank in service. This will give an indication of the impact of adding the new bank.

If frequency scans indicate the possibility of parallel resonance at the 5th or 7th harmonic, then use the base-case loading and/or reactive compensation that simulated the resonance condition in the analysis of the frequency scans. With this as the new base case, the following cases should be analyzed:

2. Run the case without the new bank.
3. Run the case with the new capacitor bank.
4. Run the case with the new capacitor bank implemented as a notch filter.

Guidelines for Voltage Distortion

IEEE 519-1992 provides the following recommended limits for voltage-distortion levels at different system voltages.

Table 12-7
Recommended Voltage-Distortion Limits from IEEE 519-1992

Bus Voltage at PCC (V_n)	Individual Harmonic Voltage Distortion (%)	Total Voltage Distortion - THD_{Vn} (%)
$V_n \leq 69kV$	3.0	5.0
$69kV < V_n \leq 161kV$	1.5	2.5
$V_n > 161kV$	1.0	1.5

Specific guidelines for measurements for comparison with these limits are not provided. However, the working group developing the next draft of this standard is recommending that the assessment be made using the recommended approach in IEC standards (95% probability level based on 10-minute samples over a one-week period).

These harmonic limits are quite strict. Many distribution systems and transmission systems have harmonic distortion levels that exceed these guidelines already, and there are not significant complaints associated with harmonic levels on most of these systems. One improvement being proposed by the working group for the next draft of the standard is another voltage level below 1 kV with higher limits for voltage distortion (6% individual and 8% total distortion for agreement with the IEC standards). However, this does not help with the limits for MV and HV systems that are being exceeded. A reasonable compromise for MV harmonic limits is 6% THD and 5% at the fifth harmonic. Other components can be limited to 3%.

For comparison, the recommended limits (called *voltage characteristics*) developed by a CIGRE Working Group are provided in Table 12-8. They also provide recommended planning levels with some margin with respect to the limits (see Table 12-9). Although the table of limits is unnecessarily complicated with many different limits depending on the frequency—triplen versus non-triplen components, even versus odd components, and so on—the limits are generally more appropriate (or maybe slightly too lenient).

Table 12-8
Recommended Voltage Characteristics (Limits) from CIGRE C4.07 Working Group Report

Harmonic Order (h)	MV Harmonic Voltage (%)	HV – EHV Harmonic Voltage (%)
3	**5**	**2,5**
5	**6**	**3,0**
7	**5**	**2,5**
11	**3,5**	**1,7**
13	**3**	**1,7**
17	**2**	**1,2**
19	**1,5**	**1,2**
23	**1,5**	**0,8**
25	**1,5**	**0,8**
THD	**8**	**4**

Table 12-9
Recommended Harmonic Planning Levels from CIGRE C4.07 Working Group Report

Odd order non-multiple of 3			Odd order multiple of 3			Even order		
Order	Harmonic voltage %		Order	Harmonic voltage %		Order	Harmonic voltage %	
	MV	HV-EHV		MV	HV-EHV		MV	HV-EHV
5	5	2	3	4	2	2	1,6	1,5
7	4	2	9	1,2	1	4	1*	1*
11	3	1,5	15	0,3*	0,3*	6	0,5*	0,5*
13	2,5	1,5	21	0,2 *	0,2 *	8	0,4*	0,4*
17	1,6	1	>21	0,2 *	0,2 *	10	0,4*	0,4*
19	1,2	1				12	0,2 *	0,2 *
23	1,2	0,7				>12	0,2 *	0,2 *
25	1,2	0,7						
>25	0,2 + 0,5 (25/h)*	0,2 + 0,5 (25/h)						
NOTE: Total harmonic distortion (THD): 6,5% at MV and 3 % at HV.								

Harmonic Limits for Customers

In order to maintain the distortion levels of the system voltage within allowable levels, it is necessary to impose limits on the amount of harmonic current that customers can inject into the system. IEEE 519 provides a relatively straightforward method of applying these limits. Current distortion limits are provided as a percent of the rated customer load current (or the *maximum demand current,* as it is referred to in the standard). These are applied at the point of common coupling (PCC) where the utility can supply other customers. The limits depend on the customer load in relation to the system short-circuit capacity at the PCC. The objective of the harmonic-current limits is to control the harmonic injection from individual customers so that the voltage-distortion limits are not exceeded on the overall system. The current limits are a simplified approach for achieving this objective, compared to procedures for assessing the impacts of each customer on the voltage distortion and then combining the impacts of multiple customers on a probabilistic basis, as outlined in IEC Standard 61000-3-6 [11].

Table 12-10
IEEE 519-1992 Recommended Limits for Harmonic Currents That Can Be Injected by Customers onto the Supply System

<20*	4.0	2.0	1.5	0.6	0.3	5.0
20–50	7.0	3.5	2.5	1.0	0.5	8.0
50–100	10.0	4.5	4.0	1.5	0.7	12.0
100–1000	12.0	5.5	5.0	2.0	1.0	15.0
>1000	15.0	7.0	6.0	2.5	1.4	20.0
<20*	2.0	1.0	0.75	0.3	0.15	2.5
20–50	3.5	1.75	1.25	0.5	0.25	4.0
50–100	5.0	2.25	2.0	0.75	0.35	6.0
100–1000	6.0	2.75	2.5	1.0	0.5	7.5
>1000	7.5	3.5	3.0	1.25	0.7	10.0
<50	2.0	1.0	0.75	0.3	0.15	2.5
	3.0	1.50	1.15	0.45	0.22	3.75

There are many issues that come up when evaluating for compliance with these limits. A few of the important issues are summarized here:

- It is difficult to tell the direction of harmonic currents, so it may not be sufficient to just measure the harmonic currents at the PCC. You need to know if the harmonic currents are coming from the customer or if the customer is acting like a filter or a load and absorbing the harmonics due to voltage distortion in the supply. This is particularly important when the customer has power-factor-correction capacitors or filters.

- The rated load current can be calculated many different ways, especially when a new customer is being evaluated (one year of historical data not available). The important point is to agree on a value that will be used for the rated current and use it.

- The measurement procedure is not specified, but the next version of IEEE 519 is likely to recommend use of IEC methods—10-minute values and assessment at the 95% level.

- It might be useful to have limits for other durations of distortion (such as short bursts). Some example values have been proposed for applying variable limits as a function of the duration of the harmonics.

Even with these issues, the harmonic limits in IEEE 519 are reasonably straightforward to apply in most cases and provide a fair method of dividing responsibility between the utility and the customer for harmonics

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HARMONIC LIMITS FOR EQUIPMENT – ARE THEY NEEDED?

No equipment limits for harmonic distortion levels are included in IEEE standards. IEC 61000-3-2 provides example limits for a wide variety of equipment, including electronic power supplies. Application of these limits in North America could be beneficial in terms of limiting triplen harmonic currents from residential customers causing neutral currents and neutral-to-earth voltage (NEV). It is very difficult to apply customer level limits for residential customers. The only real way to limit harmonics for these customers is to get the manufacturers to limit the harmonic generation at the equipment level.

Utilities have an example of a very successful campaign that limited harmonic injection from residential and commercial equipment in the 1990s—electronic ballasts. Utilities with energy-efficiency programs offered rebates to customers to retrofit fluorescent lighting with electronic ballasts. However, studies indicated that this could result in harmonic problems on the power system. Rebate programs were developed that provided rebates only if the electronic ballast was on an approved list that was based on performance of the ballast, including limiting the harmonic injection. As a result, all electronic ballast manufacturers started developing and selling ballasts with low harmonic distortion in order to be on the list. Eventually, these became the standard design, and the limits (90% true power factor) were adopted as a National Electrical Manufacturers Association (NEMA) standard.

It seems like we could use a similar approach for electronic power supplies. An initial effort in this direction is under way on the west coast, where the "80 Plus" program provides a rebate when customers buy a computer with a power supply that is more than 80% efficient. The power supply must also meet a requirement of 90% true power factor, which limits the total harmonic distortion to less than about 40%. In general, manufacturers have to use active control to achieve this, and the harmonic levels can be significantly lower than this. Maybe the lower-harmonic power supplies will become the standard like they did for electronic ballasts.

Standards for Harmonics from Distributed Generators

IEEE Std 1547-2003 essentially limits harmonic output from distributed generators to the most stringent values permitted in IEEE Std 519-1992. The values are reproduced in Table 13-1.

Table 13-1
Harmonic Current Distortion Limits for Distributed Generators

Individual Odd Harmonics, h	Harmonic Current Limit (% of rated)
h < 11	4
11 ≤ h < 17	2
17 ≤ h < 23	1.5
23 ≤ h < 35	0.6
35 ≤ h	0.3
Total Demand Distortion (TDD)	5

Guidelines for Harmonic Voltage Distortion Levels

There are various IEEE and IEC standards that govern harmonic limits at various voltage levels in a system. Guidelines given in IEEE Std 519-1992 and IEC 61000-3-6 standards are discussed in this section.

Harmonic Survey Data at Transmission-System Voltage

IEC 61000-3-6

IEC 61000-3-6 specifies limits of harmonic voltages for equipment connected to medium-voltage (MV), high-voltage (HV), and extra-high-voltage (EHV) systems. In the context of the standard, MV refers to voltages between 1 and 35 kV, HV refers to voltages between 35 and 230 kV, and EHV refers to voltages above 230 kV. This standard argues that emission limits should be evaluated on the voltage-distortion basis. This is to ensure that harmonic current injections from harmonic-producing equipment do not result in excess levels of voltage distortion.

The standard provides compatibility levels and planning levels for harmonic voltages in the MV, HV, and EHV systems. The compatibility level refers to a level where the compatibility between the equipment and its environment is achieved. Compatibility levels are generally based on the 95% probability level—that is, 95% of the time, the compatibility level can be achieved. The compatibility levels for MV, HV, and EHV systems are shown in Table 13-2.

Table 13-2
Compatibility Levels for Harmonic Voltages (in Percent of Fundamental) for MV, HV, and EHV Systems

Harmonic Order (h)	MV Harmonic Voltage (%)	HV – EHV Harmonic Voltage (%)
3	5	2,5
5	6	3,0
7	5	2,5
11	3,5	1,7
13	3	1,7
17	2	1,2
19	1,5	1,2
23	1,5	0,8
25	1,5	0,8
THD	8	4

Apart from the compatibility levels, the standard also specifies planning levels. Planning levels are design criteria or levels specified by the utility company. Planning levels are more stringent than compatibility levels. The planning levels are shown in Table 13-3.

Table 13-3
Planning Levels for Harmonic Voltages (in Percent of Fundamental) for MV, HV, and EHV Systems

Odd Order Non-Multiple of 3			Odd Order Multiple of 3			Even Order		
Order	Harmonic Voltage %		Order	Harmonic Voltage %		Order	Harmonic Voltage %	
	MV	HV-EHV		MV	HV-EHV		MV	HV-EHV
5	5	2	3	4	2	2	1,6	1,5
7	4	2	9	1,2	1	4	1*	1*
11	3	1,5	15	0,3*	0,3*	6	0,5*	0,5*
13	2,5	1,5	21	0,2 *	0,2 *	8	0,4*	0,4*
17	1,6	1	>21	0,2 *	0,2 *	10	0,4*	0,4*
19	1,2	1				12	0,2*	0,2 *
23	1,2	0,7				>12	0,2 *	0,2 *
25	1,2	0,7						
>25	0,2 + 0,5 (25/h)*	0,2 + 0,5 (25/h)						
NOTE: Total harmonic distortion (THD): 6,5% at MV and 3 % at HV. * See also footnote [1].								

The joint working group CIGRE C4.070020 collected power quality measurement data for MV, HV, and EHV systems with the intention of recommending a set of internationally relevant

[1] For some higher-order harmonics, care must be exercised to specifying very low values such as 0.2% because of practical limitations to measurement accuracy mainly at HV-EHV. Furthermore, a margin depending on system characteristics should exist between the MV, HV, and EHV planning levels in order to allow coordinating emission of disturbances between different voltage levels.

power quality indices and objectives. In the context of the report, MV refers to voltages between 1 and 35 kV, HV refers to voltages between 35 and 230 kV, and EHV refers to voltages above 230 kV.

A summary of the measurement results at HV (35 to 230 kV) is shown in Figure 13-1 . The survey had a total of 284 sites from seven different utilities. The bars indicate the planning levels recommended in Table 13-3. The blue dots are 95% probability harmonic values. The harmonic values were calculated over 10-minute intervals. The feeders were monitored for a week.

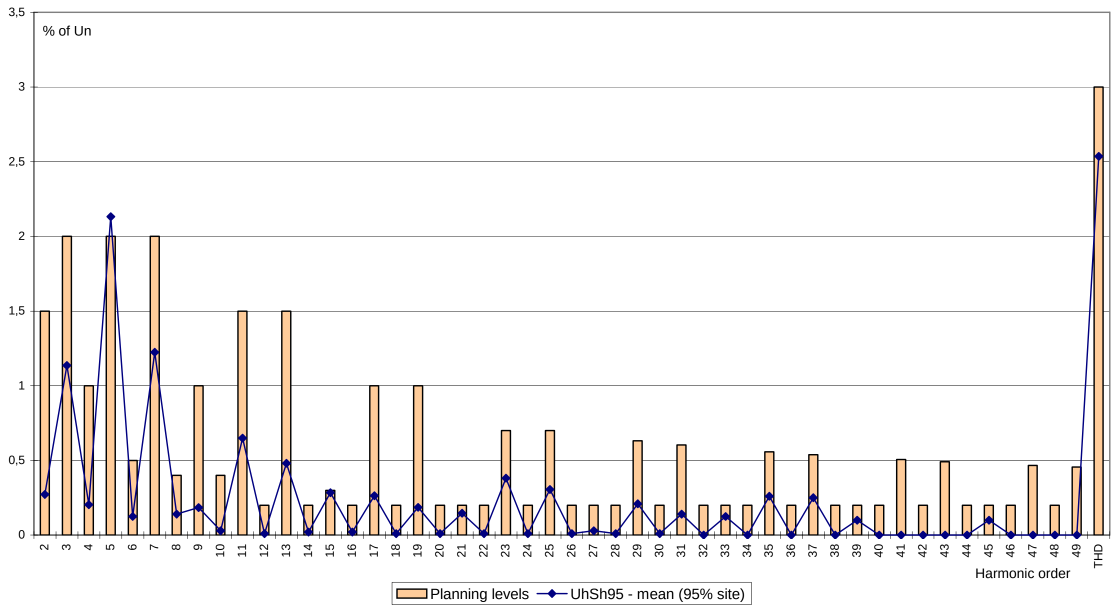

Figure 13-1
Mean Harmonic Value among Survey Versus Planning Levels of IEC 61000-3-6

Figure 13-1 shows that planning levels are exceeded for the 5th harmonic (and also the 15th harmonic). This survey is an indication that some harmonic levels, especially the 5th, are increasing at the transmission level.

IEEE 519-1992

IEEE 519-1992 provides guidelines for the acceptable levels of voltage distortion on a utility system, as shown in Table 13-4.

Table 13-4
IEEE 519-1992 Harmonic Voltage Distortion Limits

Table 11-1—Voltage Distortion Limits

Bus Voltage at PCC	Individual Voltage Distortion (%)	Total Voltage Distortion THD (%)
69 kV and below	3.0	5.0
69.001 kV through 161 kV	1.5	2.5
161.001 kV and above	1.0	1.5

NOTE — High-voltage systems can have up to 2.0% THD where the cause is an HVDC terminal that will attenuate by the time it is tapped for a user.

Note that the THD values in Table 13-4 are expressed as a function of the nominal system RMS voltage rather than of the fundamental frequency voltage magnitude at the time of measurement. This definition allows the evaluation of the voltage distortion with respect to fixed limits rather than limits that fluctuate with the system voltage.

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