Power Quality Mitigation Technology Demonstration at Industrial Customer Sites

Industrial and Utility Harmonic Mitigation Guidelines and Case Studies

Technical Report

Power Quality Mitigation Technology Demonstration at Industrial Customer Sites

Industrial and Utility Harmonic Mitigation Guidelines and Case Studies

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REPORT SUMMARY

However the restructuring of the electric power industry shakes out, the commercial/industrial customer's need for quality power will increase; and customer service will remain a key to retaining current accounts and attracting new customers. The need for demonstrating new harmonics mitigation technologies will thus be an important factor for the wire side of the business as well as for energy service companies. This report provides guidelines for implementing harmonics mitigation demonstration projects at commercial/industrial customer sites or on the distribution system.

Background

The commercial/industrial sector constitutes the majority of electric load in the United States and represents an important customer base for electric utilities. Power quality variations, such as harmonic distortion in the electric supply for commercial and industrial facilities, continue to be a customer concern. Advanced filter technologies are providing alternatives for harmonics mitigation that may be increasingly attractive from an economic perspective. Field demonstration of these technologies is the most direct way to increase customer understanding of harmonics mitigation applications and build customer confidence in the new products. By gaining first-hand experience through field demonstration of the new active and hybrid filter technologies, utilities will be able to provide a value-added service, a crucial advantage in the competition to retain customer accounts and attract new customers. This report describes guidelines for the specification, procurement, and installation of harmonics mitigation technologies; pre- and post-monitoring of the site to determine the effectiveness of the technology; and a cost-benefit assessment to determine the financial implications of the chosen technology versus other competing technologies. It is intended to provide assistance to the engineer who is applying IEEE 519 and should help to ensure proper application of that standard.

Objective

To provide a guideline to utilities for conducting technical and economic evaluations and implementing harmonics mitigation demonstration projects at commercial/industrial customer sites or on the distribution system.

Approach

The project team first identified characteristics of nonlinear loads used by typical utility customers. The team then developed a comprehensive systems approach to a successful demonstration project, including methods for conducting power quality investigations and identifying application issues associated with harmonic solutions. Finally, the team identified several EPRI software tools that may help utilities conduct some of the technical analysis for a harmonics mitigation demonstration project at a commercial/industrial customer site.

Results
Successful demonstration of emerging harmonic mitigation technologies requires a comprehensive guideline for specification, procurement, and installation of the specified technology; an elaborate plan for pre- and post-monitoring of the site to determine the effectiveness of the technology; and, eventually, a cost-benefit assessment to determine the financial implication of the chosen technology versus other competing technologies. An effective demonstration project requires very close coordination among all the parties involved. These may include EPRI, the utility, end-use customers, electrical contractors, and equipment vendors. Management of project activities should be based on the project team concept. The parties involved must have a clear understanding of the demonstrative nature of the project. It is also important to keep a good written record of all potential issues and how they were resolved during the installation, commissioning, and performance-verification stage of the harmonics mitigation project. Gaining first-hand knowledge regarding application issues related to implementation of harmonics mitigation equipment will enable utilities to apply that equipment successfully at other customer locations.

EPRI Perspective
By providing utilities with a clear roadmap for implementing harmonics mitigation technologies, EPRI is enabling utilities to better service one of their key customer segments. Because of their understanding of the power quality characteristics of electric service, electric utilities are in a unique position to help customers understand and implement these new harmonics mitigation technologies. Widespread acceptance of new harmonic mitigation technologies will ultimately benefit utilities and their customers by providing an opportunity to obtain specified levels of power quality from standard service distribution systems.

Keywords
Power Quality
Power Conditioning
End-Use Mitigation Systems
Harmonics
Active Filters
Hybrid Filters

ABSTRACT

The commercial/industrial sector constitutes the majority of electric load in the United States, and thus represents an important customer base for electric utilities. Power quality concerns continue to be an important factor in the electric supply for commercial facilities. While there is a rapid increase of non-linear load use in the commercial and industrial sectors, advanced filter technologies are providing new alternatives for harmonics mitigation that may be increasingly attractive from an economic perspective. Field demonstration of these technologies is the most direct way to increase application understanding and build confidence in products. Demonstration of emerging harmonic mitigation technologies requires a comprehensive guideline for specification, procurement, and installation of the specified technology; an elaborate plan for pre- and post-monitoring of the site to determine the effectiveness of the technology; and, eventually, a cost-benefit assessment to determine the financial implication of the chosen technology versus other competing technologies.

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INTRODUCTION

The Electrical Environment

Power quality has emerged as an important issue for the commercial/industrial customer segment. Historically, power quality issues have been the domain of electric utilities, which focused on reducing or eliminating power outages. However, the recent proliferation in office use of electronic equipment and microprocessor-based controls has caused electric utilities to redefine power quality in terms of the quality of voltage supply rather than availability of power. In this regard, *IEEE Std. 1159-1995 Recommended Practice for Monitoring Electric Power Quality* has defined a set of terminologies and their characteristics to describe the electrical environment in terms of voltage quality. Table 1-1 shows the categories of power quality disturbances with spectral content, typical duration, and typical magnitude.

Table 1-1
Categories of Power Quality Variation – IEEE 1159-1995

Categories	Spectral Content	Typical Duration	Typical Magnitudes
1.0 Transients			
1.1 Impulsive			
1.1.1 Voltage	> 5 kHz	< 200 μs	
1.1.2 Current	> 5 kHz	< 200 μs	
1.2 Oscillatory			
1.2.1 Low Frequency	< 500 kHz	< 30 cycles	
1.2.2 Medium Frequency	300–2 kHz	< 3 cycles	
1.2.3 High Frequency	> 2 kHz	< 0.5 cycle	
2.0 Short-Duration Variations			
2.1 Sags			
2.1.1 Instantaneous		0.5–30 cycles	0.1–1.0 pu
2.1.2 Momentary		30–120 cycles	0.1–1.0 pu
2.1.3 Temporary		2 sec–2 min	0.1–1.0 pu
2.2 Swells			
2.1.1 Instantaneous		0.5–30 cycles	0.1–1.8 pu
2.1.2 Momentary		30–120 cycles	0.1–1.8 pu
2.1.3 Temporary		2 sec–2 min	0.1–1.8 pu
3.0 Long-Duration Variations			
3.1 Overvoltages		> 2 min	0.1–1.2 pu
3.2 Undervoltages		> 2 min	0.8–1.0 pu
4.0 Interruptions			
4.1 Momentary		< 2 sec	0
4.2 Temporary		2 sec–2 min	0
4.3 Long-Term		> 2 min	0
5.0 Waveform Distortion			
5.2 Voltage	0–100th Harmonic	steady-state	0–20%
5.3 Current	0–100th Harmonic	steady-state	0–100%
6.0 Waveform Notching	0–200 kHz	steady-state	
7.0 Flicker	< 30 Hz	intermittent	0.1–7%
8.0 Noise	0–200 kHz	intermittent	

EPRI Distribution Power Quality Project

The EPRI "Assessment of Distribution System Power Quality (DPQ)" represents power quality data collected at nearly 300 measurement sites. These sites were selected to provide a wide diversity of distribution system conditions. The feeders that were monitored ranged in voltage level from 4.16 kV to 34.5 kV and in length from 1 km to 80 km. The 27 months of monitoring resulted in a staggering collection of data, which was statistically summarized in a three-volume EPRI report[1]. The data collected during the measurement period provides a statistically valid sample of the range of power quality events in a distribution system, although not necessarily valid at any given site.

Figure 1-1 provides some results from the DPQ study. The data shows the voltage THD and individual harmonics from all monitoring sites. Key observations are:

- The worst-case individual harmonic components were less than 2%
- The worst-case overall THD measured was less than 2.5%

While these values are typically not considered poor, there are often isolated cases in which the THD is much worse. These cases may become more common with the proliferation of harmonic producing loads.

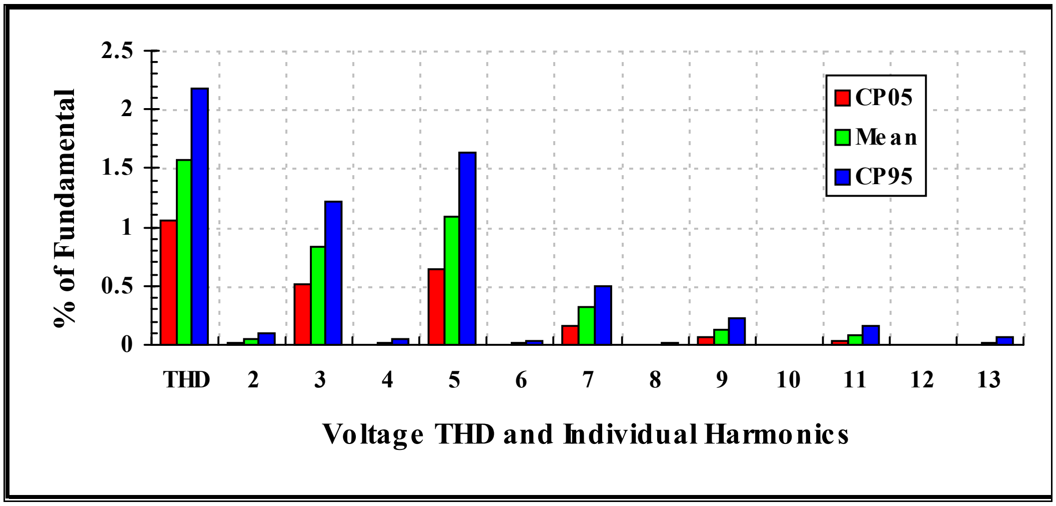

Figure 1-1
Voltage THD and Individual Harmonics (6/1/93 to 3/1/95, All Sites)

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[1] An Assessment of Distribution System Power Quality : Volumes 1-3; TR-106294-V1, TR-106294-V2, TR106294-V3.

Existing Standards and Guidelines- IEEE 519 and 519A

There has been a tremendous amount of work done in the area of harmonics mitigation, as evidenced by the two IEEE 519 documents. The IEEE standard 519 is a well-known treatise on the sources and effects of harmonics on commercial and industrial electrical systems. One of the most important accomplishments of this document was the establishment of harmonic current and voltage limits which were balloted and agreed upon in IEEE working groups and committees. These limits are intended to be applied by utilites in order to manage the harmonic levels that their customers are subjected toSimilar to the function of the National Electric Code Application Handbook, the intention of the IEEE 519A guideline is an enhancement of the previous work to assist the user in applying the limits set forth by IEEE 519.

Both IEEE 519 documents have revolutionized the capabilities of utilities to manage the distortion levels present on the electrical system. While this is a significant achievement, there is some uncertainty regarding applications of solutions to harmonic distortion when it exceeds the IEEE 519 limits. This EPRI document is intended to be a step-by-step guideline for applying the solutions available on the market today.

Advances in Filtering and Harmonic Mitigation Technologies

Traditionally, harmonic filters have been passive, that is, utilizing inductors and capacitors connected in various arrangements to achieve attenuation of currents of specific frequencies. These filters require tuning to the frequency of interest. Once tuned, they are restricted to operate on that band of frequencies. If multiple frequencies require mitigation, then additional stages of filtering are also required. These stages can be tuned independently of each other and cascaded together, but are still passive in the sense that they cannot adapt or change with system requirements. Passive filters must be designed with fundamental frequency reactive compensation in mind, and also present the possibility of creating or changing system resonances.

Active filters represent the most significant advance in harmonic mitigation technology to date, an advance that has occurred, ironically, as a result of the same power electronics devices that caused the problem in the first place. Advances in AC to DC converters and DC to AC inverters, especially at increased power ratings, have led to increased injection of harmonics into the power system. With these same types of advances, however, it is possible to compensate in real time for the harmonics injected by nonlinear loads.

Active filters use power electronics to sense the harmonic content of the load current and inject components that will cancel load-current harmonics as well as canceling harmonic voltages, thus preventing the power system from seeing these harmonic components. These filtering techniques are active in the sense that they can adapt and change with system requirements.

Typically, the active filter uses a pulse-width modulated (PWM) voltage source inverter to produce the harmonics-canceling components. These inverters are often connected in parallel to the load, and are referred to as active parallel filters. Other topologies allow a series connection of the inverters to perform current compensation. There are also filters that utilize a combination of both. The filters are usually designed to compensate for lower-order harmonics, typically less than the 20th or 30th harmonic. There is always a possibility of inverters causing some distortion themselves, but at much higher frequencies than those compensated.

The Need for Demonstration Projects from the Utility Perspective

The technical merit of using demonstration projects to gain first-hand experience in the application of new technologies is well understood. However, recent changes in the vertically integrated utility structure are raising new questions regarding utility involvement in customer power quality-related matters. One line of thinking, albeit shortsighted, is that transmission and distribution, or "wires," companies will focus only on the utility side of the power quality spectrum and will not be involved in any customer-side issues. This approach assumes that customers will be buying electricity from a third party and the wires companies' role will be limited to transportation of electricity.

However, the primary factor affecting power quality is transportation and the primary impact of power quality is on end-use loads. It is unrealistic to assume that these two sides of the power quality picture can be isolated from each other. . If power quality deteriorates, customers may turn to distributed generation sources such as fuel cells or purchase power from independent power producers instead of from electric utilities. In such a case, even wires companies will be affected by loss of revenue from reduced transportation charges.

For new utility entities such as energy service companies created to explore alternate revenue streams, the importance of demonstrating new harmonics mitigation equipment to commercial/industrial customers is critical. These new technologies have the potential for replacing many existing technologies, and their revenue potential cannot be ignored. In addition, power quality mitigation technologies in general can be bundled with other traditional service offerings into an attractive package for attracting new customers.

It is very difficult to predict the changes in utility restructuring. However this restructuring shapes up, the commercial/industrial customer's need for quality power will increase and customer service will remain a key criterion in utilities' competition to retain current accounts and attract new customers. The need for demonstrating new harmonics mitigation technologies will always be an important factor for the wire side of the business as well as for energy service companies.

Purpose of This Report

The purpose of this report is to provide step-by-step guidelines for utilities to apply harmonics mitigation technologies. Guidelines for establishing and applying harmonics limits have been developed, but none exist for application of mitigation technologies. This report provides guidelines for performing harmonics analyses for commercial and industrial customers as well as the utility distribution system. In addition, it outlines steps for applying harmonic mitigation techniques and for specifying devices.

Intended Use of This Report

The intended audience of this report includes utility account executives dealing with commercial customers; power quality and customer service engineers responsible for providing technical support to customer power quality problems; and R&D and technical applications personnel responsible for demonstrating new customer technologies. In conjunction with other EPRI reports described in Chapter 6, this report should be used to:

- Understand the application issues related to harmonics mitigation technologies.
- Understand the opportunity for demonstration of such technologies in the commercial/industrial market segment.
- Plan a systems approach to a demonstration project, including the various technical/economic issues. .
- Assess the technical and cost-benefit implication of various mitigation schemes.
- Evaluate the performance of these new technologies under field conditions.

2

GUIDELINES FOR MANAGING HARMONICS PROBLEMS WITHIN A CUSTOMER SITE

Commercial Customer Site Nonlinear Load Characteristics

Most harmonic currents in commmercial systems are caused by nonlinear loads, that is, loads that draw currents whose frequencies differ from the frequency of the source. Many electronic devices are nonlinear loads because they use solid state rectifiers at their inputs and filter capacitors after the rectifiers. An example of this type of circuit is a personal computer power supply, as shown in Figure 2-1.

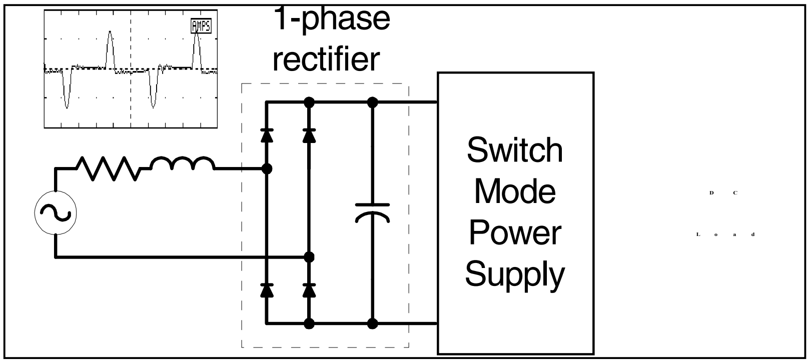


Figure 2-1
PC Power Supply Circuit Diagram

Solid state rectifiers inherently draw current in pulses, when the AC line voltage is higher than the voltage across the filter capacitor used with the rectifier. This pulsed current is very rich in harmonics, as seen in Figure 2-2. The harmonic spectrum plot shows the presence of odd harmonics, with relatively large magnitudes at the lower frequencies. As the frequency increases, the magnitudes decrease.

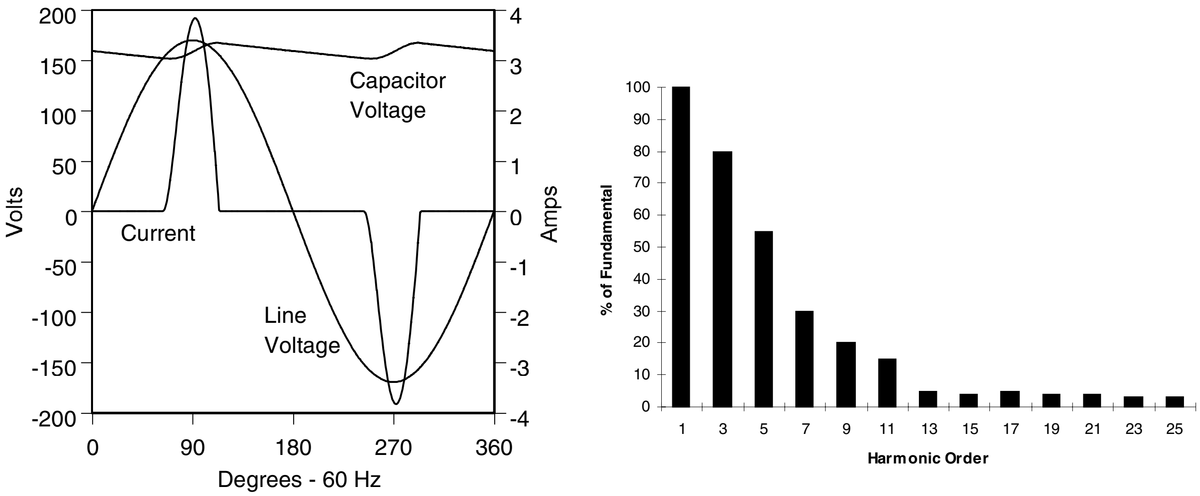


Figure 2-2
PC Power Supply Current and Spectrum

The PC power supply is only one of many possible harmonic producers in the 120-volt range. Other loads that inject harmonic currents include office equipment for communications, printing and copying and lighting with high efficiency electronic ballasts. Nonlinear loads in the 480 V range include adjustable-speed drives (ASDs) for HVAC, larger computers, uninterruptible power supplies, and 277-V lighting.

Harmonic currents are not produced by the source; rather, the nonlinear load causes harmonic currents. As these nonlinear loads become more and more prevalent, the effect on the power system becomes more pronounced. Because the harmonic currents are a result of the nature of the loads, it is appropriate to consider the load to be a source of harmonic current. As harmonic components are injected back into the system, they cause voltage drops (at the corresponding frequencies) across the cable and source impedance upstream, creating voltage distortion in the power system. As can be seen in Figure 2-3, voltage distortion is worse at points closer to the load. This voltage distortion is a direct function of the current harmonic component magnitudes and the impedance in the system (cables and transformers).

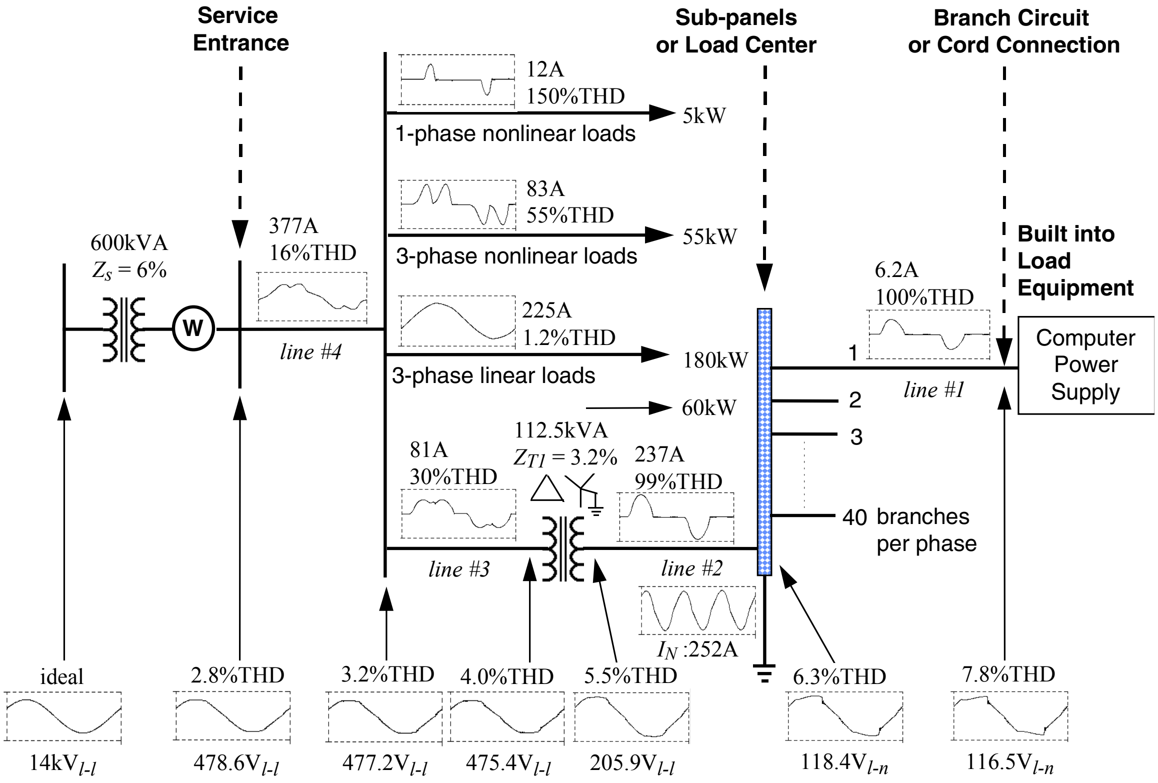


Figure 2-3
Commercial Building Distribution System

Figure 2-3 shows the wiring system of a typical commercial office building and its voltage and current profiles under mixed linear and nonlinear loads. The most significant harmonic producers in this system are the switch mode power supplies (SMPS) used in personal computers.

Line segment #1 is a 20 A branch circuit feeding single-phase computer loads.The total harmonic distortion (THD) of each branch circuit current is about 100%. The THD on line segment #2 is similar, at 99%. Line segment #2 is a three-phase feed from the delta-wye transformer secondary. The loads on different phases share the neutral, which carries a significant amount of third harmonic current. The third harmonic current, along with other harmonics that are multiples of three times the fundamental, are known as triplen harmonics. These triplen harmonics do not cancel, but rather add in the neutral, resulting in a neutral current larger than the phase current. As long as the loading is balanced, the triplens cannot show up on the primary of the Δ-Y transformer, and so the current THD is reduced to 30% at the primary. For an unbalanced system, the triplen harmonics will not be completely canceled and will show up on the primary.

Line segment #4 has a current THD of 16%. This current represents the combination of all the building loads, both linear and nonlinear. The reduction in THD occurs mostly as a result of the domination of the linear loads. The three-phase linear loads totalling 225 A tends to swamp out the nonlinear contribution, thereby reducing the THD on the service entrance feeder.

The distorted current on each line segment interacts with the line inductance, causing voltage distortions. Fig. 2.3 also shows the waveforms, THD and associated rms values of the voltages and currents in the system. The voltage at the input of the single-phase SMPS load has the highest THD at 7.8%. It also presents a flat-topping of the waveshape, which is a reflection of the rectifier output capacitor voltage. With a typical SMPS design of 5% ripple in the dc-link capacitor voltage, this flat-topping of the voltage waveshape is commonly seen in all electronic loads.

The adjustable speed drives do not represent a large load in this facility, but they do inject a large percentage of harmonic content per kW load. As seen in Figure 2-4 , this current is dominated by the 5th and 7th harmonics, which can increase the rms value of current as well as excite resonant conditions in the system, if they exist.

In the model shown in Figure 2-3, the upstream system voltages are gradually smoothed by other types of loads, especially linear loads. At the service entrance of the modeled system, the voltage THD is reduced to 2.8%. Note that the source voltage is assumed as ideal, with a 6% equivalent impedance that combines the 600 kVA transformer and the upstream source impedance.

Industrial Customer Site Nonlinear Load Characteristics

The nonlinear loads prevalent in industrial systems are typically variable-speed motor drives and heating systems that use rectifiers at their inputs. All these devices use a similar topology, that is, a rectifier, a dc bus, and an inverter output to control output frequency. Shown below is the typical topology for a variable frequency drive, with input line current and spectrum.

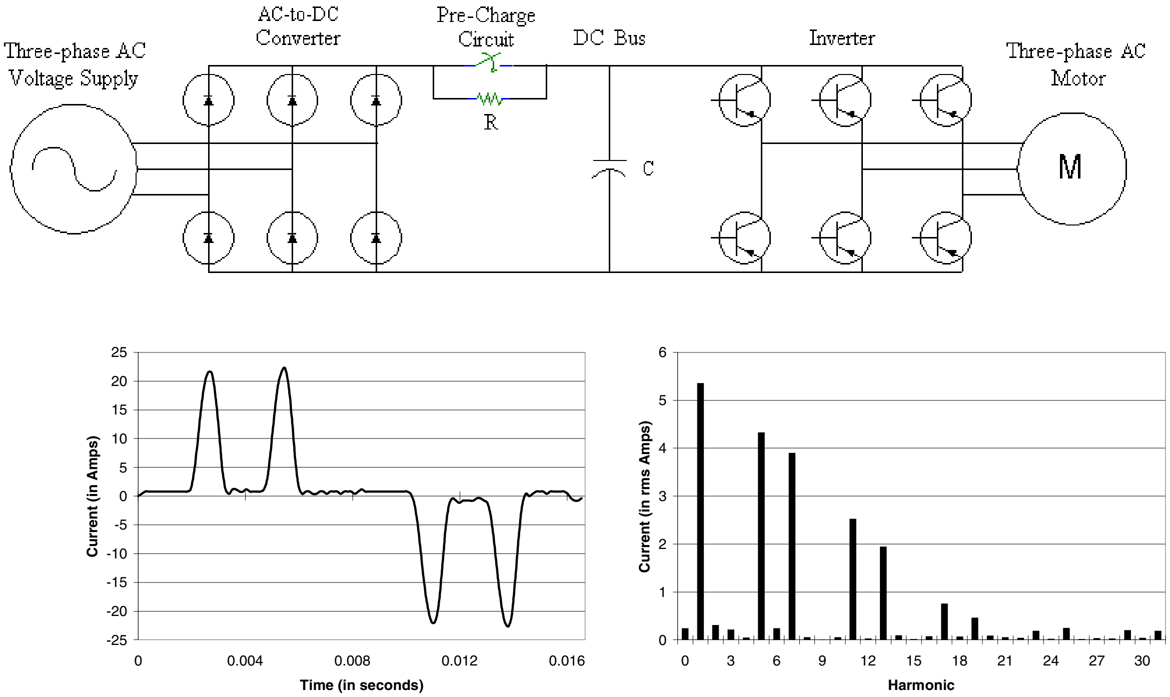


Figure 2-4
AC Drive Input Current and Spectrum

The heating applications may use a slightly different rectifier, with phase-controlled thyristors instead of diodes. The line current will still be somewhat distorted, but also with some reactive power requirement due to the phase shift induced between line voltage and line current. The topology shown in Figure 2-5 is for a DC motor drive, which has a similar front end using a controlled rectifier. The current associated with this device, along with its harmonic spectrum, are also shown in Figure 2-5.

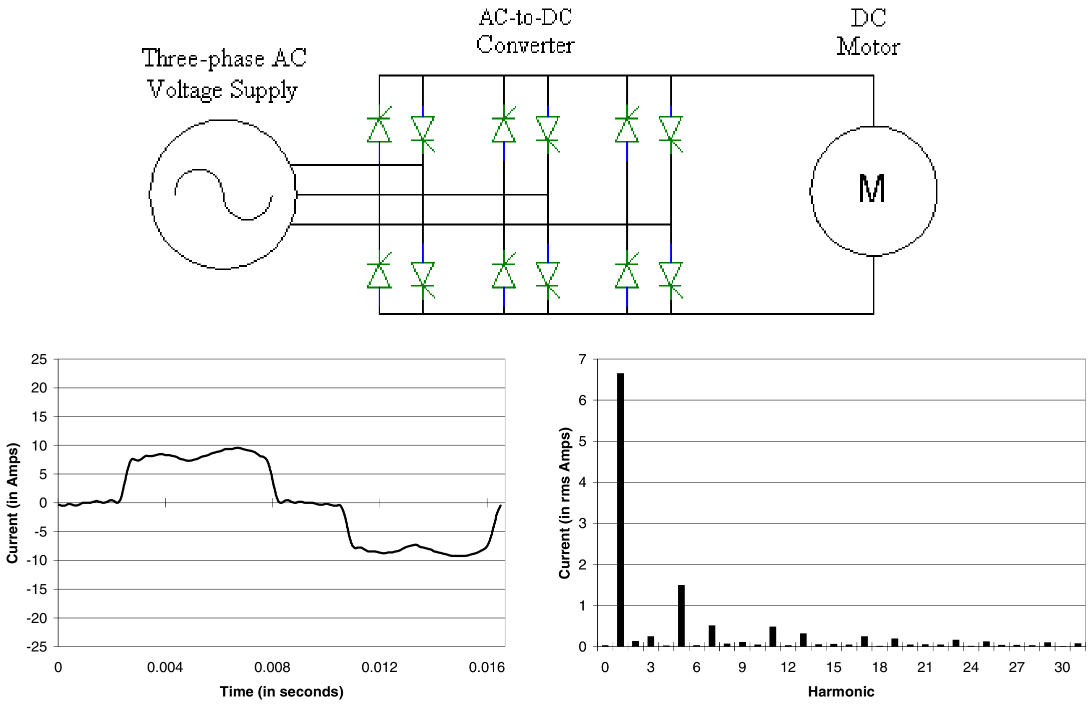


Figure 2-5
DC Drive Input Current and Spectrum

Another topology for heating applications involves the use of semiconverters for half-wave rectification. While these semiconverters are very popular, they have an interesting side-effect, in that they produce even harmonics. Even harmonics are caused by nonlinear loads that destroy the symmetry of the current waveform. Typically current waveforms possess the symmetry in question, and the even harmonic terms all have zero coefficients. If the waveform is not symmetrical about the y axis however, then there will be some non-zero even harmonic terms. The semiconverter shown below uses a half-wave rectifier such that the rectification is accomplished with three diodes and three phase controlled SCRs. The figure also shows the voltage and current waveforms and spectra associated with them.

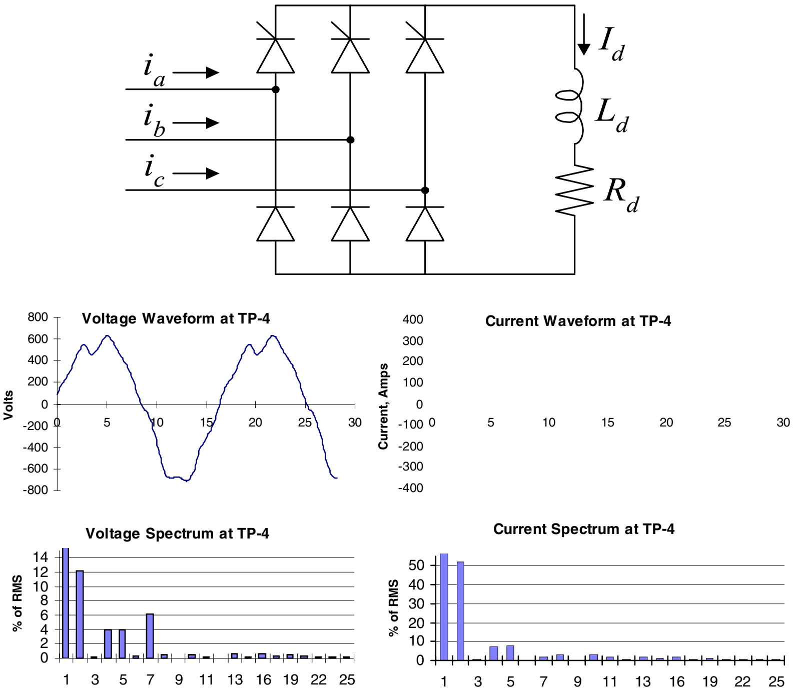


Figure 2-6
Semiconverter with Voltage and Current Waveforms and Spectra

It is easy to see the large second and fourth harmonic components. It should also be noted that there is no DC component. With a 50% second harmonic current component, the voltage distortion is nearly 12% at the second harmonic. This condition can be treated similarly to odd harmonics, but care must be taken to avoid resonances at the even harmonics also, whereas that would not normally be a consideration.

Other loads, such as arc furnaces, cycloconverters and power line carrier communication systems, can cause distortion at frequencies that are not integer multiples of the power frequency. These are known as interharmonics.These may occur anywhere in between the integer harmonics, causing further distortion of the waveform. Problems caused by interharmonics include many of the same ones that integer harmonics cause, such as transformer and cable heating, possible multiple zero crossings, and telephone interference, as well as light flicker. Filter design must take interharmonics into consideration, since there may be more frequencies to deal with and more possibilities of resonance.

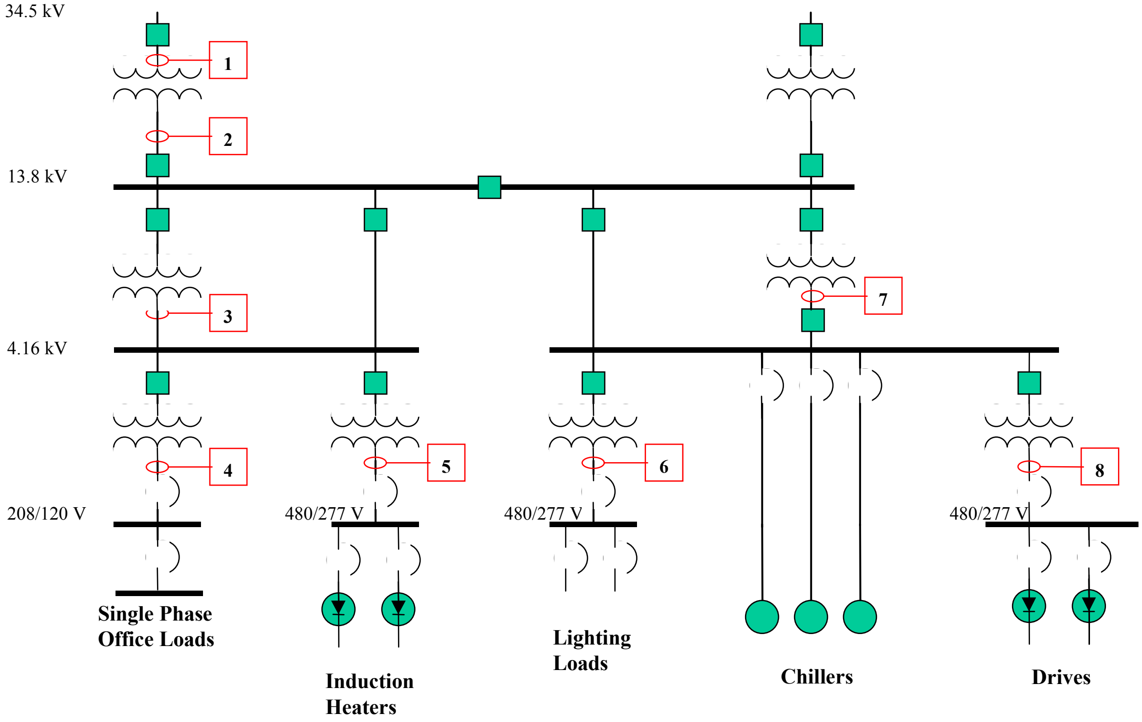


Figure 2-7
Simplified One-line Diagram of Industrial Plant

Figure 2-7 is a simplified one-line diagram of the distribution system in an industrial plant. In a harmonic study for an industrial customer, the first step is to decide where to take measurements. From IEEE 519, the voltage distortion limits should be applied at the PCC, point 1 in Figure 2-7. Point 2 can be used, but the results should be reflected to the high side of that transformer to ensure that the limits are applied at the point where other customers could be connected.

Point 3 is at the 4160 V bus feeding offices and induction heaters (bus 3), while point 7 is at the 4160 V bus for lighting, chillers, and drives (bus 7). These points also will be used to refer to the current, in that feeder point 3 will refer to feeder 3, point 7 to feeder 7, and so forth. Busses 3 and 7 can be considered intermediate busses, since they are not at the PCC, but they are not the first panel upstream of the loads, with the exception of the chillers. While some vendors use adjustable speed drives on their compressors and pumps, in the case shown in Figure 2-7 it is assumed that the chillers are using motors across the line with no speed control, so there will be no distortion issues with these loads. These loads will, however, provide some dilution of the nonlinear currents injected into bus 7. If the vendor is using ASDs on the chiller motors, the load will be nonlinear and must be considered for harmonic injection.

Bus 4 is at the 208/120 secondary of a delta-wye transformer feeding office loads. This type of panel was analyzed in the previous section on commercial office buildings. There is a significant probability of heavy current distortion in the feeders from this panel, as well as a high level of neutral current flowing at the third harmonic. The transformer feeding bus 4 will experience extra heating as a result of these currents, and the voltage at bus 4 may be distorted by the harmonic current components injected into the bus by the single phase nonlinear office loads. On a plant-wide scale, however, this effect is usually a much smaller issue than the effect of three-phase nonlinear loads. In industrial plants, the loading is dominated by three-phase devices. Thus in Figure 2-7, the induction heaters and the adjustable speed drives represent the dominant nonlinear three-phase loads, while the chillers represent a large linear three-phase load.

At bus 5, the current will be the sum of the induction heater currents. While there may be some cancellation between the individual heaters, there will still be some significant distortion in this current. The current in the feeders from bus 5 to the heaters will have the most distortion, since there is no chance for cancellation yet. The voltage at the heater terminals may be somewhat distorted, as the individual distorted heater currents flow through the feeder impedances, causing voltage drops at frequencies other than the fundamental. The voltage at bus 5 is distorted by the sum of the heater currents flowing through the transformer impedance, causing voltage drops at the frequencies predominant in the current. The bus 5 voltage distortion is less than that at the heater terminals, due to the current cancellation effect. So, as usual, the major issues at bus 5 are *conductor heating, transformer heating and voltage distortion*. In addition, since the heaters use phase-controlled rectifiers, there will be some induced phase shift which causes a reactive power requirement. This will lead to power factor correction requirements, and the possibility of resonant conditions due to capacitor banks.

At bus 6, the current is the sum of all the lighting loads. Modern electronic ballasts and fixtures for HID or HPS lights will draw nonlinear currents, but ANSI C82.11-1993 limits electronic ballast current harmonics to less than 32%. Therefore, any voltage distortion at bus 6 is limited in the same fashion. There should not be any major issues at bus 6 regarding conductor heating, transformer heating, neutral heating, or voltage distortion.

Bus 8 will be examined before 7, since the loads on bus 8 will affect bus 7. At bus 8, the adjustable speed drives are AC PWM output types and will have probably the most pronounced impact on voltage and current distortion in the whole plant. First of all, the individual feeders to the drives may experience current distortion levels as high as 150% THD. In addition, there is usually not much cancellation of these currents at bus 8 because the front end of these drives are passive diode rectifiers and all the significant harmonic components of current are displaced from the line voltage by the same amount. Thus the dominant harmonics, 5th and 7th will be in phase and simply add at bus 8. The feeder to bus 8 will then have the same distortion levels as the individual feeders. The voltage at bus 8 will be distorted by the current interaction with the transformer impedance, resulting in a voltage THD at bus 8 higher than anywhere in the plant (besides the drive terminals themselves). Any other loads to be connected to this bus must be examined for sensitivity to harmonics before connection. So, again, the major issues at bus 8 are *conductor heating, transformer heating and voltage distortion.* However, in this case the adjustable speed drives have passive diode front ends, and therefore have a displacement power factor of unity. Therefore, there will be no reactive power requirement for these loads.

At bus 7, the chiller motor loads do not inject any harmonic components into the bus. As these chillers present a significant load to the bus, they tend to dilute the THD in the current upstream. How much dilution is a direct function of the ratio of chiller (linear) load to drive and lighting (nonlinear) load. Therefore, the current distortion in the feeder to bus 7 will be less than that to bus 8, and the voltage distortion caused on 7 will be less than on bus 8.

Other possible problems stem from system resonance conditions. Even though the distortion at the PCC may be within limits, power factor may be poor and require improvement. Installation of power factor correction capacitors can often result in a parallel resonance condition with the system inductance. Current components at or near the resonant frequency may be amplified significantly. The bus voltage can be severely distorted as a result, to the point of exceeding IEEE 519 limits.

Harmonics Related Problems

As illustrated in Figure 2-3, the current distortion is not particularly high at the PCC of a commercial building, as a result of cancellation and dilution of harmonics due to nonlinear loads by other, linear loads. As a result, the voltage distortion is not very high at the PCC either. The main detrimental effect of harmonics on commercial buildings, therefore, is not voltage distortion at the PCC, since there is very little, but the additional heating in wires and transformers. In industrial plants however, as shown in Figure 2-7, there is a distinct possibility of significant distortion at the PCC. Industrial plants usually have a much different mix of loads than commercial buildings. Three-phase nonlinear loads may very well dominate the load profile in industrial plants, contributing to the voltage distortion at the PCC. In addition, the possibility of resonance with power factor correction capacitors increases the chance of voltage distortion at the PCC of an industrial plant. These are the main distinctions between the problems caused by harmonic currents in the two settings. An overview of the problems common to both settings is given below.

The RMS value of the current is given by

$$I = \sqrt{\sum_{h=1}^{\infty} I_h^{\,2}} = \sqrt{I_1^{\,2} + I_2^{\,2} + I_3^{\,2} + \ldots}$$

Since the RMS value of the current is higher, the heating associated with I^2R is higher.

Specific problems include:

- Heating effects in phase conductors as well as neutrals
- Heating in 3-phase dry-type transformers
- Harmonic voltage related heating in other equipment, such as motors
- Harmonic voltage stress on system capacitors and equipment capacitors
- Resonance with power factor correction capacitors
- Voltage distortion at the PCC

Wiring losses per kW will vary depending on the line segments and the nature of the load. The distorted current with low power factor leads to relatively higher losses per watt of connected load. Without any harmonic compensation, the highly distorted load currents of computer workstations such as those shown in Fig. 2.1 may lead to losses in the building wiring that are 2.5 times higher than for an undistorted load current. Also, the effectiveness of harmonic elimination methods will be highly dependent on location in the building wiring.

These wiring losses are representative of the heating mentioned earlier. While energy use deserves consideration, the more immediate concern is whether the wiring becomes overloaded as a result of the harmonic content of the current. Considering the factor of 2.5, it is certainly possible to exceed the recommended ampacity of a circuit when nonlinear loads are prevalent.

Neutral conductors in these situations carry triplen harmonics. The reason for this is that for any multiples of the third harmonic, the phase angle is shifted by a corresponding multiple of three. This results in three phasors that are no longer 120 degrees out of phase, but are all in phase. All other components of any frequency, including the fundamental, will have some integer multiple of 120 degrees between phasors, and as such, will cancel each other in the neutral wire. The triplens are, by virtue of this phase shift, zero sequence components of the current. As such, they do not show up on the primary of the delta-wye transformer, but are trapped in the delta windings, which contributes to the heating in the transformer.

Transformer losses are well defined, with derating for harmonics covered in ANSI C57.110. Losses are divided between load and no-load losses. The load losses include I^2R losses and stray losses. It is the stray losses that are most affected by the harmonic content of the current waveform. They are eddy current losses that cause heating in many transformer parts, but it is the windings that are of the most interest. This heating is proportional to the square of the load current and the square of the frequency. This leads to the notion of a K factor, which serves as an indication of the additional eddy current heating in the winding. This K factor is given by

$$K = \frac{\sum I_h^2 h^2}{\sum I_h^2}$$

The derated transformer current is given by

$$I_{RMS} = \sqrt{\frac{1 + P_{EC-R}}{1 + K * P_{EC-R}}}$$

which takes into account the additional eddy current heating in the windings due to the harmonic components of the nonlinear current.

Motors subjected to harmonic voltages will experience heating due to iron and copper losses at the higher frequencies. In three-phase machines, the fifth harmonic will induce a rotating magnetic field in the reverse direction, because the fifth harmonic is a negative sequence component. The excessive heating will shorten the lifetime of the motor.

Any capacitors in the system, whether for power factor correction, or for filtering or snubber applications, will exhibit lower impedance at higher frequencies. This means that for the higher frequency current components, the capacitors will carry increased levels of current. This can lead to blown fuses, increased heating and shortened capacitor life.

Power factor correction capacitors can easily cause a resonant condition. When capacitors are added to a system, there is always some frequency at which the capacitive reactance and the system inductive reactance are numerically equal. The system is said to resonate at that frequency. Depending on how the capacitors are connected with respect to the nonlinear load, this could result in a parallel or series resonance. The end result is magnification of currents and voltages at the resonant frequency, if the nonlinear load injects frequencies near the resonant frequency.

IEEE 519 limits the allowable voltage distortion at the PCC. This is the main factor of interest to the utility, since it will affect other customers. Utilities will apply IEEE 519 limits at the PCC, and the customer may be asked to make equipment modifications to bring the plant into compliance. The other possibility is for the utility to try to mitigate the harmonics on their system. This approach is covered in a later section.

Conducting a Harmonic Power Quality Investigation

Purpose

The purpose of conducting a harmonic study in a particular building is to determine whether the problems outlined in Section 2.4 above are present. The harmonic study applies the limits of IEEE standard 519 at the Point of Common Connection (PCC) o ensure that other customers connected to the utility supply are not affected by harmonics injected by the customer at the site in question.

Approach/Methodology

Measurements should be made at the PCC to determine values for voltage and current distortion, defined, respectively, as percentage of nominal voltage and average maximum demand current. Determining these values allows a basis for comparison with all loading scenarios and other customers. Problems of neutral overloading and transformer heating are typically confined to busses inside the facility, near the offending loads, as the result of cancellation of harmonic currents in feeders from upstream busses. Because of this cancellation, in many cases the voltage and current at the PCC will be very low in distortion. Their values at the PCC should still be measured, however, to ensure compliance with IEEE 519. The investigation should cover at least the following steps:

- Choose the PCC and measure the harmonic content as outlined in IEEE 519.
- Characterize the downstream busses in terms of the same features.
- Identify PWM ASD loads and the busses that supply them. Harmonic levels for each load should be measured.
- Identify controlled rectifier loads and the busses that supply them. Harmonic levels for each load should be measured.
- Identify transformers supplying wye-connected single-phase office loads.
- Identify types and relative number of single-phase loads (number per branch circuit, for example)
- Identify linear loads and their size relative to the nonlinear ones
- Establish relative current rms levels and distortion levels in all feeders to the above busses
- Examine neutral current levels for the wye-connected transformer secondary
- Identify any existing problems such as outlined in the previous section.
- Propose solutions such as circuit modifications or filtering based on application issues shown in the next section.

The most effective application of filters is usually at the offending load. However, this can sometimes lead to an inordinate number of filters required, and comparisons may have to be made with filtering at the panel level to handle multiple loads. At that point, a cost-benefit analysis may show the best course of action to take.

Solutions and Application Issues

Using Figure 2-3 as an example, different solutions can be outlined and the merits of each discussed. There are two approaches to these solutions: one is to adjust the circuit parameters such that the customer can tolerate the harmonic levels present, while the other makes adjustments at or near the offending load to reduce the harmonics to tolerable levels. This second approach usually involves filtering the current. In cases where filtering is applicable, the filters may be applied at various locations. These locations and their merits will be discussed separately.

Solutions

In the case of line losses and overloaded phase conductors, solutions include:

- larger conductors
- filters at various locations

For overloaded/overheated neutrals, solutions include:

- larger neutral wire
- double number of neutral conductors
- neutral for each phase
- third harmonic filters at loads
- third harmonic filter in neutral
- zigzag filter close to load
- active filter

For transformer heating, solutions include:

- derating transformer (larger transformer)
- applying K-rated transformer
- filters at various locations

For motor heating, solutions include:

- derating motor
- filters at various locations

For capacitor stress, solutions include:

- proper sizing of capacitors
- filters at various locations

For resonance issues, solutions include:

- filters at various locations
- de-tuning capacitor banks (creating filters)
- judicious choices of capacitor size and location

Filters at various locations can be further described as:

- filters at bus or panel level
    - series connected neutral current filter
    - parallel connected zigzag filter
    - parallel connected active power filter
- filters at loads
    - built-in types
        - series inductor
        - boost converter power factor correction
    - branch circuit or cord connection
        - parallel connected resonant filter
        - series connected resonant filter
        - neutral current filter
        - zigzag filter
        - active filter
        - choke upstream of motor drives
        - passive 3-phase filter upstream of motor drives

Application Issues

Specific issues that should be considered when applying the solutions outlined above are discussed below. The first set of solutions discussed will be those that do not attempt to remove or attenuate harmonics, but rather just allow the system to live with them.

Solutions to tolerate harmonics

Larger conductors

There are three possibilities here: one is to replace the conductor with a larger one, the second is to pull another conductor in parallel. The third is to consider these problems in the initial design stage. Issues associated with an increase in conductor size are those of complying with the National Electric Code, along with making sure there is space in any raceway and at the cable terminals, and the cost of installation.

Larger neutral

Considerations for larger neutrals are the same as for larger conductors.

Double neutral

Considerations for double neutrals are the same as for larger conductors.

Separate neutral/phase

Considerations for separate neutrals are the same as for larger conductors.

Larger transformer (derated)

In order to derate a transformer after it is installed, limits must be placed on allowed future loading. In addition, loads may have to be removed and placed on some other source, so re-wiring may be required. If the transformer is being sized *before* installation, the current spectrum will be required in order to perform the derating.

K-rated transformer

A K-rated transformer can be used to handle the expected harmonic currents if the transformer is being sized before installation. Again, this would require some knowledge of the harmonic spectrum of the current expected. To install a K-rated transformer in place of an existing one may be cost prohibitive, and the derating approach above would be more cost effective.

Derating motors

Derating motors may only be necessary in extreme cases, where the bus voltage is so distorted that it causes unacceptable heating in the windings. In order to accomplish this derating for a motor in operation, the loading must be reduced. If this is not possible, then a larger motor would be required.

Proper sizing of capacitors

This usually refers to power factor correction capacitors, so the burden may fall on the vendor who designs the cap bank. The issues here are to make sure that the capacitors are rated for the harmonic current they will have to carry. In addition, any background harmonic voltage present on the bus will contribute currents to the cap bank. Therefore, all these currents must be taken into account. Another issue is that of the dielectric stress that may be inflicted on the capacitors. Careful consideration must be taken of all background voltages present in order to avoid these conditions.

De-tuning capacitor banks

This approach uses inductors in series with the capacitor bank to change the resonant frequency. As long as the resonant frequency is not near any predominant current components being injected by the load, there should not be any problem.

Careful location of capacitors

The location of the capacitors will have an impact on system resonance. If a resonant condition is expected or does occur, simply moving the cap bank can change the effective impedance seen by the nonlinear load. Carefully applied, this approach can change the resonant frequency to a frequency that is not present in the load current.

Solutions that reduce harmonics

Solutions that reduce harmonics involve filters. Since filters can be applied at many possible locations in the system, they will be considered by application as well as location.

- filters at bus or panel level
    - series connected neutral current filter
    - parallel connected zigzag filter
    - parallel or series connected active power filter
- filters at loads
    - built-in types
        - series inductor
        - boost converter power factor correction
    - branch circuit or cord connection
        - parallel connected resonant filter (PCRF)
        - series connected resonant filter (SCRF)
        - neutral current filter
        - zigzag filter
        - choke upstream of motor drives
        - passive 3-phase filter upstream of motor drives

Neutral Current Filter (NCF)

This filter is connected in series with the neutral conductor between the step-down transformer and the circuit panel or load center, *line #2* as shown in in Figure 2-3. Because triplen harmonics all flow through the neutral conductor, it is reasonable and economical to block the triplen harmonics in the neutral instead of individual phases. Fig. 2.8 shows a neutral current blocking scheme that connects a third-harmonic tuned NCF between neutral and ground. One issue that should be considered is that the blocking action of the filter means that there will be a sizable voltage drop across the filter at the blocked frequency. Ultimately this means there will be more distortion in the load voltage than without the filter, so the neutral current can be reduced, but at the expense of distorting the load voltage. For switch mode power supplies, a significant third harmonic in the load voltage will cause flat-topping of the waveform, resulting in a lower capacitor voltage to be used by the switcher and load. This will cause a decrease in device ride-through for voltage sags. Other issues may include incompatibility of the load or other loads subjected to the distorted voltage, such as, for example, some UPSs. Whether or not the voltage distortion resulting from the use of the NCF is detrimental to device operation requires investigation on a case-by-case basis, but certainly deserves consideration before applying this type of filter.

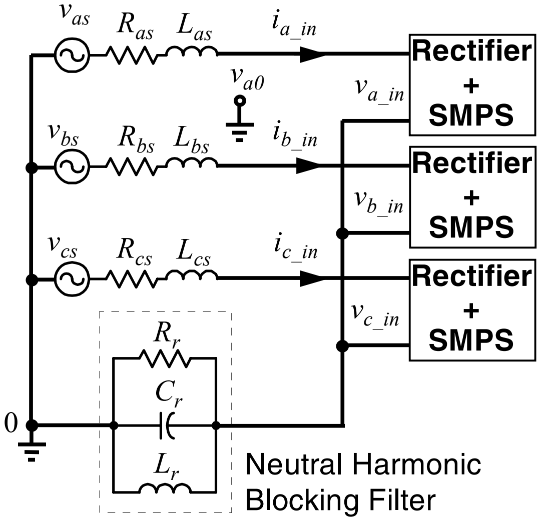


Figure 2-8
Circuit Diagram Of A Neutral Current Blocking Filter

Zigzag Filter (ZZF)

A special zigzag canceling-type auto-transformer (ZZF) is practical in canceling triplen harmonic currents from single-phase loads. The ZZF employs a three-phase auto-transformer to cancel the triplen harmonic currents and reduce the upstream neutral currents, as shown in Figure 2-9. Because all the triplen harmonic currents (zero sequence currents) are added in the neutral and flowing from load-side back to source-side neutral, the parallel-connected auto-transformer can provide a zero-sequence current path to trap and cancel the triplen harmonics.

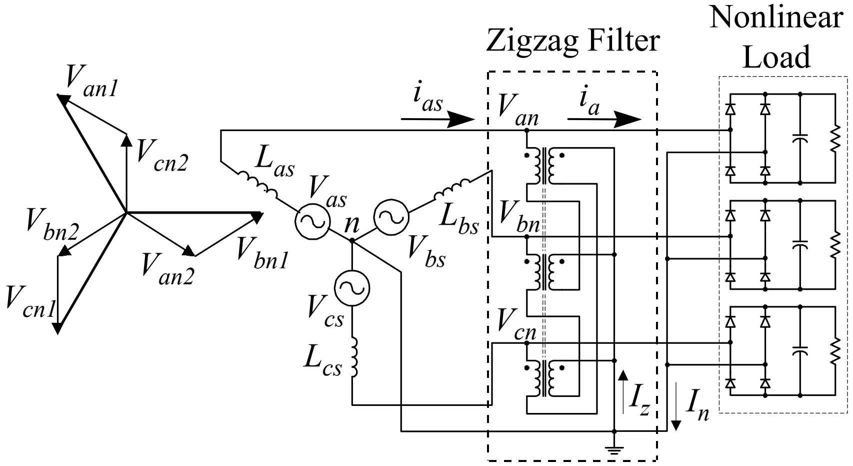


Figure 2-9
A Typical Zigzag Auto-transformer Showing Connections to Three Single-phase Non-linear Loads

Active Power Filter (APF)

Active filters can be applied at the load or at the panel level. Figure 2-10 shows a three-phase active filter containing a series filter to compensate voltages and a shunt filter to compensate currents.

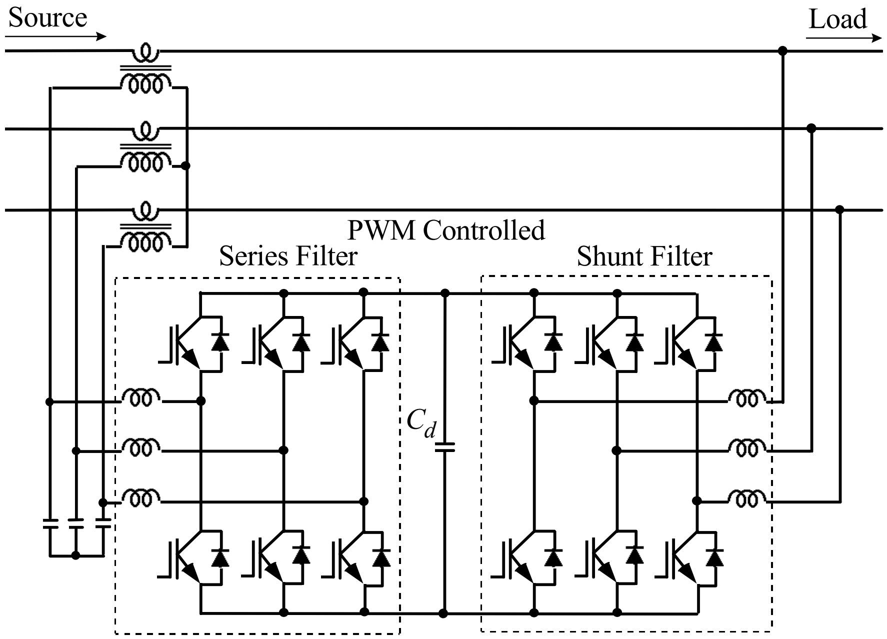


Figure 2-10
A Power Line Conditioner Containing Series and Shunt Active Filters for Harmonic Voltage and Current Compensation

When an individual shunt or series filter is applied, interactions between the filter and the load must be considered. The most commonly used APF has been the shunt-type filter. However, the *shunt* filter is only effective to harmonic current sources such as current source converters. On the other hand, the *series*-type APF is only effective to harmonic voltage sources such as the rectifier-interfaced voltage source converters.

The reason for this restriction on the shunt active filter is that the impedance of the load must be much larger than that of the source in order to be effective. (This is not the case for diode rectifiers with filter capacitors downstream.) However, a choke of approximately 6% can be used to effect this impedance ratio. This will increase the effectiveness of the shunt filter for these loads.

In the case of the series active filter, the load impedance must be much smaller than that of the source to be effective. Therefore, the series filter can't be used for controlled rectifiers with large DC inductance. However, if a passive filter is installed just upstream of the load, its effective impedance at the frequencies of interest will be much smaller than the source, and the series filter can be used.

Another common configuration for active filters is the shunt-type with passive interface filter, as shown below.

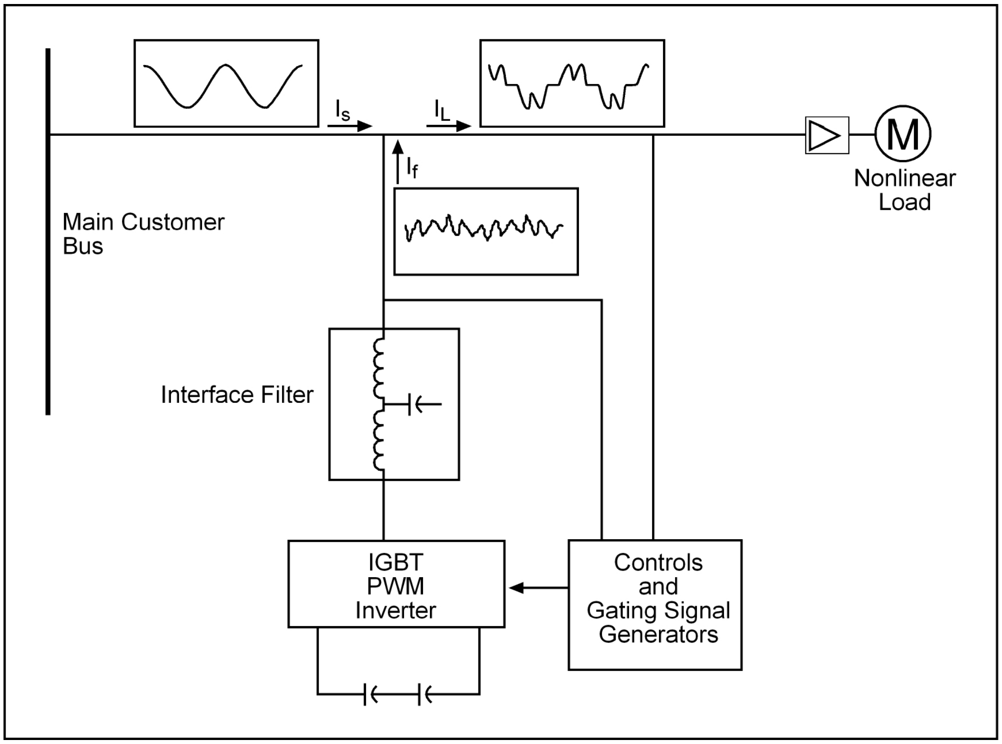


Figure 2-11
Shunt Active Filter with Passive Interface Filter

The passive interface filter consists of two series inductors and a capacitor used for isolation and to convert the inverter output voltage to a current for harmonic compensation. One of the main application issues of the passive interface filter is the limit on the derivative of the inductor current. The inductor di/dt is limited by the voltage across the inductor. The reason this is an issue is that it places a limit on the types of waveforms that can be compensated. The faster the risetime of the load current waveform, the more difficult it may be for the filter to adequately compensate for the harmonic content. Therefore, there will be an engineering tradeoff on the size of the inductor, between the degree of isolation provided and the limit on the rate of change of current.

Another area of concern with this type filter involves voltage transients. These can be caused, for instance, by capacitor switching on the power system. There is a possibility of transient magnification at the passive interface filter. In such cases, the transient voltage across the passive filter capacitors exceeds the voltage across the DC capacitors, and the driving signals for the inverter will be turned off. Active filter current can be affected by these transients, but the inverter transistors are not gating, so the main effect will be on the snubber diodes around the transistors.

Series Inductor Filter

An inductor in series with the PC power supply can restrict sudden changes in current, smoothing out the waveform, and reducing the peak value of current, as would any series impedance. The rectifier circuit operates in the same way except the harmonic content and the peak current are reduced.

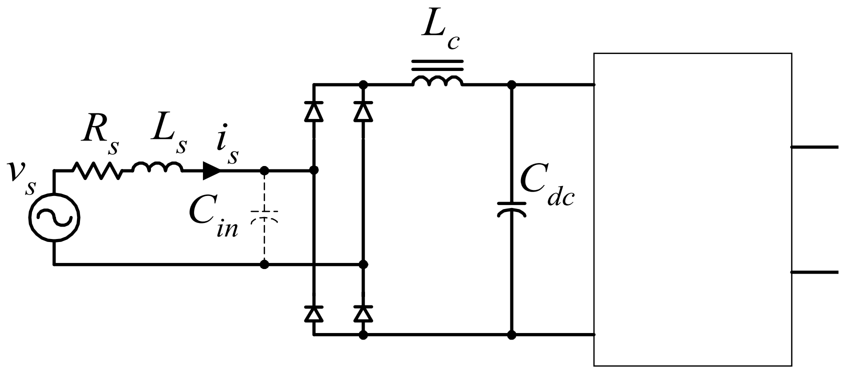


Figure 2-12
Series Inductor used for Single-phase Loads

Three-Phase Choke (Inductor)

The inductor filter can also be used on three phase loads. The harmonic content in the line current for AC and DC drives can be significantly reduced by installing a 3% to 5% line reactor upstream of the drive. The percent impedance is based on the base impedance calculated from the drive rating. It should be noted that if the drive is severely underloaded, say by 50%, the percent impedance of the reactor should be based on the load rather than the drive rating. This is because the impedance rating is actually an indication of the voltage drop across the inductor at rated current. If a 100 Hp drive is controlling a 50 Hp motor, then the voltage drop will only be a function of the 50 Hp line current, as opposed to the 100 Hp rating. In order to properly size the reactor, the simplest approach is to consult the reactor vendor, supplying them with drive and load size. Another point to consider is that some drive vendors supply their drives with the line reactor installed. The best approach would be to make sure this is included in the specification of a new drive. Use of a line reactor upstream of an AC drive (or built-in to it) can reduce the line current THD by a factor as high as two. 2-13 and 2-14 below illustrate this improvement.

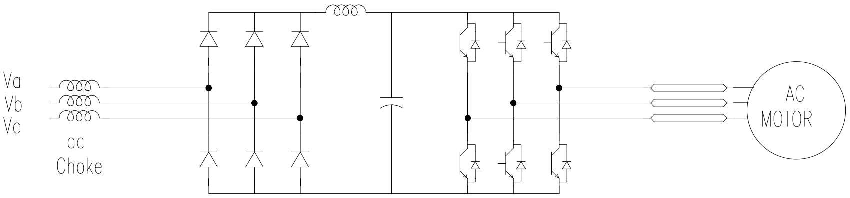


Figure 2-13
ASD with AC Choke at Input

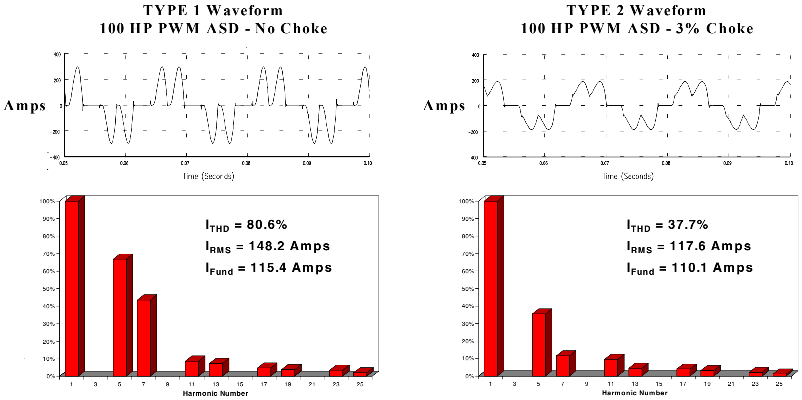


Figure 2-14
ASD Current and Spectrum with and without Choke

Boost converter with power factor correction

The boost converter is also called a "step-up converter" which converts low dc voltage to high dc voltage. Figure 2-15 shows a power supply containing a front-end boost converter. The switch *S* controls energy flow. When *S* turns on, a current builds up on the inductor L_s; meanwhile the diode *D* remains in the reverse blocking mode because the on-state of *S* means a zero voltage across. When *S* turns off, the energy stored in the inductor charges through the diode *D* to the capacitor C_s. The inductor current can be controlled to follow a desired wave shape. In a power factor correction circuit, the inductor current is normally controlled to follow the rectified voltage, and the ac-side current will be in phase with the ac voltage.

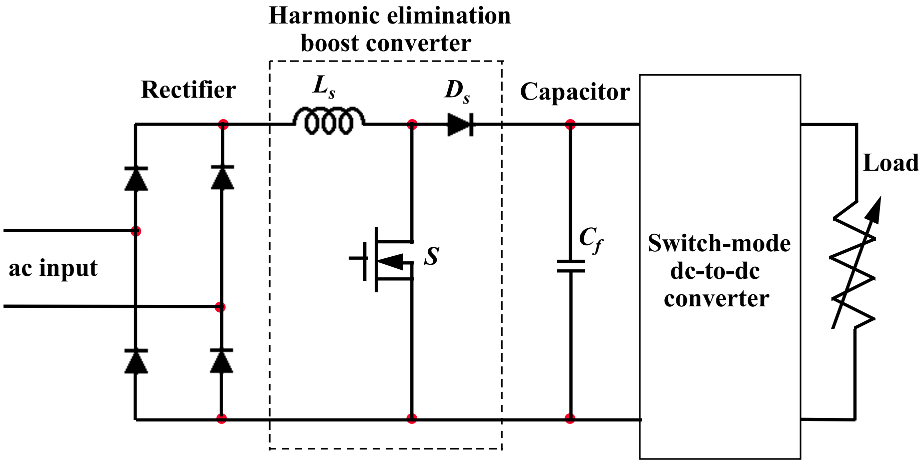


Figure 2-15
SMPS with Boost Converter

Parallel Connected Resonant Filter (PCRF)

This filter is usually configured as a plug-in convenience outlet and serves two to four electronic devices. As such, it is used as a plug-and-play device that requires no engineering in its application. Figure 2-16 shows the circuit diagram of a commercially available PCRF. The impedance of this network is zero at resonance, and thus shunts the selected harmonic current back to its source, which is the load. As a result, the harmonic current is not injected into the source. The values of inductor and capacitor dictate the resonant frequency, so to filter third harmonic, the device is tuned to 180 Hz.

In a typical power system, the source voltage may contain a small amount of third harmonic due to other nonlinear loads. This source harmonic voltage may excite the resonant branch and result in an overloaded third harmonic current. Thus, a series inductor, L_f, is normally added to detune the PCRF resonant frequency on the supply-side. The only restriction that might be considered is the power consumption of the filter itself, and the added reactive power requirement that it brings to the circuit.

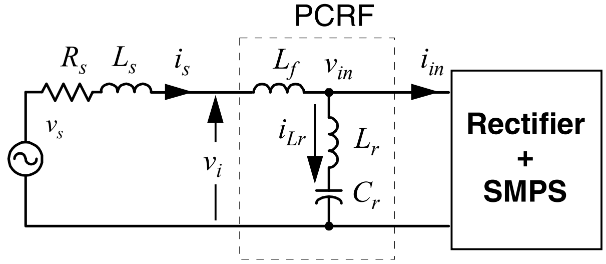


Figure 2-16
Circuit Diagram of a Parallel Connected Resonant Filter

Series Connected Resonant Filter (SCRF)

Unlike the PCRF that traps the third harmonic current, the function of the SCRF is to block the third or other harmonic currents. With a typical rating of 6 amps, it is available as a plug-in filter that serves several other electronic devices.. To block the third harmonic, the SCRF employs a single-tuned paralleled LC circuit whose impedance approaches infinity at the third harmonic frequency. The multi-tuned SCRF connects several tuned filters in series to block more harmonics. Figure 2-17 is a double-tuned SCRF containing a third harmonic tuned LC circuit, L_{r3} and C_{r3}, and a high frequency tuned LC circuit, L_{rh} and C_{rh}, to eliminate high-order harmonics.

One issue that should be considered in applying an SCRF is that the blocking action of the filter means that there will be a sizable voltage drop across the filter at the blocked frequency. Ultimately this means there will be more distortion in the load voltage than without the filter, so the current distortion can be reduced, but at the expense of distorting the load voltage. For switch mode power supplies, a significant third harmonic in the load voltage will cause flat-topping of the waveform, resulting in a lower capacitor voltage to be used by the switcher and load. This will cause a decrease in device ride-through for voltage sags.

Other issues with SCRF applications may include incompatibility of the load or other loads subjected to the distorted voltage. Whether or not the voltage distortion resulting from the use of the filter is detrimental to device operation requires investigation on a case-by-case basis, but certainly deserves consideration before applying this type of filter. Since this is a plug-and-play type device which requires no engineering to apply, this issue could easily slip by the user.

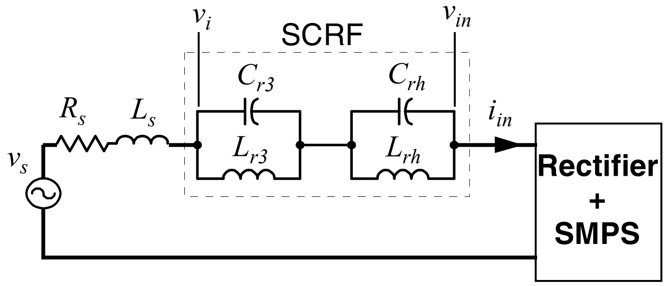


Figure 2-17
Circuit Diagram of a Series Connected Resonant Filter

Three-Phase Passive Harmonic Filter (Trap)

The three-phase passive harmontic filter is a very common configuration in industrial systems, and can be used at the load, panel, or even at the service entrance if necessary, to reduce distortion levels. Depending on the mix of nonlinear loads in a facility, it may be more economic to place the passive filter at the panel supplying many loads, if the nonlinear load is concentrated at one panel or bus. If one or a few loads are causing most of the problem, then the passive filter can be placed at the load and be cost effective.

Passive filters are based on power factor correction capacitors which are tuned to a particular frequency in order to trap the current component at that frequency. This is very effective for single frequencies, and multiple stages can be used for more than one frequency. Tuning is accomplished by choosing inductors such that the bank becomes resonant at the frequency of interest. This creates a notch (zero) in the filter's impedance frequency response and a peak (pole) just below that frequency. A plot of this frequency response is shown below, along with the filter configuration.

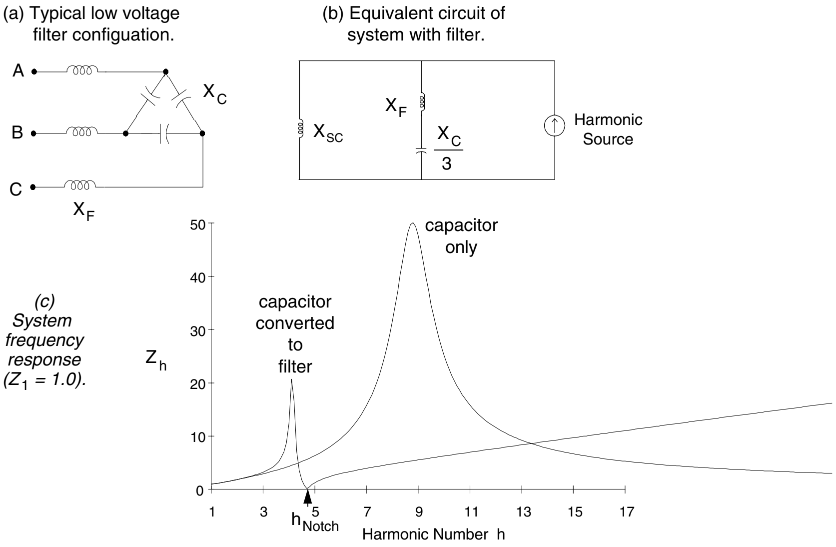


Figure 2-18
Filter Configuration and Frequency Response of Tuned Passive Filter

The filter actually should be tuned just below that frequency to ensure that any component drift will not cause the new peak to drift toward the dominant injected frequency. Components must be chosen to withstand expected voltages and currents. There will be a voltage rise across the inductor, so the capacitor must be chosen to withstand more than nominal line voltage. In addition, the filter must be specified so that harmonic current from the load as well as from the source is acceptable. Therefore, background harmonics from the source must be taken into account.

Passive filter specifications begin with the reactive compensation requirements of the load. This should be based only on the fundamental frequency, or displacement power factor. Whatever improvement is needed for this parameter will dictate the size of the capacitor bank. Tuning is then performed with the inductor.

One very important point to consider in this application is that AC PWM drives have a displacement power factor very close to unity. Therefore, no reactive compensation is necessary; only the current distortion needs to be considered. However, this makes it difficult to use a passive filter for harmonic control at AC drive terminals. In such a case, the capacitor values should be chosen as small as possible to reduce cost and minimize reactive power requirements added by the filter.

Three-Phase Low Pass Broad Band Filter

At least one vendor is promoting a low pass configuration that will allow only frequencies below 100 Hz to pass. With the cutoff frequency at 100 Hz, all the harmonic components of current expected in commercial/industrial settings will be attenuated. A schematic is shown below.

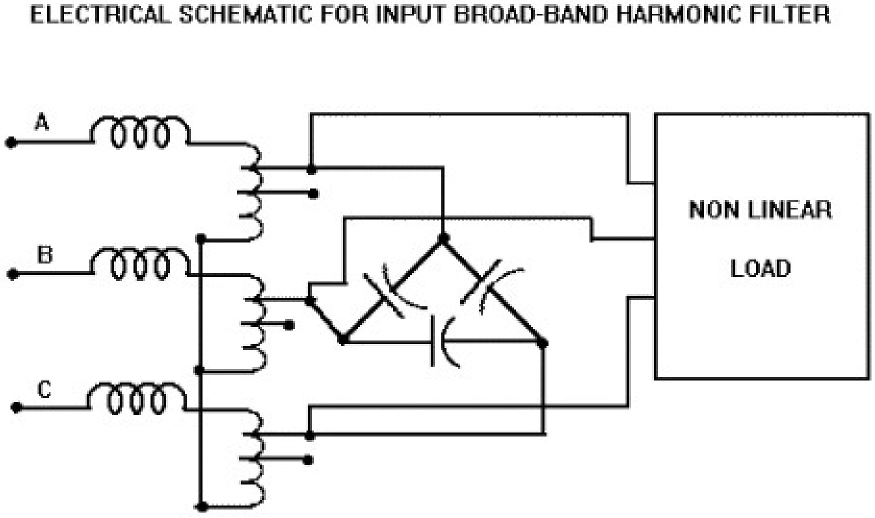


Figure 2-19
Low Pass Broad Band Filter

In this application, capacitors can cause an overvoltage at the load terminals. As an example, if a low pass broad band filter were applied at the terminals of an ASD with a diode bridge rectifier, then the voltage across the capacitors could be high enough to cause an overvoltage fault in the drive. Therefore the filter is often configured with a buck transformer on the source side to reduce the voltage across the capacitors for ASD applications. This configuration is shown in Figure 2-19.

Another consideration is system interaction. Many passive filters must be detuned from the rest of the system or derated to ensure they can withstand background harmonics from the system. With the low pass configuration, it is far less likely that any existing harmonics will affect the filter, since there is a cutoff frequency of 100 Hz.

Active Front-End Design for Adjustable Speed Drives

Three-phase PWM active rectifiers, used in newer VSI AC drives, have several advantages over passive, diode bride rectifiers. They provide for reduced low-order current harmonics, line-regenerative capabilities, and improved voltage sag and transient ride-through. A diagram of a three-phase active rectifier in a VSI AC drive is shown in Figure 2-20.

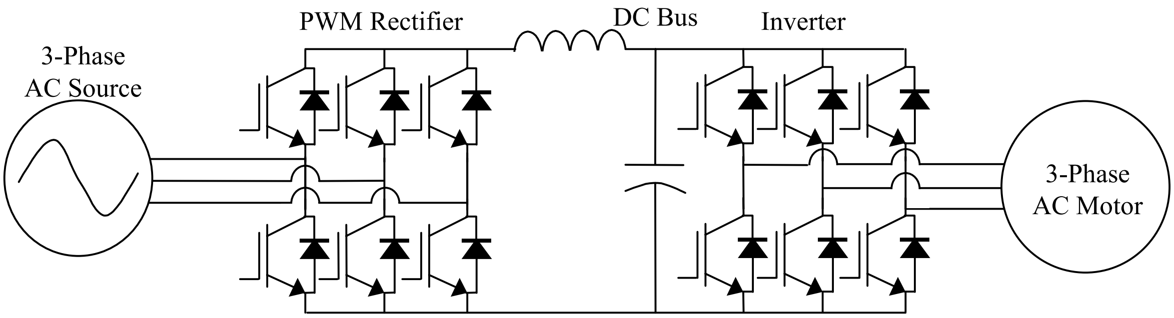


Figure 2-20
PWM Active Rectifier in a VSI AC Drive

During voltage sag conditions, the PWM active rectifier can be operated as a boost regulator to maintain the drive's DC bus voltage. Derating of the IGBTs and diodes in the rectifier must be considered to allow for increased currents during ride-through. With proper derating, the PWM active rectifier can provide full-power ride-through for sags down to 50% of nominal.

This boost regulator capability allows for harmonic control in the same fashion as the boost converter in the switch-mode power supply. This can reduce the harmonic injection by the drive considerably.

3

GUIDELINES FOR MANAGING HARMONICS PROBLEMS ON UTILITY DISTRIBUTION SYSTEMS

Interaction of Customer Harmonic Loads with Utility Distribution System

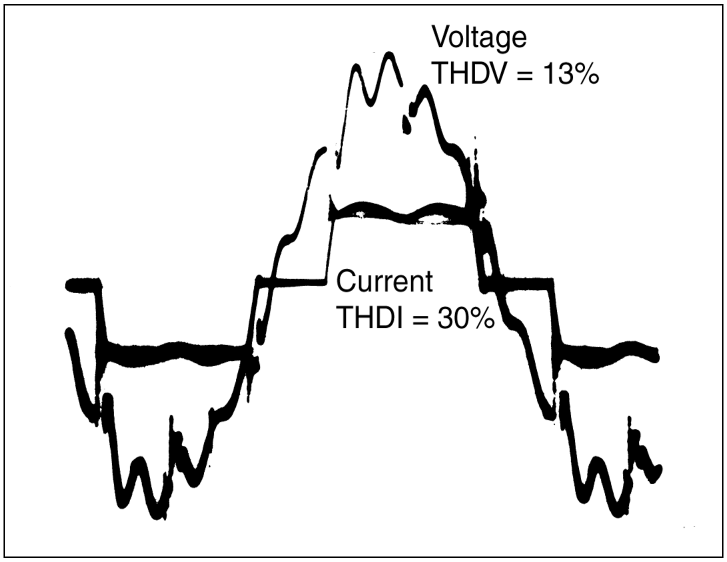
Harmonics-related problems on electric utility distribution systems are usually created by primary-metered customers. Typically, these problems are due to 500kVA (and larger) ASDs or induction heaters. In weaker systems, or near the end of long feeders, 100 – 200kVA nonlinear loads may be sufficiently large to create problems. The significant harmonics are almost always 5th, 7th, 11th, or 13th, with the 5th harmonic being the problem in most instances.

Classic utility-side symptoms of harmonics problems are distorted voltage waveforms, blown capacitor fuses, and transformer overheating. Capacitors are sensitive to harmonic voltages. Transformers are sensitive to harmonic currents.

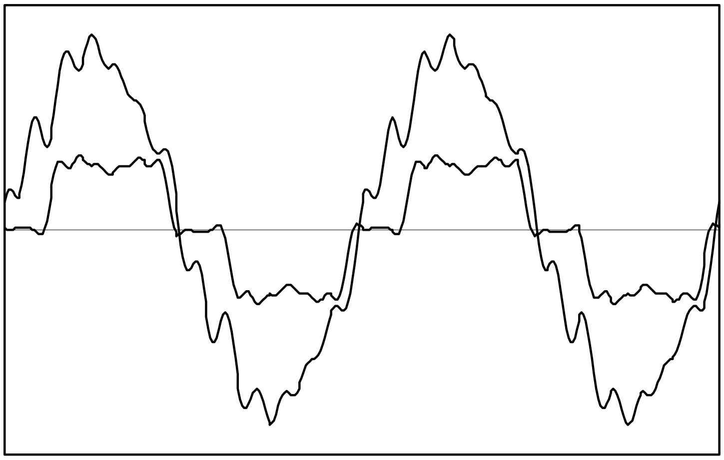
Typical utility-side symptoms of harmonics problems are described in the following sections.

Resonance

Consider the resonant case shown in Figure 3-1, where the rectangular current injection of a 5000HP six-pulse current-source ASD produced voltage resonance on a 25kV distribution system. The 13% THD_V caused nuisance tripping of computer-controlled loads, and the 30% THD_I distortion caused overheating of parallel 25kV/480V 3750kVA transformers that supplied the ASD. The dominant voltage harmonics are the 13th (8.3%), and the 11th (7.0%).



Oscilloscope Image of Six-Pulse LCC Current Waveform and the Resulting Voltage Resonance (courtesy of Mr. Bobby Carroll, TXU Electric)

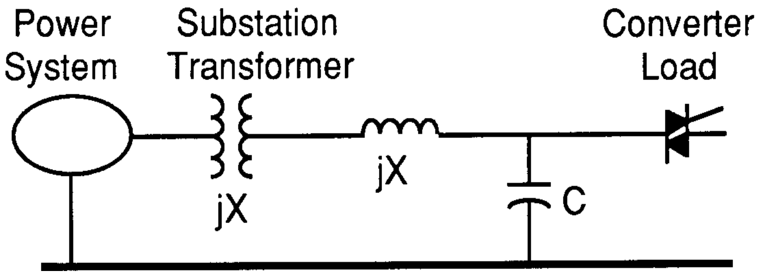


Fourier Series Reconstruction Using Harmonics through the 17th (Although the phase angles were not recorded, they were manually adjusted in the plotting program to match the oscilloscope waveshapes.)

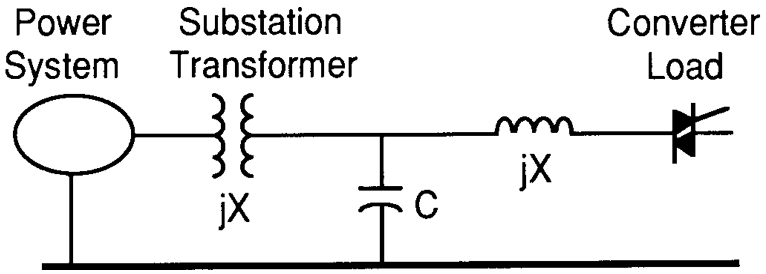
Figure 3-1
Resonance Due to 5000HP Six-pulse Line-commutated ASD

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.

To better understand resonance, consider the simple parallel and series cases shown in the one-line diagrams of Figure 3-2. Parallel resonance occurs when the power system presents a parallel combination of power system inductance and power factor correction capacitors at the nonlinear load. The product of harmonic impedance and injection current produces high harmonic voltages.



Parallel Resonance (High Voltage Distortion at Converter Load, Low Voltage Distortion at Points Down the Feeder)



Series Resonance (Low Voltage Distortion at Converter Load, High Voltage Distortion at Points Down the Feeder)

Figure 3-2
Simple Examples of Parallel and Series Resonance

Series resonance occurs when the system inductance and capacitors are in series, or nearly in series, from the converter point of view.

For parallel resonance, the highest voltage distortion is at the nonlinear load. However, for series resonance, the highest voltage distortion is at a remote point, perhaps miles away or on an adjacent feeder served by the same substation transformer. Actual feeders can have five or ten shunt capacitors, so many parallel and series paths exist, making computer simulations necessary to predict distortion levels throughout the feeder.

In the simplest parallel resonant cases, such as an industrial facility where the system impedance is dominated by the service transformer, shunt capacitors are located inside the facility, and distances are small. In such cases, it is possible to use a simple parallel resonance approximation formula (3-1) below.

$$f_{res} = f_o \sqrt{\frac{MVA_{SC}}{MVA_{CAP}}} \tag{3-1}$$

Thus, “stiff systems” (i.e., relatively high MVA_{SC}) have higher resonant frequencies. When capacitors are added, the resonant frequency is lowered.

The risk of using (3-1) is that it represents only a small part of the true harmonics situation. Three important points to remember are:

1. While Equation 3-1 predicts a resonant frequency, it gives no information about the broadness of the resonant curve. Thus, if a system is resonant at, for example the 6th harmonic, one might innocently conclude there is no harmonics problem. However, due to the broadness of the resonance curve, the 5th and 7th harmonics will be greatly affected.
2. Anytime there are shunt capacitors, there are resonant frequencies. In fact, almost all distribution feeders are strongly resonant near the 5th and 7th harmonics. However, resonance is a problem only if there are sufficient harmonic amperes to excite harmonic voltages so that THD_v exceeds 5%.
3. Most utility distribution feeders have five or more capacitor banks, so that there are many parallel and series paths. Thus, computer simulations are required to accurately predict distortion levels through the feeder and adjacent feeders connected to the same substation transformer.

To illustrate the broadness of the resonance curve, consider the case shown in Figure 3.3. This curve represents the “driving point impedance,” or “Thevenin equivalent impedance” at the customer bus. The situation is simple parallel resonance. Note that as the amount of power factor correction is increased by adding additional kVArs, the peak of the resonance curve moves toward lower frequencies.

Figure 3.3 illustrates the following two important facts concerning resonance:

1. The resonance curve is very broad.
2. Typical power factor correction practices to the 0.95-0.98 DPF range will cause distribution feeders to resonate near the 5th and 7th harmonics.

Figure 3.3 is also useful in estimating the harmonic voltages that will exist at the customer bus. Consider, for example, the 0.95 power factor correction case. At the 5th harmonic, the driving point impedance is approximately 200% (i.e., 2 pu). If the converter load is 0.18 pu, then the 5th harmonic current will be (assuming the 1/k rule) $\frac{0.18}{5} = 0.036$ pu. The 5th harmonic voltage estimate is then $0.036 \bullet 2 = 0.072$ pu. Thus, a 5th harmonic voltage of 7.2% can be expected, meaning that the THD_V will be at least 7.2%. Of course, the THD_V will be higher after the contributions of the 7th, 11th, and 13th (and higher) harmonics are included.

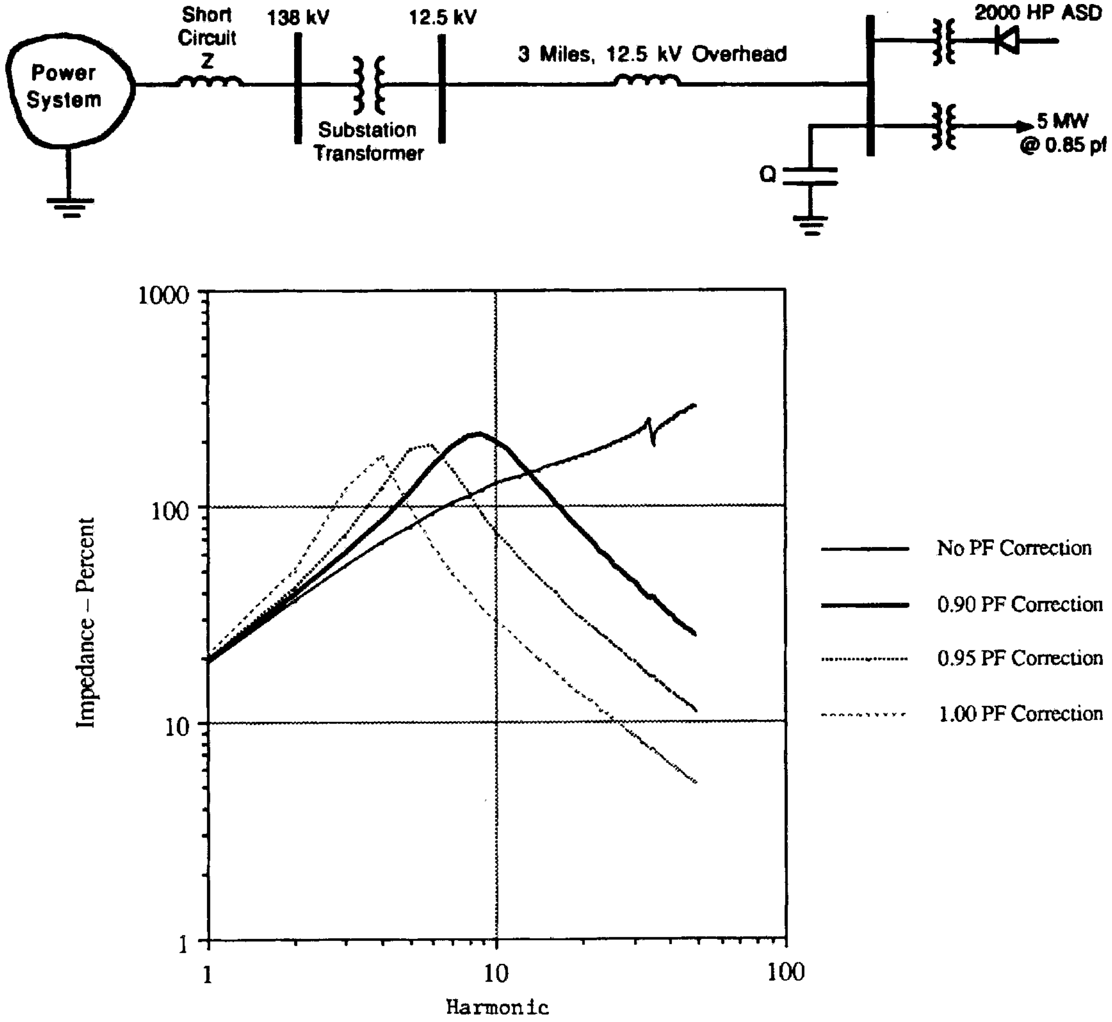


Figure 3-3
Thevenin Equivalent Impedance at Customer Bus

Nuisance Tripping of Sensitive Loads

Some computer-controlled loads are sensitive to voltage distortion. Although it is difficult to find reliable data on this subject, one case documented by Mrs. Diane Ammons and Mr. Scott Cryer, Reliant Energy – HL&P, showed that a THD_V of 5.5% regularly shut down computerized lathes at a large pipe company's heat treatment operation in Houston. While voltage distortions of 5% are not usually a problem, voltage distortions above 10% will cause significant nuisance tripping.

Blown Capacitor Fuses, Failure of Capacitor Cells, and Degradation of Internal Capacitance

A common harmonics-related complaint comes from capacitor crew foremen or other distribution feeder maintenance personnel who complain that "a capacitor bank has to be rebuilt often," "fuses on a capacitor bank blow regularly," "a capacitor bank hums," or "the capacitance of a bank is diminishing."

Harmonic voltages produce exaggerated harmonic currents in capacitors because of the inverse relationship between capacitor impedance and frequency. To illustrate this point, the measured current waveform of a 300kVAr, 480V bank at a commercial bank building is shown in Figure 3-4. The waveform is dominated by an 11th harmonic (23.3%). The principal distorting load in the building was a large UPS.

Capacitors with excessive harmonic currents often produce a loud humming noise. This is in part because the human ear is relatively insensitive to 60Hz, but quite sensitive to the 5th harmonic and above (i.e., 300 Hz and above).

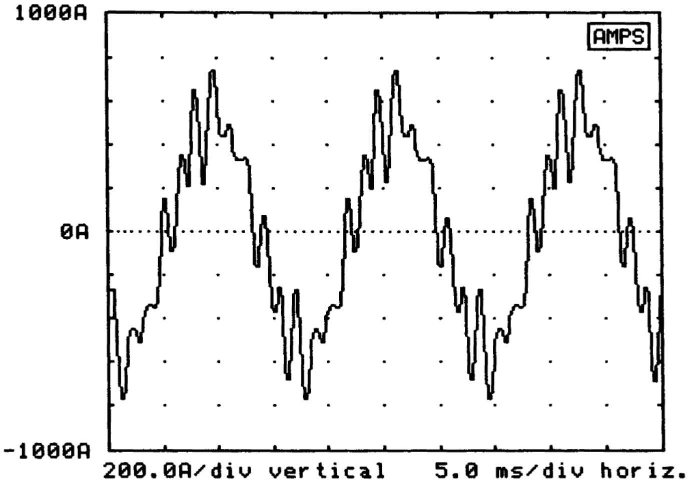


Figure 3-4
300 kVAr, 480V Capacitor Current Waveform at Commercial Bank Building (courtesy of Bob Almonte, Reliant Energy - HLP)

Since capacitor impedance varies according to $\frac{1}{j\omega C}$, then the impedance for harmonic k is $\frac{1}{jk\omega_o C}$, where ω_o is the fundamental radian frequency (e.g., 120π radians/sec for 60 Hz systems). Because of this inverse relationship, moderate harmonic voltages can produce large currents in capacitors. For example, if a capacitor has 10% voltage distortion due entirely to the 5th harmonic, the induced 5th harmonic current is $0.10 \bullet 5 = 0.50$ pu on the capacitor base. The corresponding rms current in the capacitor increases to $\sqrt{1^2 + 0.50^2} = 1.12$ pu times the fundamental current. A 10% 11th harmonic voltage produces an even greater rms current, 1.49 pu.

Now, consider an example where voltage distortion on a capacitor is assumed to be divided among six-pulse characteristic harmonics through the 25th, in inverse proportion to frequency. This assumption implies that the harmonic currents have equal magnitudes. Since the voltages are expressed in per unit of fundamental, the squared voltage THD is

$$THD_v^2 = V_5^2 + V_7^2 + V_{11}^2 + V_{13}^2 + V_{17}^2 + V_{19}^2 + V_{23}^2 + V_{25}^2 \ .$$

Because the harmonic voltages in this example are assumed to vary inversely with frequency, then

$$V_7 = V_5 \bullet \frac{5}{7},\ V_{11} = V_5 \bullet \frac{5}{11}, \text{ etc., so}$$

$$THD_v^2 = V_5^2 \bullet \left(1 + \frac{5^2}{7^2} + \frac{5^2}{11^2} + \frac{5^2}{13^2} + \frac{5^2}{17^2} + \frac{5^2}{19^2} + \frac{5^2}{23^2} + \frac{5^2}{25^2} \right),$$

$$THD_v^2 = V_5^2 \bullet 2.108 .$$

Taking the square root, $V_5 = \frac{THD_v}{1.452}$, then the current on the capacitor base is

$$I_5(pu) = 5V_5(pu) = \frac{5 \bullet THD_v}{1.452} \ .$$

Since all eight harmonic currents are equal, the total squared rms capacitor current, including fundamental, is

$$I_{rms}^2(pu) = 1^2 + 8 \bullet \left(\frac{5 \bullet THD_v}{1.452} \right)^2 = 1 + 94.9 \bullet THD_v^2 \ .$$

The square root of the above formula is used to compute rms currents for a range of voltage distortion values, and the results are given in Table 3-1.

Table 3-1
RMS Capacitor Current (in pu for harmonics through the 25th) versus Voltage Distortion (assuming that voltage harmonics decrease in proportion to frequency)

THD_v	RMS Capacitor Current Pu
0.00	1.000
0.05	1.112
0.10	1.396

Thus, it is reasonable to expect a 40% increase in capacitor rms current when voltage distortions are in the 10% range.

Capacitors may also fail because of overvoltage stress on dielectrics. A 10% harmonic voltage for any harmonic above the 3rd increases the peak voltage by approximately 10% because the peak of the harmonic often coincides, or nearly coincides, with the peak of the fundamental voltage.

Transformer Overheating that cannot be Explained by kVA Load Level Alone

Another common harmonic-related complaint is that "my transformer is only 70% loaded, but it is too hot to hold my hand on." These cases are usually limited to situations where the transformer serves a large nonlinear load.

There are two reasons for overheating:

1. Losses in a conductor increase when harmonics are present because losses are proportion to the square (at least) of rms current, and rms current increases with current distortion according to

$$I_{rms} = \sqrt{1 + THD_I^2} \quad . \tag{3-2}$$

2. Because of the resistive skin effect and winding proximity effect, one ampere of harmonic current produces more losses than does one ampere of fundamental current.

The impact of harmonic currents on transformers is more serious than on conventional conductors because the resistive skin effect is enhanced within closely-spaced transformer windings. Good engineering practice calls for the derating of transformers that serve nonlinear loads to an equivalent 80% of nameplate kVA.

To examine the rms current effect, consider a transformer that serves an ideal six-pulse converter with classical $\frac{1}{k}$ harmonic magnitude currents. In terms of the fundamental current $I_{1,rms}$, the squared rms current is

$$I_{rms}^2 = I_{1,rms}^2 \bullet \left(1^2 + \frac{1}{5^2} + \frac{1}{7^2} + \frac{1}{11^2} + \frac{1}{13^2} + \frac{1}{17^2} + \frac{1}{19^2} + \cdots \right). \tag{3.3}$$

The above infinite series converges to the form

$$I_{rms}^2 = I_{1,rms}^2 \bullet \frac{\pi^2}{9} = 1.0966\, I_{1,rms}^2 \ .$$

Since losses increase by the square of rms current, the winding losses automatically increase to at least 1.0966 times the fundamental-only case. Thus, if losses are to be held constant at their rated value so that transformer heating is not excessive, the rms current (and equivalent kVA rating) should be lowered to at least $\sqrt{\frac{1}{1.0966}}$ = 0.955 pu. of nameplate. If harmonics above the 25th harmonic are ignored, the equivalent kVA rating is 0.960 pu (i.e., practically the same as the infinite series case).

However, the major transformer derate comes from the resistive skin effect. The resistive skin effect occurs because higher-frequency currents migrate to the outermost portions of a conductor, increasing its equivalent resistance. For power transformers, this phenomenon is usually modeled by dividing resistance into two parts, a non-frequency dependent part and a frequency-dependent part. The frequency-dependent part is assumed to increase in proportion to the square of frequency, as given by

$$R_k = R_{DC} \bullet (1 + k^2 P_{EC-R}) \tag{3-4}$$

where R_k is the winding resistance at harmonic k, R_{DC} is the winding resistance at DC, and P_{EC-R} is the winding eddy current loss factor. P_{EC-R} ranges from 0.01 for low voltage service transformers with relatively small conductors to 0.10 for substation transformers having large conductors.

Since heating is proportional to squared current times resistance, the above variation can be incorporated into an equivalent rms current that takes into account skin effect. Incorporating (3-4) into (3-3) yields equivalent rms current

$$I_{rms,equiv}^{2} = I_{1,rms}^{2} \bullet \left(1^{2} + \sum_{k=5,7,11,13,\cdots}^{\infty} \frac{1}{k^{2}} \bullet \frac{(1+k^{2} \bullet P_{EC-R})}{(1+1 \bullet P_{EC-R})} \right). \tag{3-5}$$

The above series does not converge if $P_{EC-R} \neq 0$. Thus, it is appropriate only to discuss a finite number of terms, such as through the 25th harmonic. Using the square root of (3.5) to give the derate, and ignoring harmonics above the 25th, the equivalent kVA rating for a realistic range of P_{EC-R} is given in Table 3-2.

Table 3-2
Equivalent kVA Rating for Transformers Serving Six-pulse Loads

(ignoring harmonics above the 25th, and assuming that current harmonics decrease in proportion to frequency)

P_{EC-R}	Equivalent kVA Rating pu
0.00	0.960
0.02	0.928
0.04	0.900
0.06	0.875
0.08	0.853
0.10	0.833

End-User Symptoms

Symptoms experienced by end-users *due to distortion on the utility system* include the utility symptoms described above, plus the items described in next sections below.

Digital Clocks Gaining Time

Digital clocks work off the principle of counting zero crossings or slope changes in the 60Hz fundamental voltage. There may be some filtering present in the clock circuitry, but if voltage harmonics are strong enough, then it is possible to have multiple zero crossings or slope changes that cause the clocks to run fast. Older digital clocks are reported to be the most sensitive to voltage harmonics.

An example of a voltage waveform that was responsible for this phenomenon is shown in Figure 3-5. The waveform has a 2%, 36th harmonic.

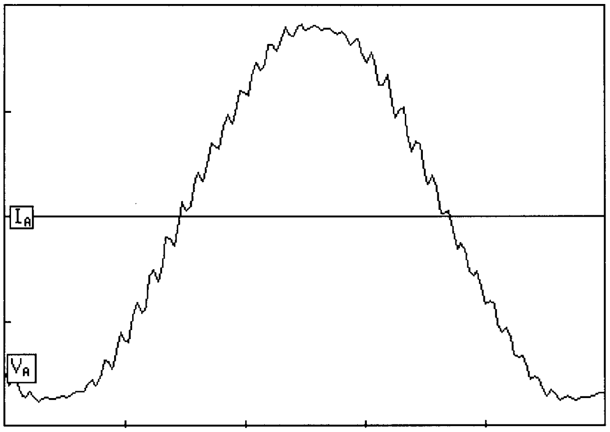


Figure 3-5
Voltage Waveform that Caused Digital Clocks to Gain Time (courtesy of Mr. Dennis Hansen, PacifiCorp)

Telephone Interference

Telephone interference has been a harmonics-related concern for many decades, but the gradual phasing out of open-wire telephone circuits has reduced the number of interference problems. While the frequency response of the combined telephone circuit and human ear is largely immune to 60 Hz interference, higher harmonics fall into the low-audio range.

When harmonic currents on power lines inductively couple into nearby phone lines, they can cause significant interference. Typically, the problem harmonics are either characteristics six-pulse harmonics due to large converters, or 9th and higher multiples of three (i.e., zero sequence) due to transformer saturation. All things being equal, zero sequence harmonics are more problematic than positive and negative sequence harmonics because a-b-c zero sequence fields are additive and, therefore, do not decay as rapidly with distance.

The telephone influence factor (TIF) curve shown in Figure 3-6 gives the relative interference weighting that applies to inductively-coupled harmonic currents flowing in power lines.

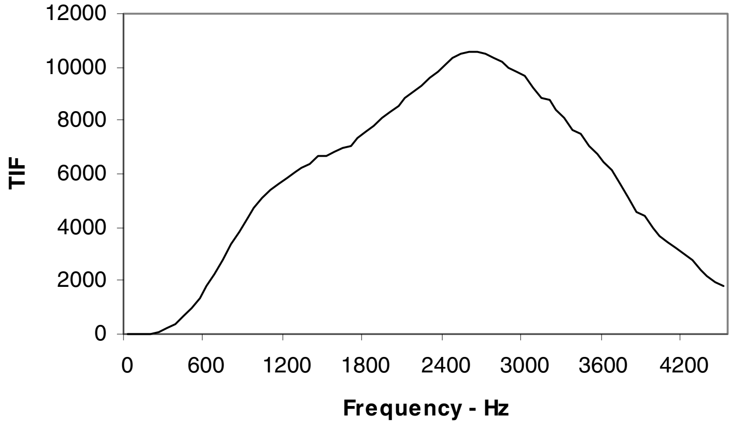


Figure 3-6
Telephone Influence Factor (TIF) Curve

Telephone interference problems are usually solved by the telephone company in cooperation with the electric utility involved. Solutions are often trial-and-error and usually consist of moving or disconnecting capacitors banks that have high harmonic currents, or placing tunable reactors in the ground path of wye-connected capacitor banks that have high harmonic currents. The tuning reactors are invisible to positive and negative sequences, but they can change the zero-sequence resonant frequency of a distribution feeder and often eliminate the resonance problem.

Motor Heating

For frequencies higher than fundamental, three-phase induction motors can be approximated by positive/negative shunt impedances

$$Z_k = R_{winding} + jkX'' ,$$

where $R_{winding}$ is the motor winding resistance, and X'' is the fundamental frequency subtransient reactance (typically 0.20 pu on motor base). Since most motors are three-wire delta or ungrounded-wye connected, motors appear as open circuits to zero sequence harmonics.

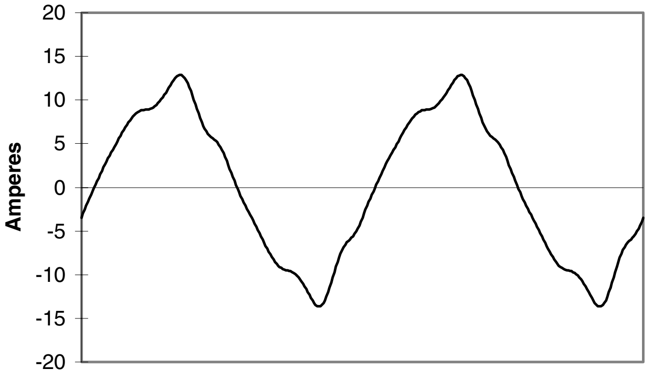
Assuming $X^{"} = 0.20$, relatively small $R_{winding}$ with respect to $kX^{"}$, and a 5th harmonic voltage of 10%, the induced 5th harmonic current will be

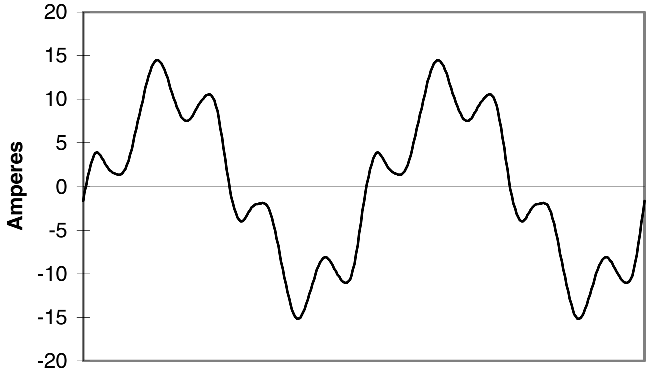
$$I_{5,rms} = \left| \frac{0.10}{5 \bullet 0.20} \right| = 0.10 \text{ pu on the motor base.}$$

Thus, harmonic voltages can create additional rotor winding currents and increase the $I^2 R_{winding}$ losses in three-phase motors by several percent.

High efficiency single-phase induction motors are more sensitive to voltage harmonics than are three-phase motors. Auxiliary parallel windings with series-run capacitors create a quasi-sinusoidal flux wave to improve efficiency. The series auxiliary winding inductance and run capacitor create a series resonant path in the 4th – 11th harmonic range.

To illustrate this phenomenon, current waveforms for a 2HP, 230V, fully loaded motor were measured, with and without significant 5th harmonic voltage applied. Waveforms for both cases are shown in Figure 3-7. The strong 5th harmonic current causes additional heating and produces noticeable audible noise.





Applied 5th Harmonic Voltage = 5.4%. Resulting THD_I = 34.0%.

Figure 3-7
Sensitivity of Fully Loaded 2HP, 230V Single-phase High-efficiency Induction Motor Current to 5th Harmonic Voltage (courtesy of Dr. Ewald Fuchs, University of Colorado at Boulder)

Conducting a Power Quality Investigation to Identify Harmonic Sources

Electric utility engineers may be confronted with harmonic problems on their own distribution feeders, or within customer facilities. Distribution feeder cases are the most difficult to deal with, since a large harmonics source can pollute the voltage waveform for many miles, including adjacent feeders connected to the same substation transformer. Customer facility cases are the simplest to investigate because 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 distribution feeder problems where the combination of harmonic current injection and resonant networks act together to create objectionable harmonic levels. Such investigations should include the following:

- Field measurements should be taken to identify the source of the harmonics.
- Identify all capacitor banks in local system.
- Identify any existing filters in system.
- Identify large (>= 500 kVA) customer loads in vicinity.
- Measurements should be taken at that customer's metering point.
- If necessary, take measurements at successive points in the system, such as the cap banks, to track down the source of the harmonics.
- If possible, capacitor banks should be turned off during measurements to prevent resonance from clouding the measurements.

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 500kVA (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 (e.g. 1500Hz 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. These 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. While there is debate on the subject, most power quality engineers believe that harmonic power is a good indicator of the source of harmonics. 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, further confirming that the harmonics source is inside the customer's facility. The 5th harmonic usually has the largest harmonic power.

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. Using voltage and current, net harmonic power can be calculated. The expectation is that the net harmonic power flows away from the source.

A wire loop (i.e. "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. The search coil has been used for decades by telephone companies to detect the presence of high harmonic currents. While the search coil gives no power or voltage information, it is useful because large harmonic currents exist on either 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 problems in advance. For example, if a customer desires to add a 5000 Hp ASD, then a study is needed in advance so that problems can be resolved before the ASD is installed. A harmonics study proceeds in much the same way as a loadflow, short circuit, or motor starting study.

Unless a distribution system is badly unbalanced, or there is a very large single-phase harmonics-producing load such as an electric train, harmonics analysis can usually be performed using the balanced assumption. The reasons are as follows:

- Most problem-causing loads are large three-phase balanced loads such as ASDs.
- Distribution capacitors are usually applied in the form of three-phase banks, having a balancing effect on harmonics propagation.
- 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 in advance, so that not all of the actual data are available.

In spite of these difficulties, experience has shown that distribution feeder harmonic simulations match “real world” measurements very well, and that simulation is a reliable tool for studying solutions such as passive filtering. The term “accurate” 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 study all the feeders 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. Transmission line capacitance 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, or the model can be an RL network, to include any necessary reactance.

5. The worst-case for harmonics is usually when the harmonics-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. 100 kVAr is a good rule for being "important." The capacitance of power cables is approximately 125pF per meter per phase.

8. When the system has multiple sources operating at various power levels (i.e., 10 or more sources), then it is important to consider harmonics cancellation brought about by phase angle diversity. The simplest way to consider diversity is to multiply the harmonic injection currents for each load by the following:
   - 3rd harmonic, multiply by 1.0 (i.e., no diversity)
   - 5th and 7th harmonics, multiply by 0.9
   - 11th and 13th harmonics, multiply by 0.6
   - Higher harmonics, multiply by 0.2

There are two basic techniques for performing harmonics studies – 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 studies 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 by constructing a three-mile 12.5kV overhead feeder from a dedicated 138/12.5kV substation transformer. The customer will have 5MW @ *dpf* = 0.85 of conventional load and a 2000Hp, six-pulse adjustable-speed drive (ASD). The customer also has 1800kVAr of shunt power factor correction capacitors.

The 138kV substation bus has the following characteristics:

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

The dedicated substation transformer has the following characteristics:

- $P_{base} = 15MVA$
- 138kV delta / 12.5kV grounded-wye connection

- 0.95 per unit tap on the 138kV side
- $Z^+ = 0.5 + j10.5\%$ (on 15MVA 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.

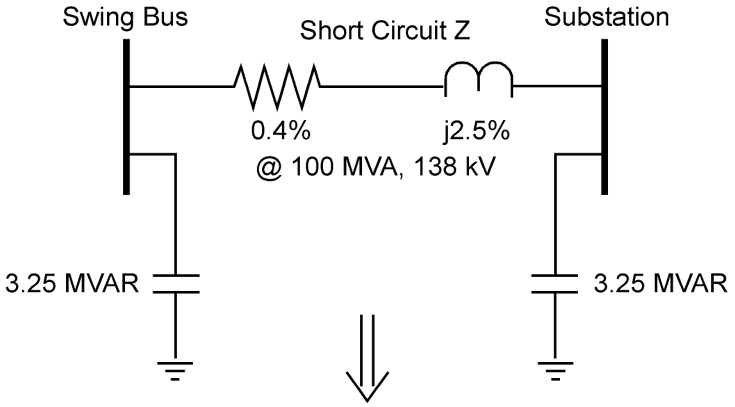
The conventional load transformer is rated at 7.5MVA and has $Z^+ = 0.50 + j5.0\%$ (on 7.5MVA base).

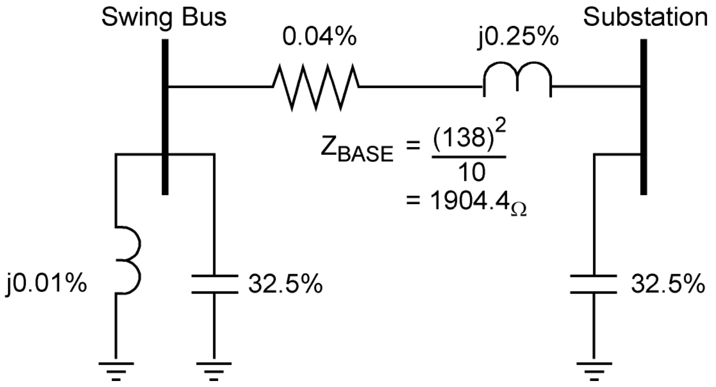
Once the data have been gathered, the next step is to draw a one-line diagram with all impedances and loads expressed on a common base. The base values are selected as 10MVA throughout, and 12.5kV on the feeder section. The voltage base varies throughout the circuit according to nominal transformer turns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

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

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

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

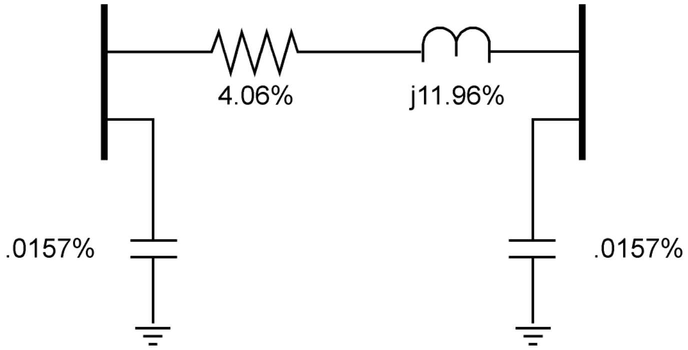
$Z_{BASE} = (12.5)^{2} / (10) = 15.625\Omega$

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

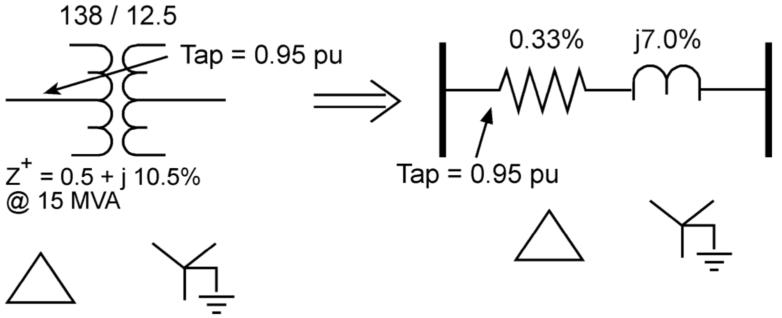
$$= 3.144\ \text{kVAr} = 0.03144\ \%\ @\ 10\text{MVA}$$

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

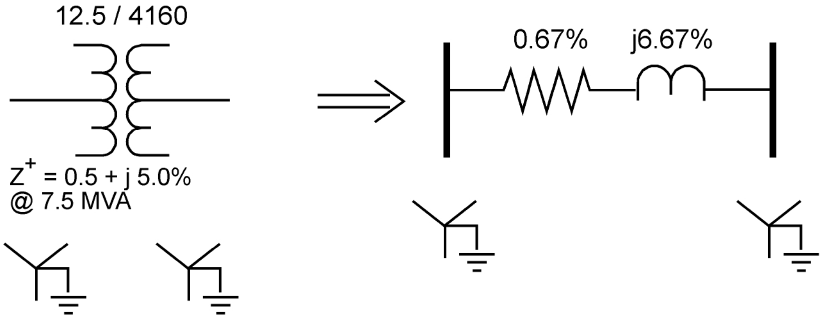
$$X_{pu} = \frac{1.869}{15.625}(100) = 11.96\%$$



For the substation transformer,



For the conventional load transformer



The 1800kVAr of shunt power factor correction capacitors becomes 18% on a 10MVA base.

The final one-line diagram is shown in Figure 3-8.

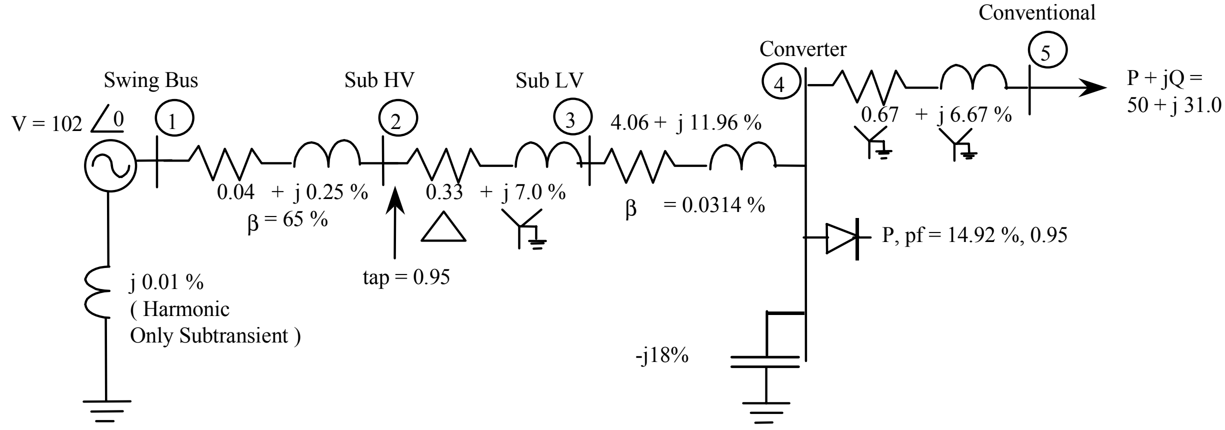


Figure 3-8
System One-line Diagram for Five-bus Example

Application Issues Regarding Harmonic Mitigation Equipment

Passive Filters

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 in 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 (i.e., 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 power factor correct 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.

Since a filter capacitor usually experiences 1.2 to 1.3 pu rms voltage, plus significant harmonics, care must be taken that the capacitor voltage rating is adequate. The fact that kVArs decrease by the square of voltage must also be taken into consideration.

To illustrate filter design, the five-bus system is modified by converting the 1800kVAr capacitor bank into a 4.7th harmonic filter. First, a new bus (#6) is created, and the 1800kVAr capacitor bank is moved from Bus 4 to Bus 6. In reality, the 1800kVAr bank would be replaced with a higher-voltage rated bank, with sufficient kVArs so that it produces 1800kVAr 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 below in Figure 3-9.

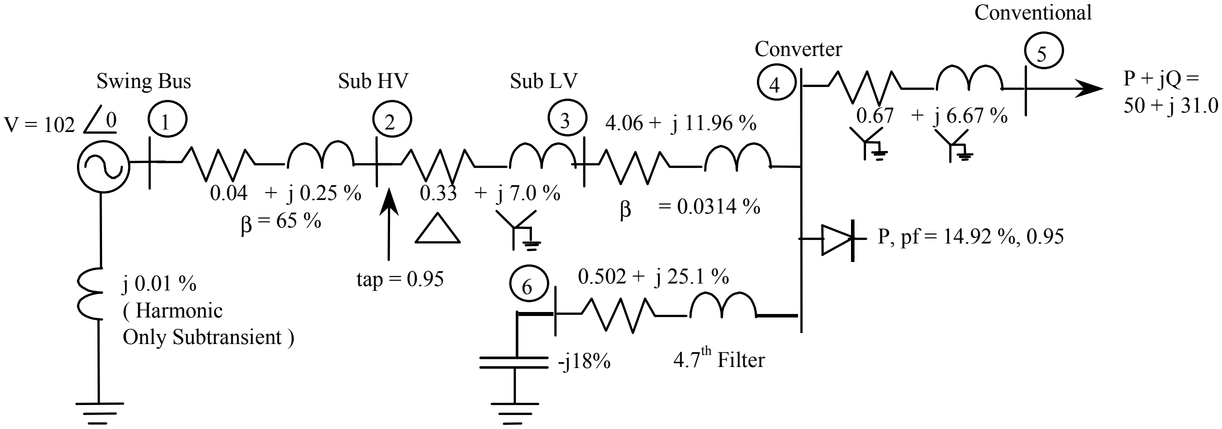


Figure 3-9
System One-line Diagram for Five-bus Example with Filter

Filter performance is checked using three steps:

1. Impedance scans are performed, without and with the filter. The filter notch should be at the design harmonic.

2. The converter bus voltage waveform, without and with the filter, is examined. 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 committed to a filter. A good rule for dedicating kVAr when multiple filters are needed is to stairstep 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. The filter current waveform is checked 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 3-10-3-12.

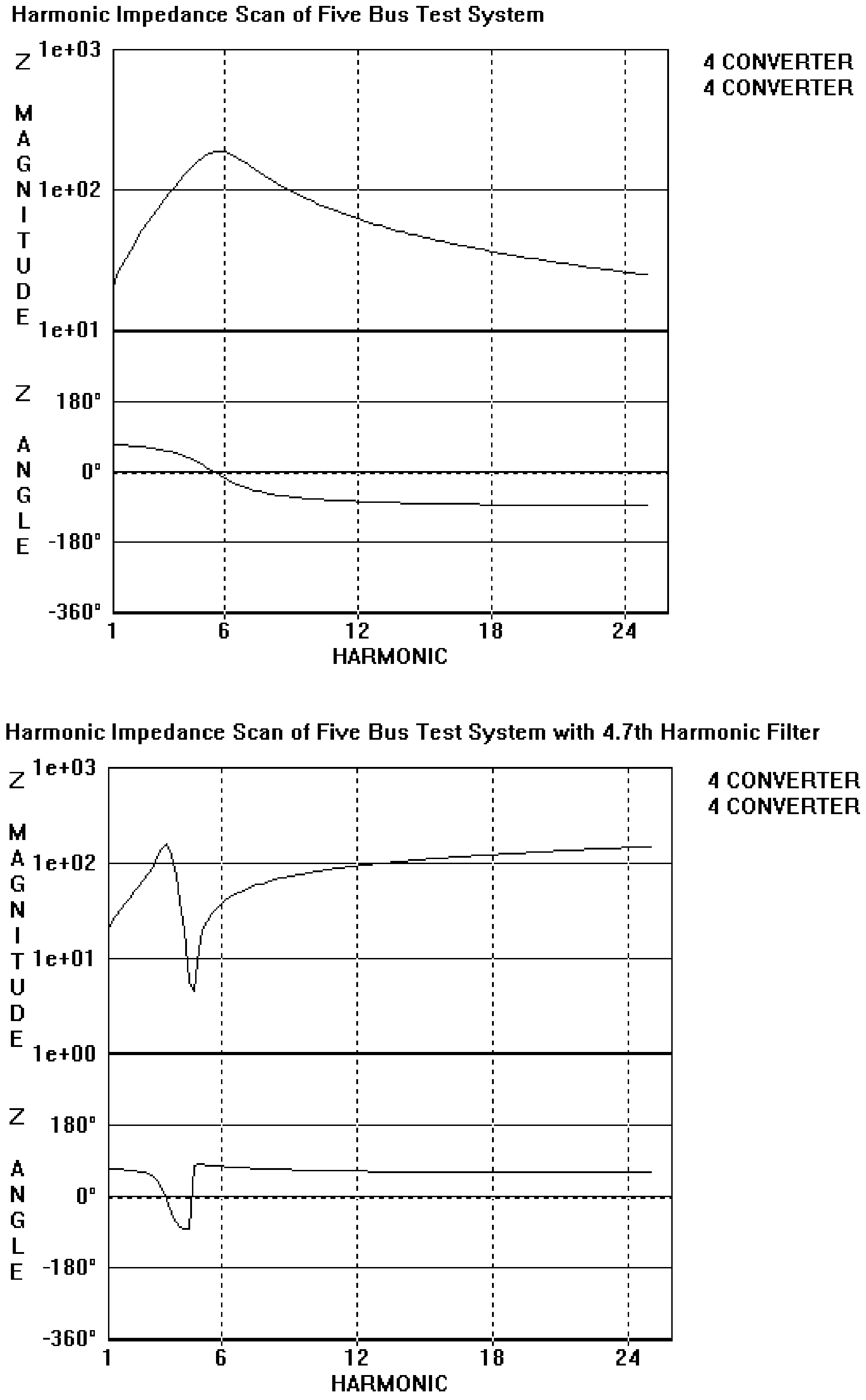
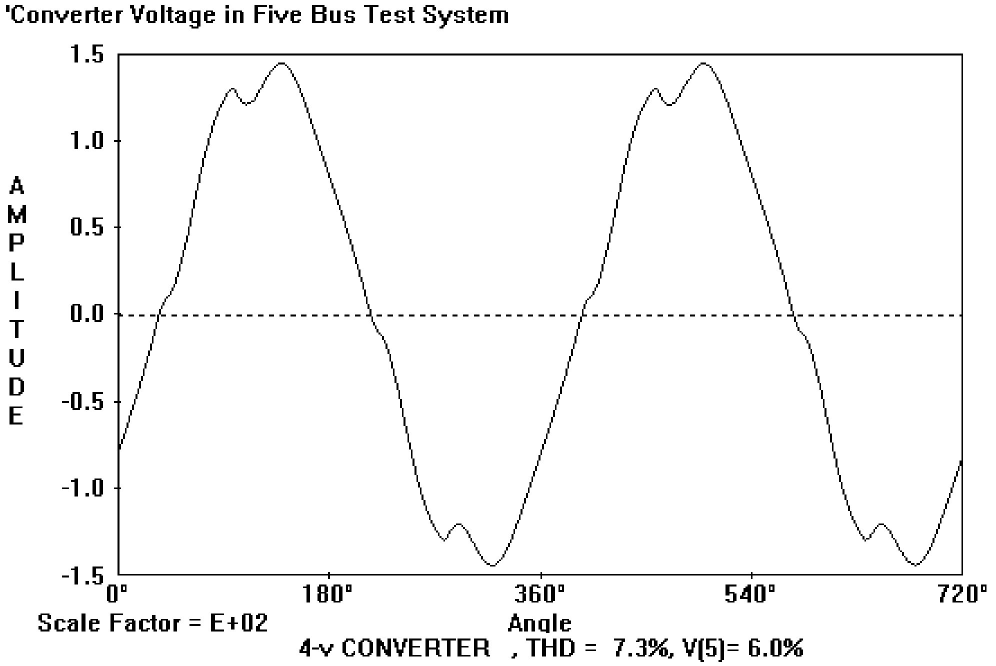


Figure 3-10
Impedance Scans at Converter Bus (without Filter at Top, with Filter at Bottom)



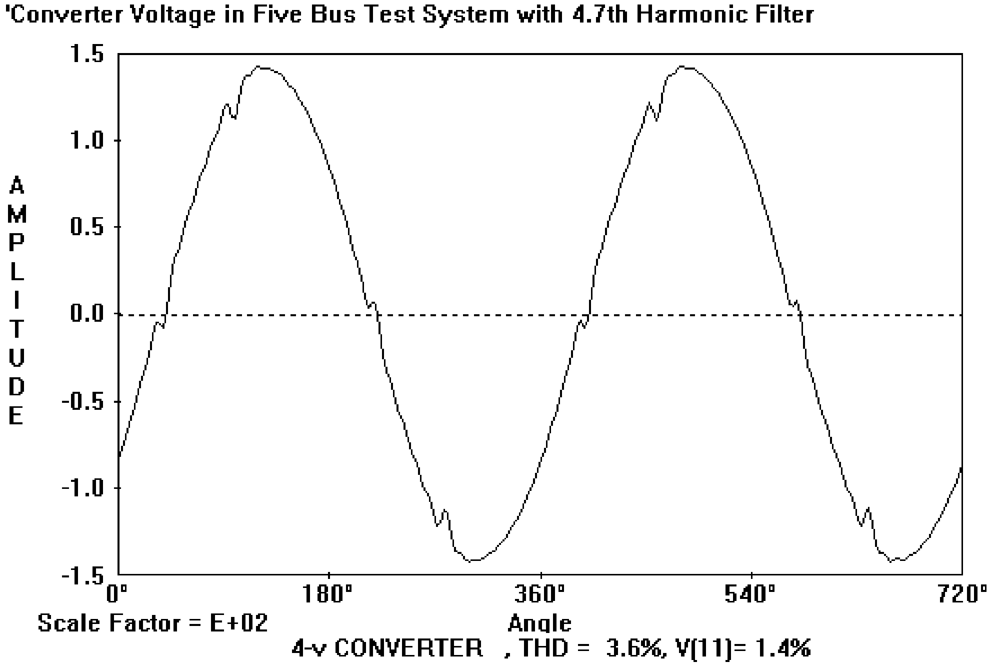


Figure 3-11
Converter Bus Voltage Waveforms Bus (without Filter at Top, with Filter at Bottom)

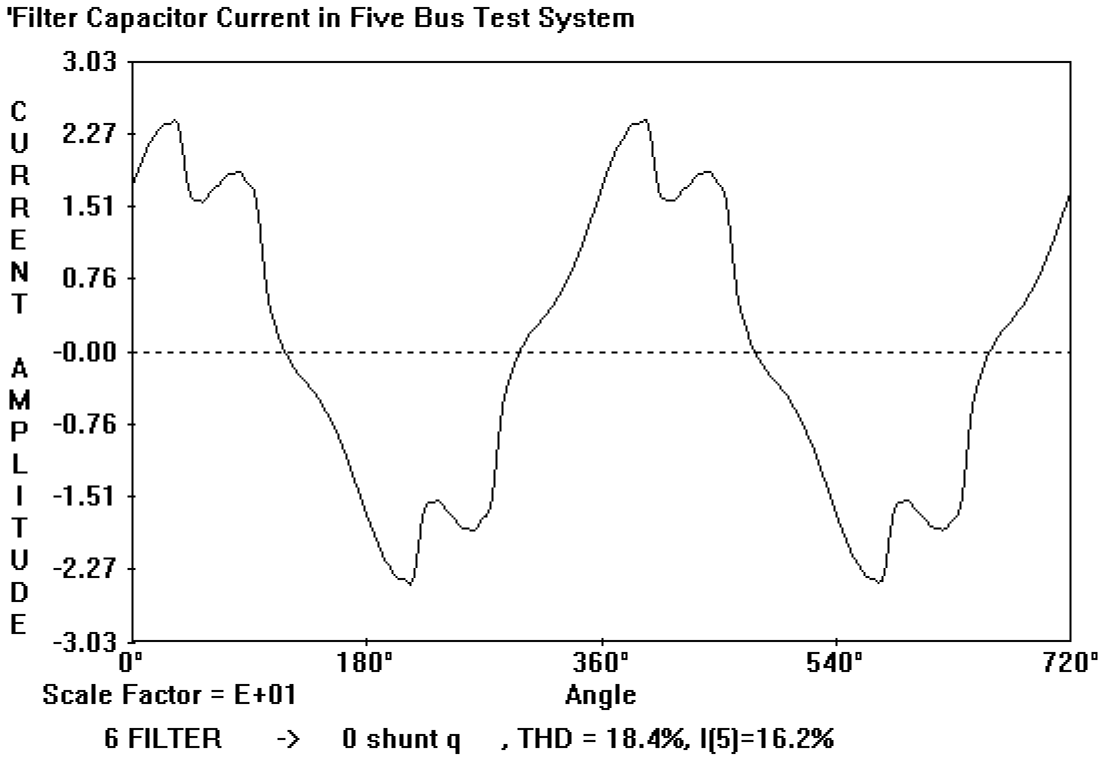


Figure 3-12
Filter Current Waveform

Active Filters

This is a new and promising technology, but there are as yet few distribution feeder installations. Active filters are power electronic converters that inject equal-but-opposite distortion to yield more sinusoidal voltage waveforms throughout a network. Active filters have the advantages of:

- time-domain operation so that they automatically "tune" to the problem harmonic or harmonics
- current limiting capability to prevent overload by new or unknown sources of harmonics on the network
- multi-point voltage monitoring so that they can simultaneously minimize distortion at local and remote busses

Utility Survey of Standards used by PUCs

IEEE 519

The most often-quoted harmonics standard is IEEE 519, “Recommended Practices and Requirements for Harmonic Control in Electric Power Systems.” IEEE 519 attempts to establish reasonable harmonic goals for electrical systems that contain nonlinear loads. The objective is to propose steady-state harmonic limits that are considered reasonable by both electric utilities and their customers. The underlying philosophy is:

- customers should limit harmonic currents
- electric utilities should limit harmonic voltages
- both parties share the responsibility for holding harmonic levels in check

IEEE 519 applies to all voltage levels, including 120V single-phase residential service. While it does not specifically state the highest-order harmonic to limit, the generally accepted range of application is through the 50th harmonic. Direct current, which is not a harmonic, is also addressed and is prohibited. Since no differentiation is made between single-phase and three-phase systems, the recommended limits apply to both.

It is important to remember that IEEE 519 is a recommended practice and not an actual standard or legal document. Rather, it is intended to provide a reasonable framework within which engineers can address and control harmonic problems. It has been adopted by many electric utilities and by several state public utility commissions.

Definitions and Terms

THD. Total harmonic distortion (or distortion factor) of voltage or current is the ratio of the rms value of harmonics above fundamental, divided by the rms value of the fundamental.

PCC. Point of common coupling is a point of metering, that is, any point from which both the utility and the customer can either 1) access the point for direct measurements of the harmonic indices meaningful to both, or 2) estimate the harmonic indices at the point of interference through mutually agreeable methods. Within an industrial load, the PCC is the point between the nonlinear load and other loads.

There is some flexibility in determining the PCC, but in most instances, it is at the meter. An electric utility might also interpret the PCC to be on the high-voltage side of the service transformer, which would have the effect of allowing a customer to inject higher harmonic currents.

ISC. Maximum short circuit current at the PCC.

IL. Maximum demand load current (fundamental frequency component) at the PCC, calculated as the average current of the maximum demands for each of the preceding twelve months. For new customers, this value must be estimated.

TDD. Total demand distortion, which is the THD of current (using a 15 or 30 minute averaging measurement period) normalized to the maximum demand load current IL.

Utility Limits

Electric utilities are responsible for maintaining voltage harmonics and THD_V. The limits are divided into two categories: voltages 69kV and below, and voltages above 69kV. For electric utility distribution systems (i.e., corresponding to 69kV and below), the limits are

Table 3-3
THD_V Limits For Voltages 69kV and Below

Individual Voltage Harmonic %	Total Harmonic Distortion THD_V %
3.0	5.0

Customer Limits

Customers are responsible for maintaining current harmonics and THD_I. Again, the limits are divided into two categories: voltages 69kV and below, and voltages above 69kV. For 69kV and below, the limits are

Table 3-4
THD_I Limits For PCC Voltages 69kV and Below

Maximum THD_I in % of IL for Odd Harmonics k

ISC/IL	$k < 11$	$11 \le k < 17$	$17 \le k < 23$	$23 \le k < 35$	$35 \le k$	TDD
<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

* All power generation equipment is limited to these values of THD_I, regardless of the actual ISC/IL.
Even-ordered harmonics are limited to 25% of the odd harmonic limits given in the tables. Loads that produce direct current offset, e.g. half-wave converters, are not allowed.

Public Utilitity Commission Standards

Several states, including Texas and Oklahoma, have adopted harmonic standards. These standards are based upon IEEE 519. Texas state ruling 25.51, "Power Quality," permits an electric utility to charge a fee for having to investigate and remedy a customer-created excessive harmonics condition. The fee is limited to actual cost incurred plus a reasonable administrative cost.

Interacting with Customers

It is wise for an electric utility to develop a written document of harmonics policy that can be distributed to large industrial customers as the need arises. While a good basis for the document is IEEE 519, other procedural items should also be addressed. The following key points should be considered for inclusion in the document.

Modeling

Data are needed to determine whether a proposed customer's facility will cause harmonic limits to be exceeded. These data include:

- One-line drawings of the customer's facilities, showing ratings and connections of all electrical equipment
- Location, connection, size, and control method of capacitors
- Conductor sizes and impedances
- Location and type of nonlinear loads
- Overall plant load and portion that is nonlinear
- Location, rating, connection, and impedance of transformers

Customers should be responsible for modeling their systems to project harmonic levels and determine whether the utility's harmonic limits will be exceeded.

The utility should provide information regarding the local power system to support the customer's modeling efforts. This information should include:

- Available fault duty at customer's location
- Ultimate available fault current
- Impedance and ratings of service transformers
- Possible voltage range variation

Filter modeling should include the utility's background voltage distortion allowed by IEEE 519, which is 3% for a single harmonic and 5% THD_V. Failure to include this allowed background distortion may result in inadequate filter designs.

The utility may need copies of the customer's harmonic analysis for review prior to approving the customer's proposed facilities. The utility may need the customer to submit manufacturer's documentation and test data demonstrating the harmonic content of nonlinear loads.

Measurements

The utility should reserve the right to measure the amount of a customer's harmonic current injection at any time at the point of common coupling (normally the electric meter). These measurements are usually spot checks, but additional monitoring may be required.

Mitigation Devices and Methods

The customer should be responsible for the design, installation, operation, and maintenance of mitigation devices required to meet the utility's harmonic limits. Mitigation devices may include current limiting reactors, passive filters, active filters, or other devices that minimize the flow of harmonic currents onto the utility's distribution system.

The customer should submit mitigation device maintenance records to the utility upon request. The installation and testing of mitigation equipment should be subject to the approval of the utility. The mitigation devices must be capable of handling the IEEE 519 permitted background voltage distortion that can exist on the utility's distribution system.

The utility will likely reconfigure the distribution system regularly in response to load changes and to resolve outages. The mitigation equipment should operate independently of these changes.

Solutions

Solution techniques fall into two broad categories – preventive and remedial.

Preventive Measures

Preventive measures focus on minimizing the harmonic currents that are injected into power systems. Preventive measures include:

- Strict Adherence to IEEE 519.
- Phase Cancellation. The use of twelve-pulse converters instead of six-pulse converters should be encouraged. Most utility harmonic problems are associated with high 5th and 7th harmonic currents, and if they are eliminated through phase cancellation, harmonic problems

rarely develop. In situations where there are multiple six-pulse converters, serving half of them (in terms of power) through delta-delta or wye-wye transformers, and the other half through delta-wye or wye-delta transformers, achieves net twelve-pulse operation.

- Encouragement of Low Distorting Loads. Because of IEEE 519, increasing attention is being given to the THD_I of distorting loads. A customer often has a distortion choice in loads. For example, twelve-pulse (or higher) ASDs and low-distortion fluorescent lamp ballasts can be purchased.
- Computer Simulations. It is always better to simulate the impact of a large distorting load before it is ordered and installed. Solutions can be proposed and evaluated "on paper" and perhaps implemented when the load is installed. Once the distorting load is connected, the customer will likely be under considerable pressure to operate it and perhaps less likely to commit additional funds to deal with a distortion problem.

Remedial Measures

Remedial measures include:

- **Circuit Detuning.** By using only field measurements such as capacitor current waveforms and search coil readings, it is possible to identify the capacitor banks that are most affected by resonance. As a temporary measure to "buy time" before a real solution can be found, the affected capacitor bank can be switched off to see if the resonance problem subsides. Of course, the problem may simply transfer to another capacitor bank, so post-switching measurements at other capacitor banks must be made to see if the temporary solution is satisfactory. If switching a capacitor bank off temporarily solves the problem, computer simulations may be in order to test filtering options and possible relocation of the capacitor bank.
- **Passive Filters.** These are widely used to control harmonics, especially the 5th and 7th harmonics. Most filters consist of series L and C components that provide a single-tuned notch with a low-impedance ground path. At 50/60Hz, these filters are, for all practical purposes, capacitors. Thus, passive filters provide both power factor correction and voltage distortion control.
- **Active Filters.** This is a new and promising technology, but there are as yet few distribution feeder installations. Active filters are power electronic converters that inject equal-but-opposite distortion to yield more sinusoidal voltage waveforms throughout a network. Active filters have the advantages of:
    - time-domain operation so that they automatically "tune" to the problem harmonic or harmonics
    - current limiting capability to prevent overload by new or unknown sources of harmonics on the network
    - multi-point voltage monitoring so that they can simultaneously minimize distortion at local and remote busses

Procedure for On-Site Field Test During Equipment Commissioning

The range of final acceptance tests of the complete mitigation system installation at the user's site is limited by the availability of suitable test equipment at the user’s site. Visual inspection upon receipt of the unit is the first priority. The system as a whole and the components should be checked to verify if there is any sign of visual damage that may have happened during shipment of the unit. Following is a list of start-up tests that can be considered for a harmonic mitigation system.

Dummy Load Tests (If Available)

Output voltage

Output voltage should be measured and verified, under normal operation and duringtransfers to and from bypass.

Current Harmonics Test (If applicable)

The current harmonic content should be compared with and without the filter to ensure that the desired harmonic reduction is achieved.

Bypass switch

Performance of the bypass switching and synchronizing circuitry should be shown in various modes:

- Manual switchover
- Automatic switchover, such as simulating an inverter failure Switchover inhibitions
- Forced switchover to utility mains during momentary overload

Instrumentation, controls, and indicators

Satisfactory operation of all meters, controls, and indicators, visual and aural, should be verified.

System ground

The integrity of the system ground may be ensured by following the applicable codes and regulations, the supplier recommendations, and established procedures.

Serviceability

The supplier should demonstrate the service aids and supplier-furnished equipment.

Live Load Tests

Having satisfactorily tested the system with a dummy load, the user may now connect the load system to the power quality mitigation equipment output power distribution system.

Output voltage verification

Same parameters as for the dummy load

Current harmonics test

The current harmonic content should be compared with and without the filter to ensure that the desired harmonic reduction is achieved.

Bypass switch operation

Proper system operation and output voltage parameters are maintained during both manual and automatic switchover.

Long-term run

All facets of the system should be proper and within defined parameters during an extended operational period of not less than 24 hours.

Safety

Compliance with all safety codes and regulations should be verified.

Environment

Previous, certified data obtained from a similarly designed harmonics mitigation device may be used to show satisfactory performance with respect to:

- Temperature variations
- Humidity

- Altitude
- Acoustics
- EMC

Overtemperature protection may be tested by obstructing the airflow through the unit.

Instrumentation, controls, and indicators

Satisfactory operation of all meters, controls, and indicators, visual and aural, should be verified.

Plan for PQ Monitoring, Data Collection and Analysis

The performance of mitigation equipment must be verified by extensive monitoring, both before and after commissioning. At least two days of recordings before commissioning and one week of recordings after commissioning should be made to assure that the mitigation equipment is performing as planned. One week of measurements is needed so that the entire weekly load cycle can be observed. Monitoring should include time traces of voltage and current THD, spectra, sample waveforms, power, and harmonic power.

One key aspect of a demonstration project is to adequately quantify the performance of the harmonic mitigation device under field conditions. Monitoring both the line side and load side of the harmonic mitigation device is essential for accurately quantifying the impact of the device on the electrical system and end-use load. The key aspect of any performance-monitoring program is monitoring and database management.

For the monitoring aspect, *IEEE Std. 1159-1995 Recommended Practice for Monitoring Electric Power Quality* is a good reference document for a power quality mitigation technology demonstration project. Some key issues regarding performance monitoring are:

- The number of measurement points that will be selected for the performance monitoring. In most cases, the preferred option is to have one monitor to measure the input and output voltages and currents simultaneously. In addition to measuring the phase conductors, the monitor should have enough channels to measure the voltages and currents of the neutral and ground conductors. In some cases, the DC bus voltage and some other key points within the device may need to be monitored. For example, demonstration of an active filter ideally requires the following monitoring points:
- Three-phase voltage and current on input and output (six voltage channels and six current channels)
- Neutral and ground current and neutral-to-ground voltage on input and output (four current channels and two voltage channels)
- DC bus voltage (one voltage channel)

For effective performance verification, the functionality of the monitor needs to meet the specific requirements of the monitoring site, such as type of expected electrical disturbances. The monitoring equipment should be capable of monitoring the following quantities:

- Voltage and current harmonics, up to at least the 50th harmonic
- Capacitor switching transients
- Lightning/load switching transients
- Steady-state voltage, current, real, apparent, and reactive power and power factor
- An understanding of whether the monitor returns the sine or cosine form of the Fourier Series

Remote data collection from the monitor using telephone line or Ethernet is the preferred option. Because the monitoring period may extend up to a year, manual download of data is not an effective way for collecting this data. Almost all major vendors of power quality monitoring instruments provide capability for remote monitoring. The facility where the monitor will be installed needs to have a telephone line or Ethernet connection available for this purpose. If a dedicated telephone line is not available, an existing telephone line can be used for the monitoring by using telephone-sharing devices that are readily available in the market.

- In addition to the power quality monitoring, many power quality mitigation devices may have their own monitoring and self-diagnostic capability that may be accessed via remote communication, either through telephone line or Ethernet. The performance verification plan should be implemented in such a way so that all monitoring data can be correlated with a time stamp or other method.

- Monitoring database management becomes critical, especially because the amount of data collected during a six-month or one-year monitoring period can easily exceed 1 Gigabyte. Many power quality-monitoring devices have proprietary software that is a good platform for database management. However, it is preferred that the monitoring software be able to provide monitoring data in the PQDIF (Power Quality Data Interchange Format) format so that data analysis can be done using an open platform such as EPRI PQ Measurement module or any other software that can analyze PQDIF format data.

- It is possible that during the performance verification project, there will be instances where all the parties involved need to interact to solve any hardware/performance issues during the verification period. A chain of command needs to be established with personnel, with responsibilities clearly defined. The key person during the performance verification period is somebody who has day-to-day responsibility of data collection and analysis. In addition, personnel from the customer, utility, power quality mitigation equipment vendor, and monitoring equipment vendor need to be identified and their roles defined during this verification period.

Data Presentation/Organization for Performance Verification

After the performance verification, the results of the performance verification need to be compiled into a report. The report should identify the following issues:

- A comprehensive analysis of any hardware/software/performance deviations that were observed during the monitoring period. If there were any equipment problems, then the report should identify the nature of the problem and how it was resolved.
- A summary of the power quality monitoring data both from the line side and the load side of the power quality mitigation equipment to establish the baseline performance of the equipment.

Figure 3-13 through Figure 3-17 show how the monitoring data was organized and presented during the Active Power Line Conditioner (APLC) demonstration project[2] at the Museum of Television & Radio in New York, NY. EPRI and Empire State Electric Energy Research Corporation (ESEERCO) jointly conducted this project with Consolidated Edison Company. This example shows an effective way of presenting performance verification data from a power quality mitigation technology demonstration project.

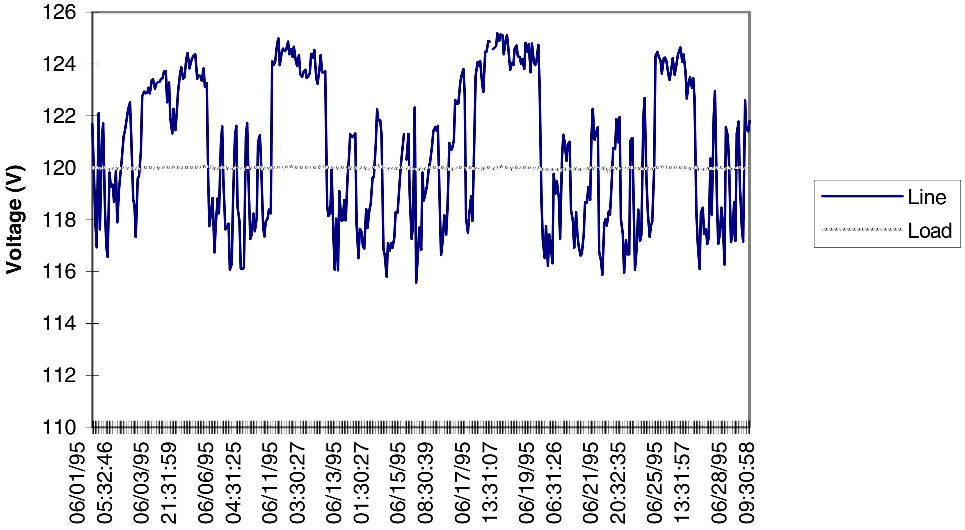


Figure 3-13
Voltage Regulation Performance of PQ Mitigation Device

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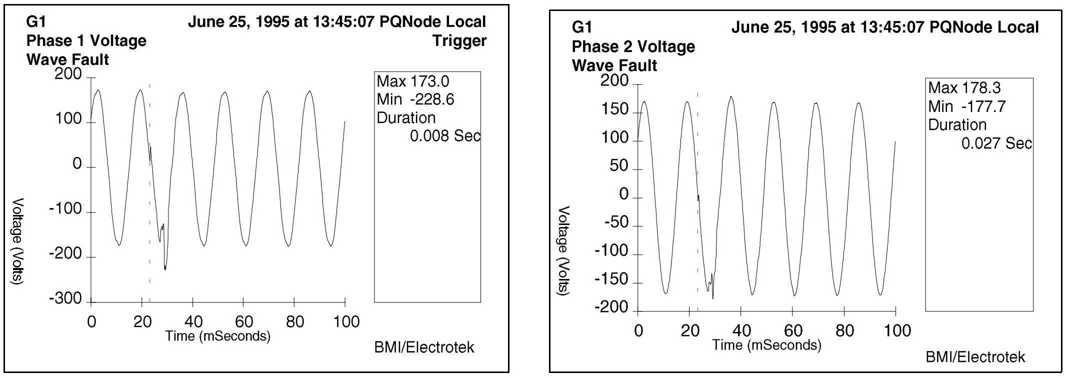
[2] EPRI Report, Active Power Line Conditioning Technologies Application Guide, TR-106535



Line Side

Load Side

Figure 3-14
Capacitor Switching Mitigation Capability Performance of PQ Mitigation Device

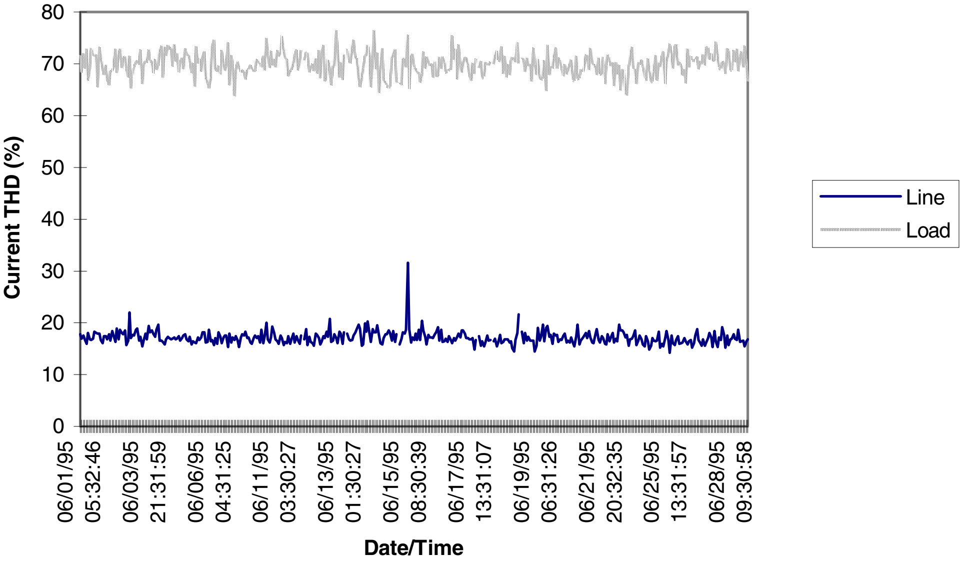


Figure 3-15
Line-side Harmonic Current Mitigation Capability Performance of PQ Mitigation Device

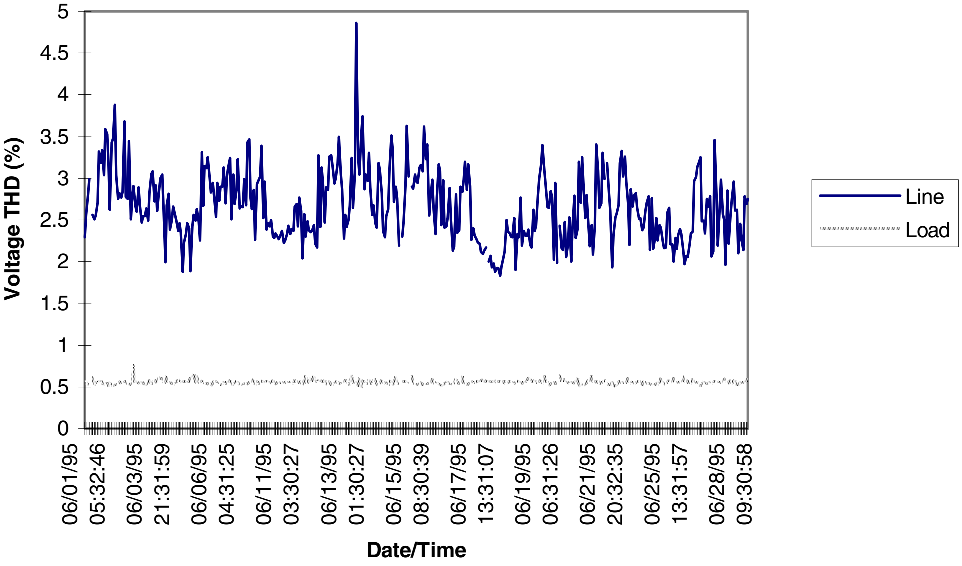


Figure 3-16
Load-side Harmonic Voltage Mitigation Capability Performance of PQ Mitigation Device

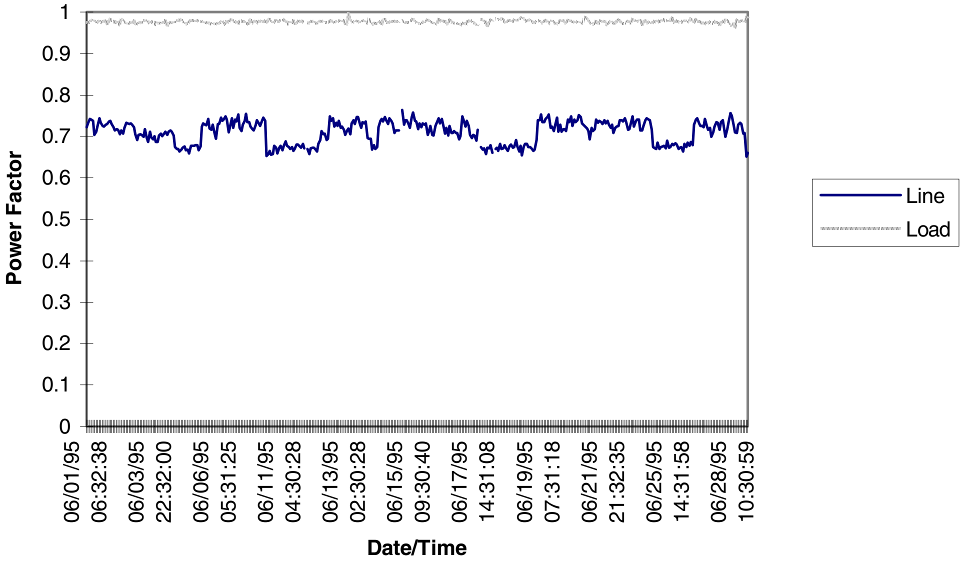


Figure 3-17
Power Factor Improvement Capability Performance of PQ Mitigation Device

Cost Benefit Analysis Methodology

Economic Justification of Mitigating Measures

From a customer's perspective, the most common economic justification for harmonics mitigation is in minimizing down-time due to nuisance tripping of sensitive loads. This cost is totally customer-dependent.

From a loss perspective, harmonics can be considered as a reduction in power factor. True power factor can be shown to be

$$pf_{true} \approx \frac{dpf_1}{\sqrt{1+THD_I^2}} .$$

Thus, the true power factor of nonlinear loads is limited by THD_I. Consider a nonlinear load with perfect displacement power factor (dpf_1). When current distortion is included, the true power factor degrades, as shown in Table 3-5.

Table 3-5
Maximum True Power Factor for Nonlinear Loads

THD_I %	Maximum pf_{true}
10	0.99
20	0.98
30	0.96
50	0.89
100	0.71

Since the true power factors given above are for the special case of unity dpf_1, they represent *maximum* true power factors for nonlinear loads. Actual true power factor is the product of *maximum* true power factor and *displacement* power factor, and the product can be significantly lower.

The power factor comparison presents a rather optimistic picture, because harmonic currents actually cause more losses per ampere than do fundamental currents.

Voltage harmonics have been shown to cause additional losses in motors, especially high-efficiency single-phase motors. Voltage harmonics induce harmonic currents that increase motor losses and insulation temperature. Research by Dr. Ewald Fuchs at the University of Colorado at

Boulder has shown that voltage distortions in the 6% range with predominant 3rd and 5th harmonics can reduce the expected lifetime of single-phase motors by 25%-30%.

In general, cost-benefit analysis is not the only justification for a harmonics mitigation demonstration project at a customer site or on the utility system. The main objective of a demonstration project is to evaluate the new technology and gain field experience so that the technology can be applied at other locations properly. The demonstration project provides a market leadership position for the utility nvolved by furthering the understanding of the application, limitations of the technology, support requirements, and areas for improvement. However, the motivation in demonstrating a new technology is that it will provide customers with a cost-effective solution compared to existing technologies.

For this reason, once a demonstration project is completed, a cost-benefit analysis should be conducted using the fair market value (existing or anticipated) of the mitigation system. This cost-benefit analysis should not include the costs of research, development, and technology transfer associated with the demonstration project.

The cost elements that should be included in order to determine the annualized value of the net investment should include:

- Fair market value of the power quality mitigation system
- Installation cost including material and labor
- Annualized cost including maintenance, rent, HVAC, warranty, and so on

The other part of the cost-benefit equation is to quantify the benefit of installing the mitigation system. This is usually the most difficult data to gather, because customers do not document the financial impact of power quality and therefore are not able to provide good data to ascertain the cost benefit of the power quality mitigation system.

IEEE 1346 Recommended Practice for Evaluating Electric Power System Compatibility with Electronic Process Equipment provides a methodology for quantifying the cost of power quality disturbances. Key elements of the cost items relevant to the commercial/industrial sector are summarized below:

Downtime Related (from nuisance tripping)

Lost work

Idled labor

Disrupted process (man-hours, unloaded labor rate) ______
Starved process (man-hours, unloaded labor rate) ______

Makeup Labor

Overtime labor + premium ______
Overtime operating cost ______
Expedited shipping premiums ______
Late delivery fees ______

Cost of recovery

Secondary equipment failures (treat as repairs) ______
Recovery labor inefficiency ______

Rework cost

Labor ______
Manufacturing supplies ______
Replacement parts ______

Power Factor Related

Current induced line losses ______
Voltage/current induced motor losses ______
Reduced lifetime of equipment ______

Miscellaneous

Customer dissatisfaction

Lost business ______
Avoided customers due to longer lead time ______
Fines and Penalties for late delivery ______
Penalties for power factor ______

TOTAL ______

Key elements of relevant cost related to utility harmonics problems may be similar, but involve dissatisfaction of the utility’s customer and larger system requirements associated with poor power factor.

Economic Analysis Criteria

Once the data for total power quality mitigation system cost and annualized benefit to the customer has been quantified, the next step is to conduct an economic analysis to determine the cost effectiveness of the power quality mitigation system. The net present value (NPV) described below is considered the standard economic investment measure. Other common economic investment criteria include: future value, annual equivalent, internal rate of return, Solomon’s average rate of return, modified internal rate of return, aggregate benefit/cost (B/C) ratio, netted B/C ratio, Lorie-Savage ratio, and project balance.

Net Present Value

The net present value (NPV) method of investment is used for analyzing the life-cycle cost of power quality mitigation systems. The NPV method of investment evaluations accounts for the time value of money by discounting all cash flows to present value using the required rate of return. NPV can be presented by the following formula.

$$\mathrm{NPV} = \sum_{\mathrm{t}=0}^{\mathrm{n}} \left[\frac{\mathrm{A}_{\mathrm{t}}}{(1+r)^{t}} \right]$$

Where

At cash flow for the period

n equipment life in years

r required rate of return

After the cash flow for competing systems has been transformed to NPV, a comparative analysis could be done to assess the life-cycle cost of the system

4

CHECKLIST FOR SPECIFICATION OF HARMONIC MITIGATION EQUIPMENT

Whatever the specific design basis, the purpose for the harmonic mitigation device is improvement to the electrical characteristics of the voltage and current as seen by the connected equipment and other customers, thereby increasing productivity and equipment lifetime. This prime consideration dictates the following requirements:

- The device shall be at least as capable of surviving in the electrical environment as the equipment used to deliver the supply to the site. This relates to BIL levels, withstand voltages, MCOV, and other parameters traditionally associated with transformers, breakers, insulators, surge arrestors, and traditional electrical equipment.
- The device shall not cause any unacceptable decrease in the quality of supply while being placed into or removed from service.
- Failure of the device shall cause no interruption or decrease in the level of normally supplied voltage while it automatically isolates itself from service.
- The device shall be tolerant of any and all source conditions that may be anticipated due to utility system operation.
- The device shall be tolerant of any and all loading conditions that may be expected due to facility operation.
- The device shall perform in a predictable manner for events exceeding its design capability. It shall not cause any degraded condition that would be worse than those seen by the plant were it not installed.
- The device shall not, itself, be the source of any degradation to the utility's distribution system to which it is connected, or radiate any emissions exceeding established standards.
- The device should be self-monitoring and shall provide annunciation of any failure so that repairs may be initiated.

General Electrical Specifications

Specifications are essential to purchasing a power quality mitigation product. There are a large number of different specifications that are published by manufacturers. Some of the specifications are of universal importance to all users, and some are of more interest in one application than another. The procurement specifications should emphasize those specifications of particular interest for the application. Any items that can have the specification relaxed should be treated appropriately in the procurement. This approach helps to assure that the product is the best combination of performance and price for the requirements of the particular installation. Appendix C contains a generic checklist describing the essential specification issues that need to be addressed for a harmonic mitigation device.

Input Specifications: Normal Service Conditions

Compatibility with public low-voltage supplies

Equipment conforming to this specification shall be capable of operating in normal mode of operation when connected to an input supply having the following conditions, if not otherwise specified:

- Input voltage variation: ±10 % of nominal voltage
- Input nominal frequency variation: ±2 % of nominal frequency
- For three-phase inputs, the ratio of negative to positive sequence components shall not exceed 5 %
- Input voltage total harmonic distortion: < 8% with the following maximum level of individual harmonic voltages according to Table 4-1 (extract from Table 4-1 of IEC 61000-2-2 for public low-voltage supplies) up to the 40th harmonic

Table 4-1
Compatibility Levels for Individual Harmonic Voltages in Low-voltage Networks - (Extract from IEC 61000-2-2)

Odd harmonics Non-multiple of 3		Odd harmonics Multiple of 3		Even Harmonics	
Harmonic Order N	Harmonic voltage %	Harmonic order n	Harmonic voltage %	Harmonic order N	Harmonic voltage %
5	6	3	5	2	2
7	5	9	1,5	4	1
11	3.5	15	0,3	6	0,5
13	3	21	0,2	8	0,5
17	2	>21	0,2	10	0,5
19	1,5			12	0,2
23	1,5			>12	0,2
25	1,5				
>25	0,2+0,5 x 25/n				
NOTE – All the above harmonic levels are assumed not to occur simultaneously.					

Rated values and characteristics

The following rated values and characteristics shall be specified for the harmonic mitigation equipment:

- Rated AC input voltage
- AC input voltage tolerance
- Rated input frequency
- Input frequency tolerance
- Number of phases (if more than a single phase)
- Rated input current
- Maximum continuous input current (worst-case condition, including current from source, mains tolerance, and permitted overload)
- Input current total harmonic distortion (the goal of the device)
- Input current individual harmonic current levels (the goal of the device)
- Maximum input current (where applicable, curve of current against time)
- Input power factor
- Input neutral requirements
- Inrush current requirements
- Earth leakage current requirements
- In case of three-phase inputs, the maximum allowable mains voltage unbalance
- Power system grounding configurations

Output Specifications

Output characteristic - Non-sinusoidal output voltage

Where the output voltage waveform exceeds the limits of Table 4-1 in any mode of operation and where the load equipment will tolerate such waveforms, the advice of the load equipment manufacturer should be sought for operation on this type of waveform beyond a limit of 15 minutes.

Rated output values and characteristics

The following rated values and characteristics shall be specified for the harmonics mitigation equipment (if applicable):

- Rated output voltage
- Output voltage tolerance
- Number of phases

Checklist for Specification of Harmonic Mitigation Equipment

- Rated output current for specified load
- Permissible load unbalance (multi-phase only)
- Relation between load unbalance and voltage unbalance
- Phase angle displacement tolerance between line-to-line or line-to-neutral voltages (multi-phase only)
- Permissible range of load power factor
- Output voltage transient deviation (RMS, time integral) and recovery time for a step change in load current for both linear and nonlinear loads
- Efficiency at rated load
- Overload capability. The overload is given by the ratio of overload current to rated output current, which can be applied to the device for specified time values without exceeding the established limitations under prescribed conditions of operation. The duration of overload capability is valid after steady-state operation when rated load has resulted in thermal equilibrium. The overload power factor shall be specified.
- Current limit identification. If current-limiting circuits are provided in the equipment, the voltage versus current characteristic shall be provided (if requested).

Performance and Component Specifications

- Rated load kVA
- Load power factor, true and displacement
- Nominal tuned frequency and frequency pass band or notch band
- Filter technology, active or passive
- Passive filter approach, blocking or trapping
- If blocking, phase voltage distortion limits
- If trapping, existing background harmonics limits
- Load impedance relative to source impedance
- di/dt requirements of load current
- High-frequency content of waveform to be compensated. Higher pulse order drives will require higher frequency current components to be compensated, This forces limitations on capacitors in broadband filters and passive interface filters used in active configurations.
- Voltage transient limits. Voltage transients on the power system will stress the current capacity of snubber diodes in the inverter sections of active filters. Limits on those transients must be given in order to properly suppress them.
- System conditions, resonance, etc.

By-pass switch specification

For switches that are not regarded as integrated parts of the equipment, such as transfer switches and tie switches, the following values and characteristics shall be specified by the manufacturer/supplier:

- Normal service conditions
- Continuous duty
- Automatic or manual by-pass
- Asymmetrical current duty

General Ambient Service Conditions

Normal environmental and climatic service conditions

Equipment that complies with these specifications shall be capable of withstanding the conditions defined in this section, unless other values are agreed upon between manufacturer/supplier and purchaser.

Altitude

The device conforming to this standard shall be designed to operate under rated conditions at a height up to and including 1000 meters above sea level.

NOTE - The manufacturer can state on request a necessary derating of equipment to be applied at a height exceeding 1000 meters.

Ambient service temperature

The equipment shall be able to operate under rated conditions in a minimum temperature range from 0 °C to + 40 °C, except for indoor office ambient temperature range from +10 °C to +35 °C.

NOTE - Using the equipment at the limit of the above-mentioned ranges guarantees operation, but may affect the effective life of certain components. Refer to the manufacturer for details on life limitations.

Relative humidity

The device shall be designed for a minimum ambient relative humidity range from 20% to 80% (non-condensing).

Ambient Storage and Transportation Conditions

The equipment shall be able to be stored non-operating in the conditions defined in this section, if no other conditions are given by the manufacturer's instructions.

NOTE - Storage duration may be limited because of recharging requirements of the energy-storage device (if applicable). The manufacturer states these requirements on request.

Altitude

The equipment shall be able to be transported by pressurized aircraft up to 15,000 meters above sea level in normal shipping containers or packages for a flight duration of maximum 16 hours. Normal storage height shall not exceed 1000 meters above sea-level.

Transportation and storage temperature

The equipment shall be transportable in its normal shipping container, for example by aircraft or by truck, in a minimum ambient temperature range from -25 °C to +55 °C. For stationary storage within a building, the minimum temperature range shall be from -25 °C to +55 °C.

Relative humidity

During transportation and storage in its normal shipping container, the unit shall withstand relative humidity from 20% up to 95%. The shipping container shall be designed adequately, unless dry ambient conditions are guaranteed. Adequate warning labels shall mark containers not designed for wet ambient conditions.

Unusual service conditions

The specification of the harmonic mitigation device shall identify any deviations from the normal service conditions including:

- Damaging fumes
- Moisture
- Dust
- Abrasive dust
- Steam
- Explosive mixtures of dust or gases
- Salt air
- Weather or dripping water

- Extreme changes in temperature
- Cooling water containing acid or impurities that may cause scale, sludge, electrolysis, or corrosion of the converter parts exposed to the water
- Strong electromagnetic fields
- Radio-active levels above those of the natural background
- Fungus, insects, vermin
- Restriction of ventilation
- Radiated or conducted heat from other sources
- Battery service conditions

Mechanical Conditions to be Identified

The specifications of the harmonics mitigation device shall identify any special mechanical conditions including:

- Exposure to abnormal vibration, shocks, tilting, or earthquakes
- Special transportation or storage
- Space and weight limitations

Safety Instructions and Documentation

If it is necessary to take special precautions to avoid the introduction of hazards when operating, installing, maintaining, transporting, or storing the harmonics mitigation equipment, the manufacturer shall make available the necessary instructions to the user. The manufacturer shall provide the user with guidance on the level of competence necessary for installation, for example:

- Operator installable. Any equipment that can be safely installed by the operator.
- Service personnel installable. Any equipment not installed when delivered to the user, which requires technical skill to complete the installation.

The manufacturer shall provide the user with guidance on the level of competence necessary to operate the equipment, such as:

- Can be operated by an individual with no previous experience.
- Can be operated by individuals with previous training.

Equipment Safety

Maintenance isolation provision

All energized terminals, including AC, DC, and control-voltage exposed points shall be insulated or enclosed to ensure the safety of maintenance personnel. Warning signs shall also be installed to indicate those terminals which are energized when the equipment is bypassed.

Emergency power off (EMO) switch

The EMO switch shall be separate from the equipment and shall disconnect all breakers, including energy storage, input, output, and bypass breakers, when activated.

Audible Noise

The amount of noise that is generated varies greatly from one system to another. Depending on the importance of noise level, any additional soundproofing or special enclosure for noise reduction should be specified.

Optional Items

The specification should include any optional item that may be required for the power quality mitigation equipment. A list of possible optional items includes:

- Microprocessor-based diagnostics
- Remote communication
- Instrumentation and control panel
- Power quality monitoring instrument
- Alarm controls
- Remote monitor panel

5

CASE STUDIES

Case Study #1- Harmonics, Ltd 3rd Harmonic Blocking Filter

Location: Data Center at International News Agency, Boston, MA

Dates:
Initial Facility Survey (Before Filtering) - 5/15/99
Facility Survey After Filtering Applied – 10/29/99

Distribution Transformer Rating and Loading: 112kVA, 480/208V ΔY, >95% Non-Linear

Type of Loads: Single-Phase Personal Computers, 208/120V

Measurement Instruments Used: Fluke 41

Problems Experienced Included:

- Need more system capacity
- Wire overheating
- Transformer overheating
- High neutral harmonics
- High neutral current
- High downtime cost

Filter Description, Topology and Method of Operation

The "Neutralizer Series" blocking filter is an LCR circuit, tuned to have its maximum impedance at the 3rd harmonic (180Hz for 60Hz distribution systems.) The main circuit consists of reactors and capacitors connected in a parallel-resonant tank, with the Thevenin-equivalent circuit shown in Fig. 5-1.

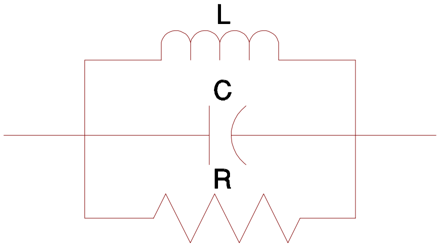


Figure 5-1
Thevenin-equivalent Circuit for Harmonics Limited Blocking Filters

The parallel-resonant tank circuit is characterized by an infinite impedance at the tuning frequency and a relatively low impedance at all other frequencies. In the neutralizer filter the circuit is used to prevent the flow of 3rd-harmonic currents, thus protecting the electrical distribution system.

Figures 5-2 through 5-5 show some of the pertinent waveforms with and without the filter in place, demonstrating the effectiveness of the filter installation.

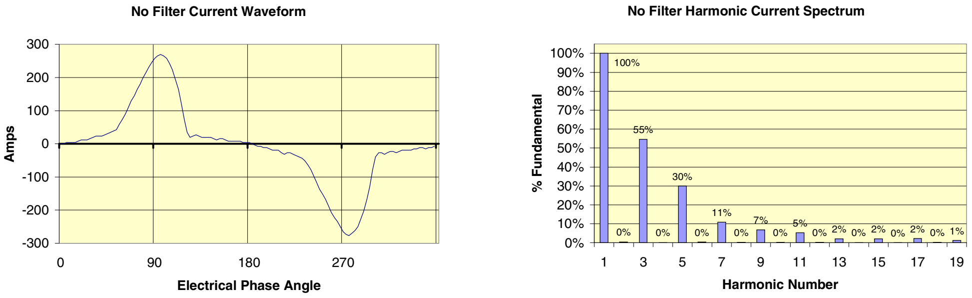


Figure 5-2
Phase A Transformer Current Waveform and Spectrum Before Filtering

In Figure 5-2, the following points should be noted:

- 60Hz current = 103 amps.
- The rms current = 122 amps.
- The rms harmonic current = 66 amps; this is 64% of the fundamental current.

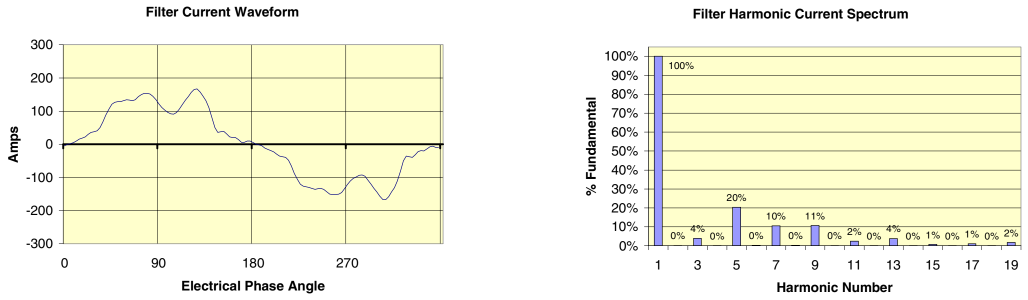


Figure 5-3
Phase A Transformer Current After Application of Neutralizer Filter

The following data are true for Figure 5-3:

- The 60Hz current = 100 amps, the loading is almost the same.
- The rms current = 103 amps, a reduction of 16%.
- The rms harmonic current = 26 amps; this is 26% of the fundamental current.
- Use of the filter results in a 61% reduction of the rms harmonic current.

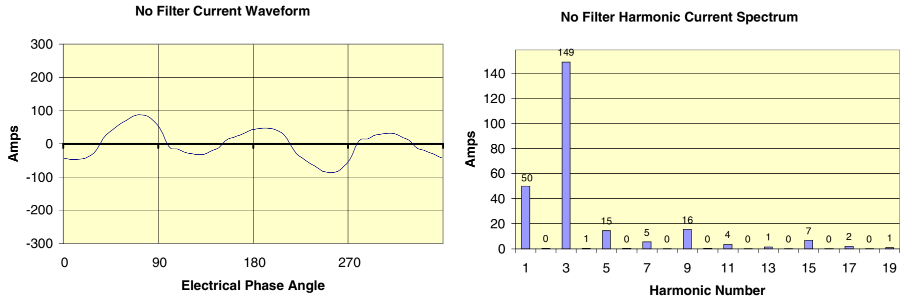


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Figure 5-4
Neutral Current Waveform and Spectrum Before Filtering

Note: The “No Filter” neutral readings were taken in four separate measurements. The waveform in Figure 5-4 is typical of shape but not magnitude. Figure 5.4 waveforms have the following values:

- The 60Hz current = 50 amps.
- The rms current = 160 amps.
- The 3rd harmonic current = 149 amps.

- The rms harmonic current = 151 amps.

Note: "No Filter" neutral readings were taken in four separate measurements. This spectrum represents those combined readings.

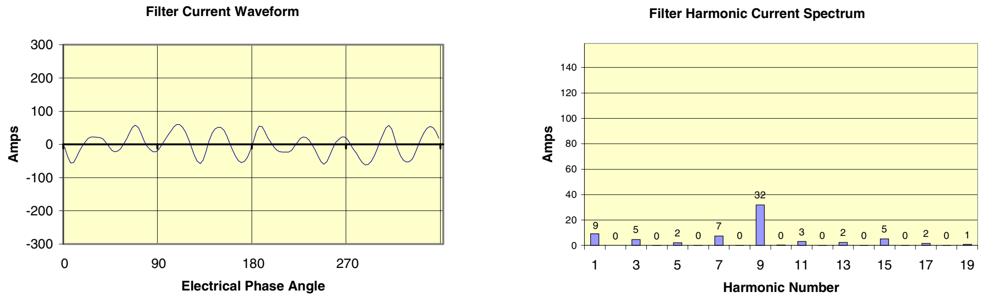


Figure 5-5
Neutral Current Waveform and Spectrum After Filtering

Note: Unlike the "No Filter" neutral readings, the "Filter" readings were taken in a single measurement.

In Figure 5-5, the waveform has these values:

- The 60Hz current = 9 amps, the fundamental decreased due to balancing of loads.
- The rms current = 36 amps.
- The 3rd harmonic current = 5 amps, this is a 97% reduction in the 3rd harmonic.
- The rms harmonic current = 34 amps.
- Use of the filter results in a 77% reduction of the rms harmonic current.

The Survey and the Filter Application resulted in the following improvements:

- Customer added loads and/or re-distributed loads resulting in improved phase balancing.
- The rms harmonic current was reduced in each of the phases (ranging from 39% to 61%), thereby releasing capacity.
- Neutral rms harmonic current was reduced from 151 to 34 amps, a 77% improvement.
- Neutral 3rd harmonic current was reduced from 149 to 5 amps, a 97% improvement.
- It was noted that the application of the Neutralizer Filter greatly reduced neutral current and released capacity in all three phases.
- This will result in lower transformer temperatures, reduced I^2R heat losses in all the wiring, and an improvement in the overall safety/reliability of the distribution system.

Harmonics Limited also has a family of 3-phase shunt filters designed to eliminate industrial harmonic problems. 5th harmonic tuned filters can be sized for a single load or multiple loads. Switched filters, designed for an entire electrical distribution system, use controllers to provide harmonic mitigation while maintaining a set system power factor. For rapidly changing loads, such as elevators, special units can switch filter steps in and out to follow the load on a half-cycle basis.

Case Study #2- Use of MTE Corp 5HF Third Harmonic Blocking Filter

This is a case involving computer loads, where line current distortion was high without the filter. Installation of the filter resulted in significant improvements, as shown in the figures and tables below.

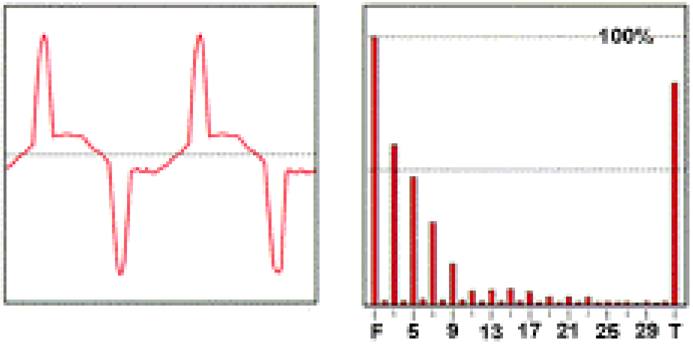


Figure 5-6
Input Current: Four Personal Computers with No Filter (Characteristics in Table 5.1)

Table 5-1 Circuit Parameters from Fig. 5-6

Circuit	H	%	H	%	THD thru the 31st
Total 5.9A rms	3	59.2	19	2.1	% THD 82.8
Fund 4.5A rms	5	46.7	21	2.4	% Triplen 61.2
Har 3.7A rms	7	29.3	23	2.1	K factor 10.7
	9	14.5	25	0.8	
	11	4.0	27	0.7	
	13	4.6	29	0.6	
	15	5.5	31	0.6	
	17	4.2			

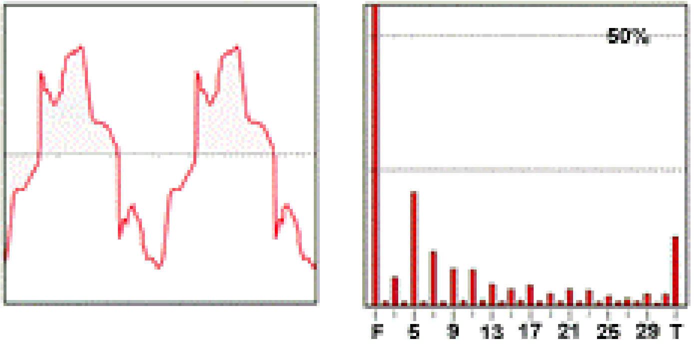


Figure 5-7
Input Current: Four Personal Computers with 5HF Filter (Characteristics in Table 5.2)

Table 5-2 Circuit Parameters from Fig. 5-7

Circuit	H	%	H	%	THD thru the 31st
Total 4.35A rms	3	5.1	19	2.1	% THD 26.4
Fund 4.28A rms	5	20.7	21	2.9	% Triplen 9.4
Har 1.11A rms	7	9.7	23	2.6	K factor 10.7
	9	6.7	25	1.3	
	11	6.3	27	1.2	
	13	3.7	29	2.0	
	15	2.7	31	2.0	
	17	3.4			

Case Study #3- MTE Broadband Filter

This example involves the use of a broadband filter on an adjustable speed drive. Figure 5-8 shows the current and harmonic spectrum before and after the installation of the filter.

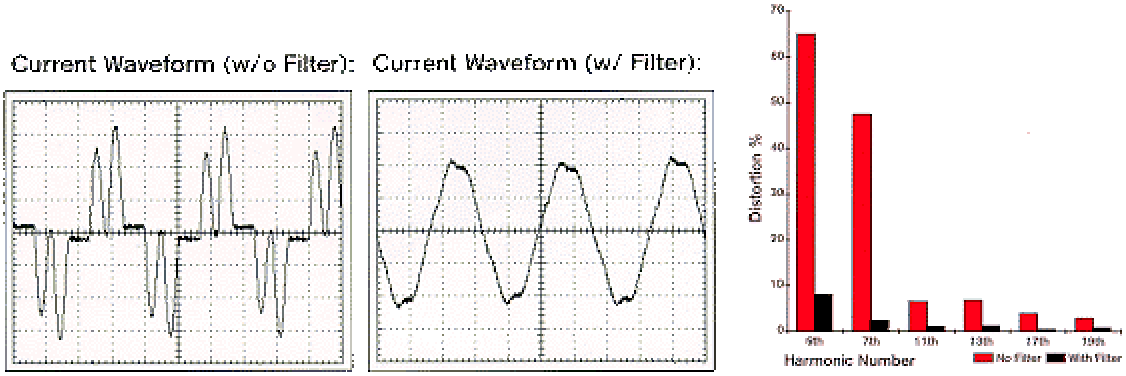


Figure 5-8
Current Waveforms and Distortion Spectrum with and without MTE Broad Band Harmonic Filters

From Figure 5-8, it is clear that the filter was quite effective in mitigating all the low frequency harmonics prevalent in the drive current waveform. For example, the fifth harmonic was reduced from about 65% to less than 10% of the fundamental. In addition, the filter reduced the seventh harmonic from nearly 50% to less than 5% of the fundamental.

Case Study #4- Harmonix Active Filter used on Multiple Nonlinear Single Phase Loads

The active Harmonix cancellation system has been installed at a beta-site and has performed well. A facility with a high density of non-linear loads was selected and a harmonic survey was performed. Based on the rating and high neutral current, a distribution panelboard was chosen and the active Harmonix filter was installed. Figures 5.9 and 5.10 illustrate the neutral and phase current of the panel board without the filter. Figures 5.11 and 5.12 depict the neutral and phase current with the active Harmonic cancellation system in service. Table 5.3 compares the parameters of interest with and without the Harmonix filter.

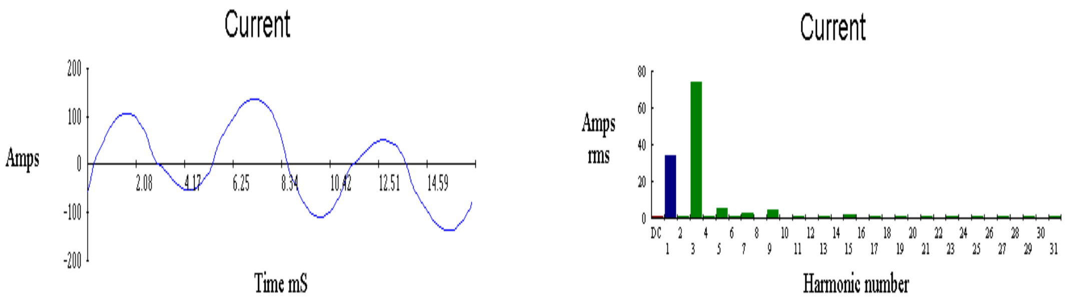


Figure 5-9
Neutral Current Waveform and Spectrum without the Harmonix Filter (Beta-site)

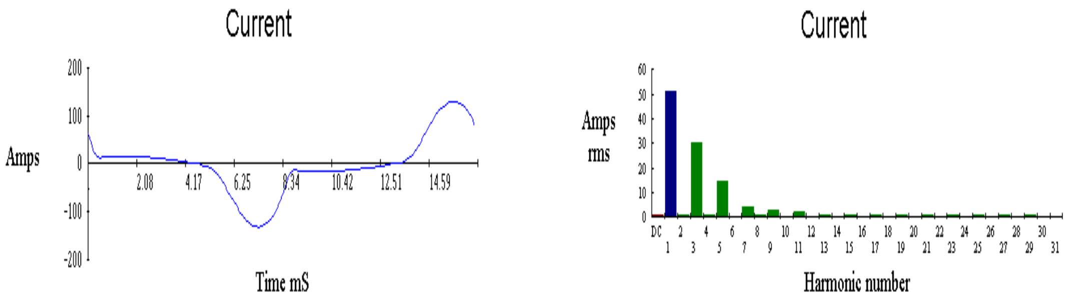


Figure 5-10
Phase B Current Waveform and Spectrum without the Harmonix Filter (Beta-site)

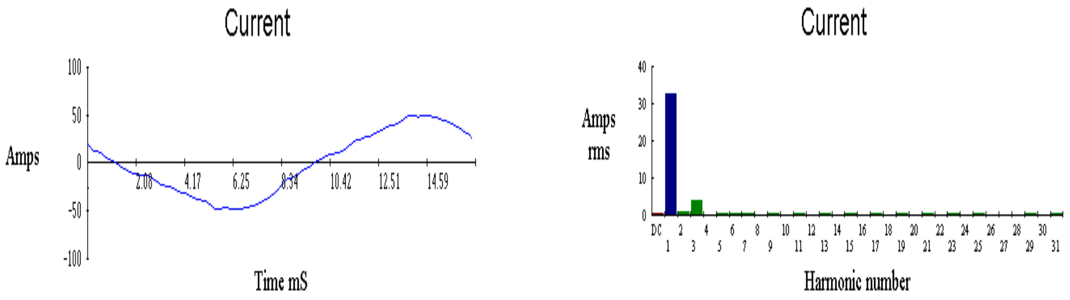


Figure 5-11
Neutral Current Waveform and Spectrum with the Harmonix Filter (Beta-site)

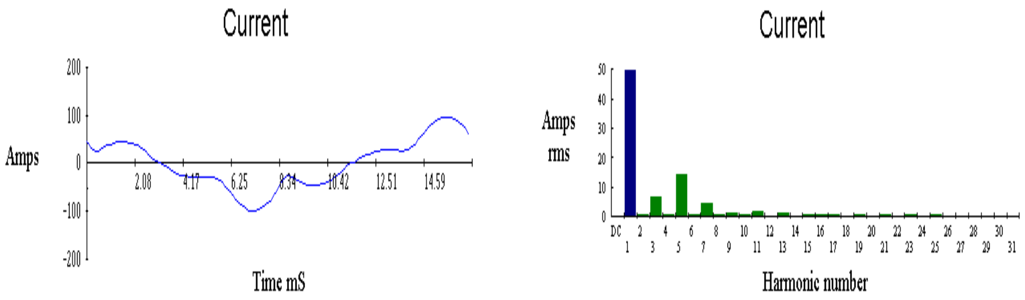


Figure 5-12
Phase B Current Waveform and Spectrum with the Harmonix Filter (Beta-site)

Table 5-3
Improvement in Key Parameters with the Active Harmonics Cancellation System

Variable	Without filter	With filter
Neutral current (Arms)	82.1	33.0
Non-60HZ Zero-Sequence current in neutral (Arms)	71.54	4.14
60 HZ current in the neutral (Arms)	34.3	32.7
Voltage THD (% Fund)	3.3	2.9
Current THD (% Fund)	67.2	33.3
Cancellation Effectiveness	-	94.2

Case Study #5- Accusine Active Filter Installed at Substation

Location: Ft. James Paper Company, Camas, WA.
Date: 08/18/00
Type of Loads: 3-phase industrial loads such as drives, motors, etc.
Filter specifications: AccuSine Power Correction System, 420kVA, 2400V (Employing two 300A units and a transformer), Installed at substation
Measurement Instruments Used: RPM power analyzer
Problems Experienced at this Location Included: Presence of harmonics made application of power factor correction capacitors risky.

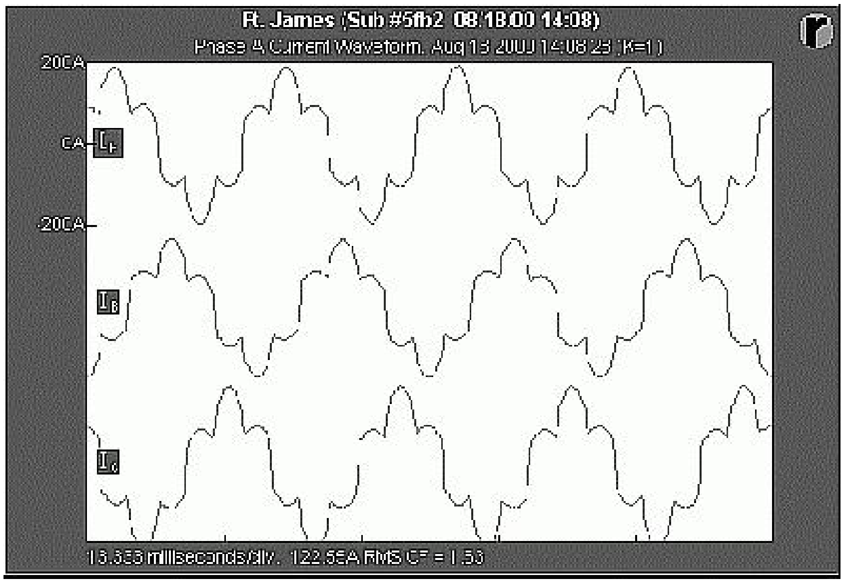


Figure 5-13
Current Waveform Before Filtering

Current Distortion	Value
Phase A average	**27.63%**
Phase B average	**26.40%**
Phase C average	**27.17%**

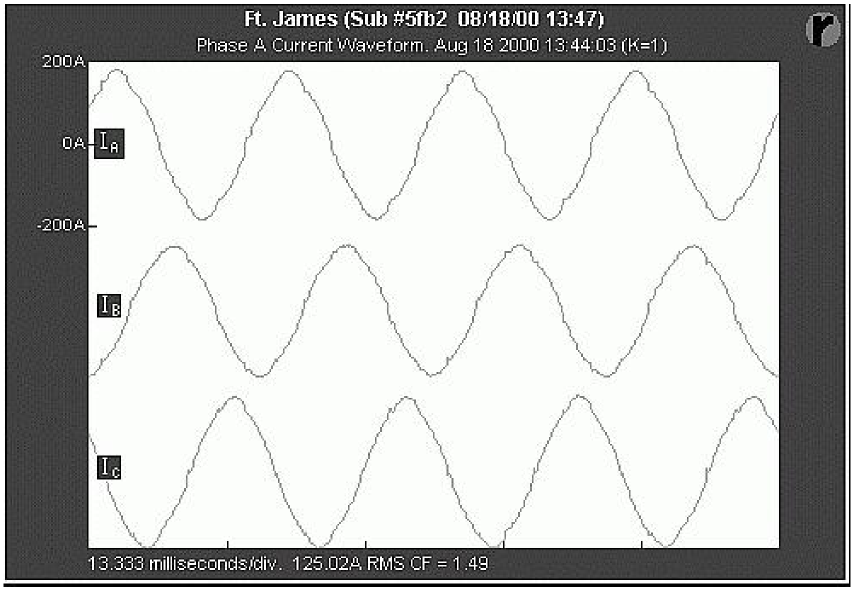


Figure 5-14
Current Waveform After Application of AccuSine

Current Distortion	Value
Phase A average	**5.467%**
Phase B average	**4.768%**
Phase C average	**4.167%**

The Survey and the Filter Application resulted in the following improvements:

- Current THD improved significantly. This will allow the use of power factor correction capacitors and result in cost savings due to improved power factor.

Case Study #6- Accusine Active Filter used at MCC Panel for Multiple Three-Phase Drives

Location: Methane gas wells, Wyoming.
Date: 04/06/00
Type of Loads: Multiple 3-phase drives
Filter specifications: AccuSine Power Correction System, 50A, Installed at MCC panel.
Measurement Instruments Used: RPM power analyzer
Problems Experienced at this Location Included: Non-compliance with IEEE-519 specification. Leading power factor.

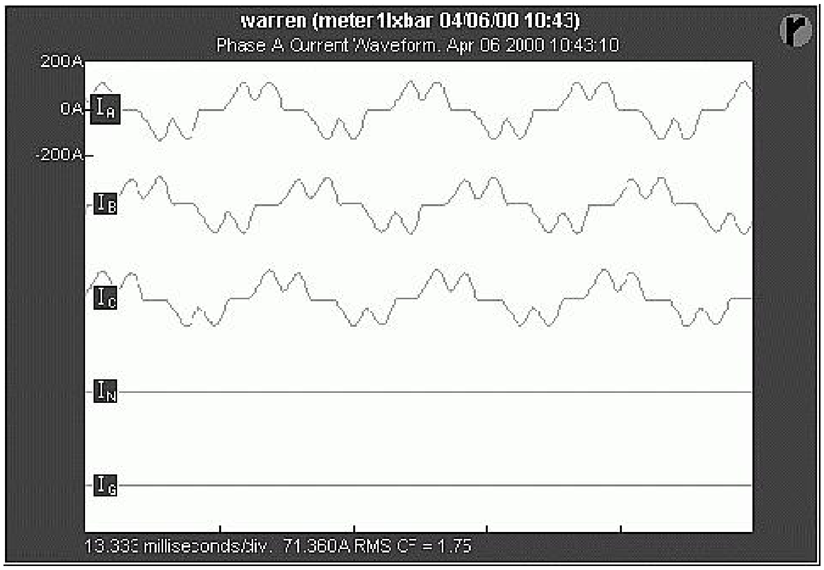


Figure 5-15
Current Waveform Before Filtering

Current Distortion	Value
Phase A average	**42.77%**
Phase B average	**48.02%**
Phase C average	**43.79%**

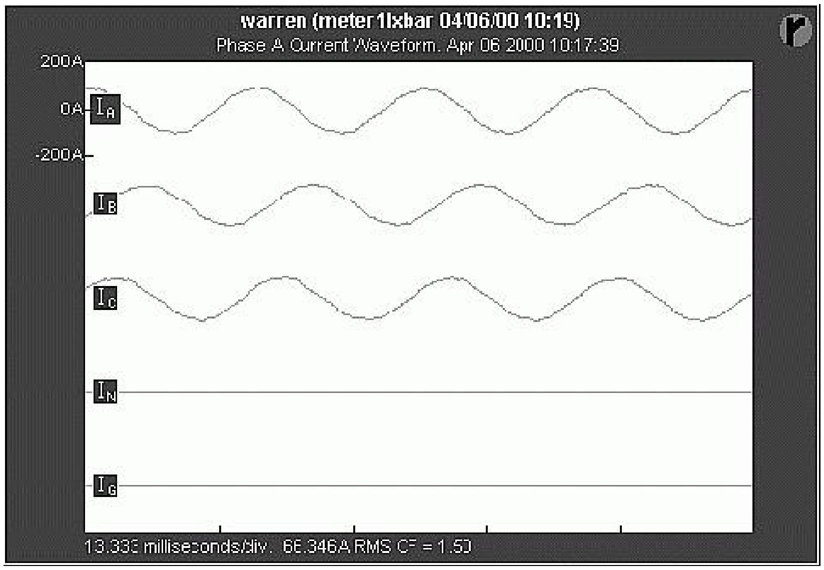


Figure 5-16
Current Waveform After Application of AccuSine

Current Distortion	**Value**
Phase A average	**4.512%**
Phase B average	**4.626%**
Phase C average	**4.978%**

The Survey and the Filter Application resulted in the following improvements:

- Current THD improved significantly. Also, remaining capacity was used to correct the displacement power factor.

Case Study # 7 Application of Times One Active Filter on Personal Computers

Location: Knoxville, TN, (Company name withheld at customer request)
Dates: August 1999
Initial Facility Survey: Harmonic currents greater than 99% with high peak currents.
Facility Survey After Filtering Applied: Reduced harmonic currents to 5%.
Distribution Transformer Rating and Loading: 120/0/120 Tap on 1-side of Delta transformer with 7% impedance.
Type of Loads: Personal Computers with switching Power Supplies.
Filter specifications: TimesOne™ Series 1000, Model ALC-1102-W rated at 120VAC at 20 A.
Measurement Instruments Used: Fluke 41.
Problems Experienced at this Location Included: Random lockups (freezing) of various Personal Computers.

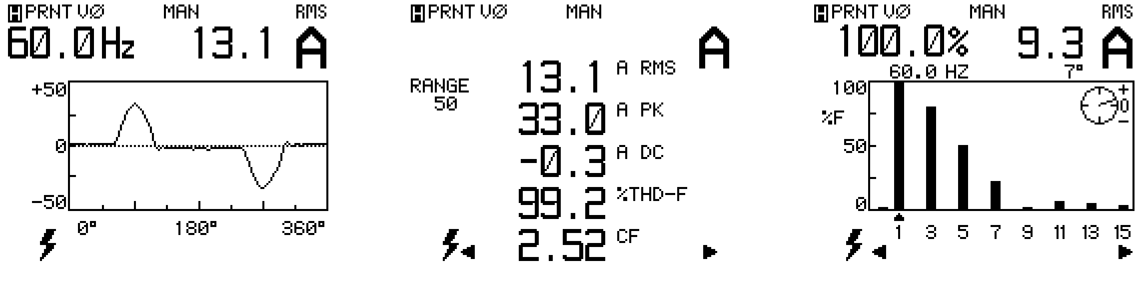


Figure 5-17
Single-phase Transformer Current Waveform and Spectrum Before Filtering

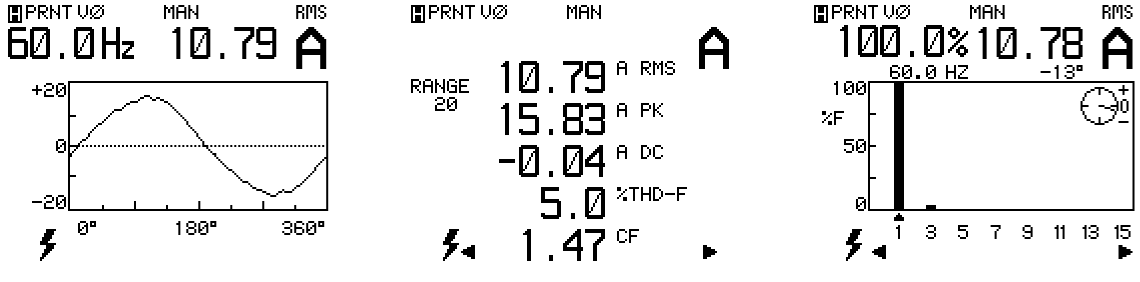


Figure 5-18
Transformer Current After Application of TimesOne™ Series 1000 Filter

The Survey and the Filter Application resulted in the following improvements:

- Problem Solved. Eliminated random lockups (freezing) of various personal computers.
- Current Reduction Analysis. The Active Harmonic Filter reduces the load RMS current from 13.1A to 10.79A, a 17.5% savings. Peak current is reduced from 33.0A to 15.83A, a 52% reduction. I_{THD} is reduced from 99.2% to 5.0%.
- Voltage Analysis. The Active Harmonic Filter provides voltage stabilization and eliminates low and fluctuating voltage supply to the load. Also, it removed the 'flat topping' of the AC waveform and stabilized the line voltage from 115VAC to 118VAC.
- Power Factor Analysis. The Active Harmonic Filter corrects the Power Factor from 0.70 to 0.97, a 38% improvement.
- KVA Analysis. KVA demand is reduced by 15.4%.

Case Study # 8- Application of Times One Active Filter on 6 Pulse Drives

Location: Gountermann Peipers India Limited
Dates: June 2000
Initial Facility Survey (Before Filtering): Harmonic currents of 110A were observed at Transformer #15.
Facility Survey After Filtering Applied: Harmonic currents were reduced to 10A at Transformer #15.
Distribution Transformer Rating and Loading >95% Non-Linear: Transformer #15 is rated at 2,000kVA and 440VAC with an impedance of 5%.
Type of Loads: 6-Pulse Variable Speed Drives.
Filter specifications: TimesOne™ Series 2000, Model ALC-2410-W – 480VAC at 108 A.
Measurement Instruments Used: BMI-PP1
Problems Experienced at this Location Included: Capacitors blown fuses, voltage imbalance and resonances.

The survey and the filter application resulted in the elimination of blown fuses, reduced resonances and improved voltage unbalance. Fig. 5-19 demonstrates the type of THD improvements with and without a Power Correction Systems filter for a 6-pulse drive.

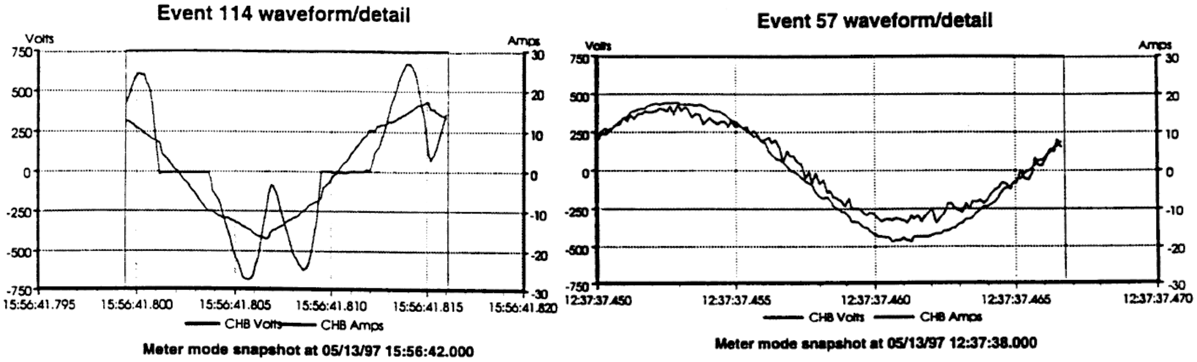


Figure 5-19
Example Improvement in THD with and without a Power Correction Systems Filter for a 6-pulse Drive

Case Study #9- 5000HP Chiller Motor ASD on 25kV System

Overview. This case has severe voltage resonance with nuisance tripping of sensitive loads and overheating of the ASD transformers. Simulations compare favorably with field measurements.This is a serious resonance case where a 3.9MW six-pulse line commutated ASD driving a chiller motor excites resonance in the 25kV underground distribution system shown in Figure 5.20. The ASD is served by feeder 2203, but the resonance problem is intense throughout the entire subsystem served by S.W. Substation Transformer #1 (i.e., feeders 2202, 2203, and 2204). The subsystem load at the time harmonics measurements are taken is 9.5MW @ *dpf* = 0.855, consisting of 5.6MW of conventional load plus the ASD that draws 3.9MW @ *dpf* = 0.830. The subsystem contains 16.27 miles of three-phase underground trunk and lateral cables.

The voltage and current waveforms at the ASD in this case were shown previously in Figure 3.1 of Section 3, and the voltage distortion throughout the 25kV subsystem is approximately 10%. Voltage distortion is highest at night, when the chiller is running at full power and the conventional load (i.e., harmonics damping load) is at low power. The high voltage distortion regularly trips off a computer-controlled automated train system in the late night hours. Also, there is concern that the resonant overvoltages will cause cable dielectric failure.

The chiller is centrally located so that it can be easily switched from feeder 2203 to feeder 2606, which is served by the N.W. substation. The switching arrangement is shown in Figure 5.21. Unfortunately, field switching of the ASD from the preferred feeder (2203) to the secondary feeder (2606) did not improve the harmonics situation and simply transferred the problem from one subsystem to the other.

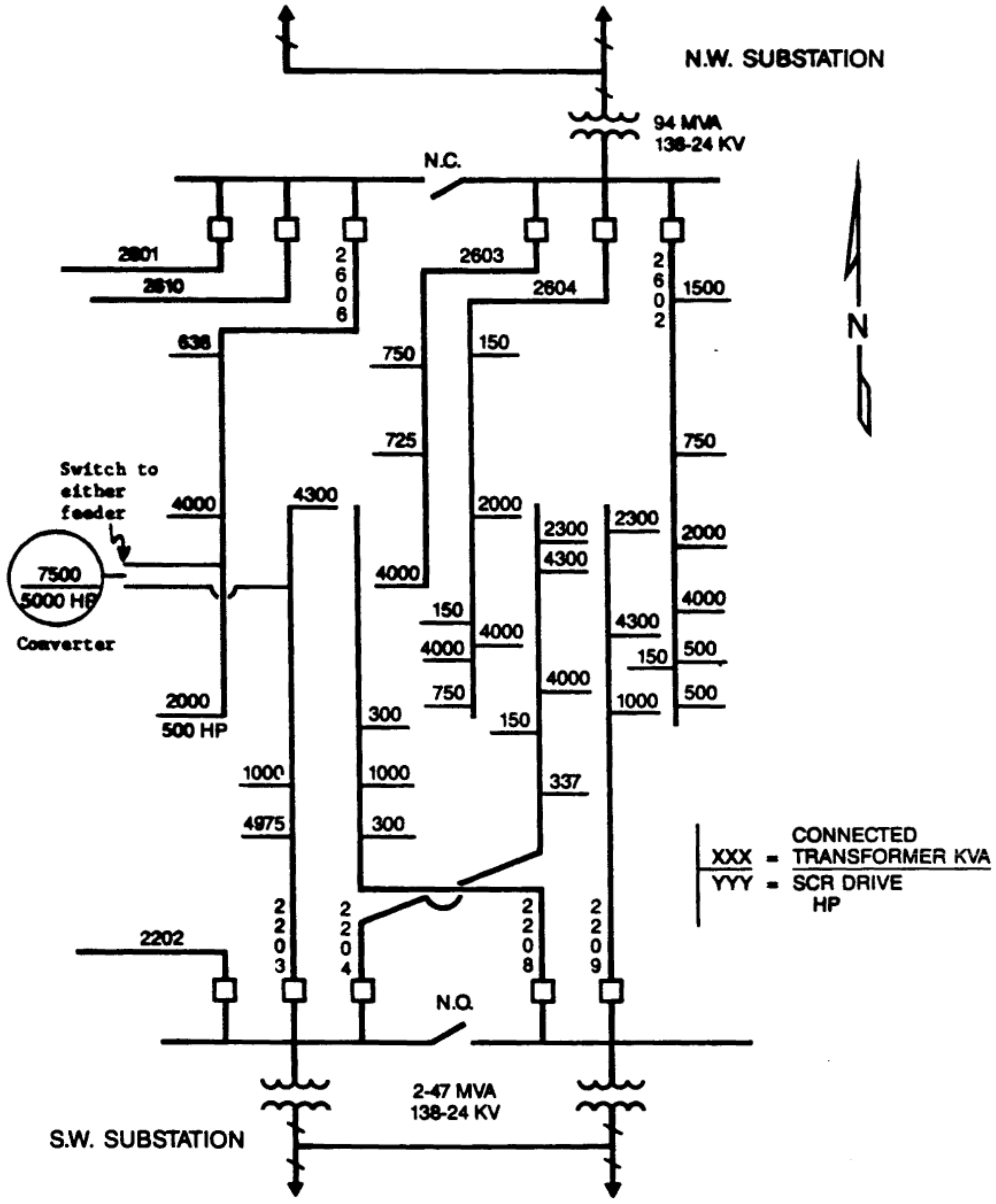


Figure 5-20
25kV System Serving 5000Hp Chiller Motor ASD

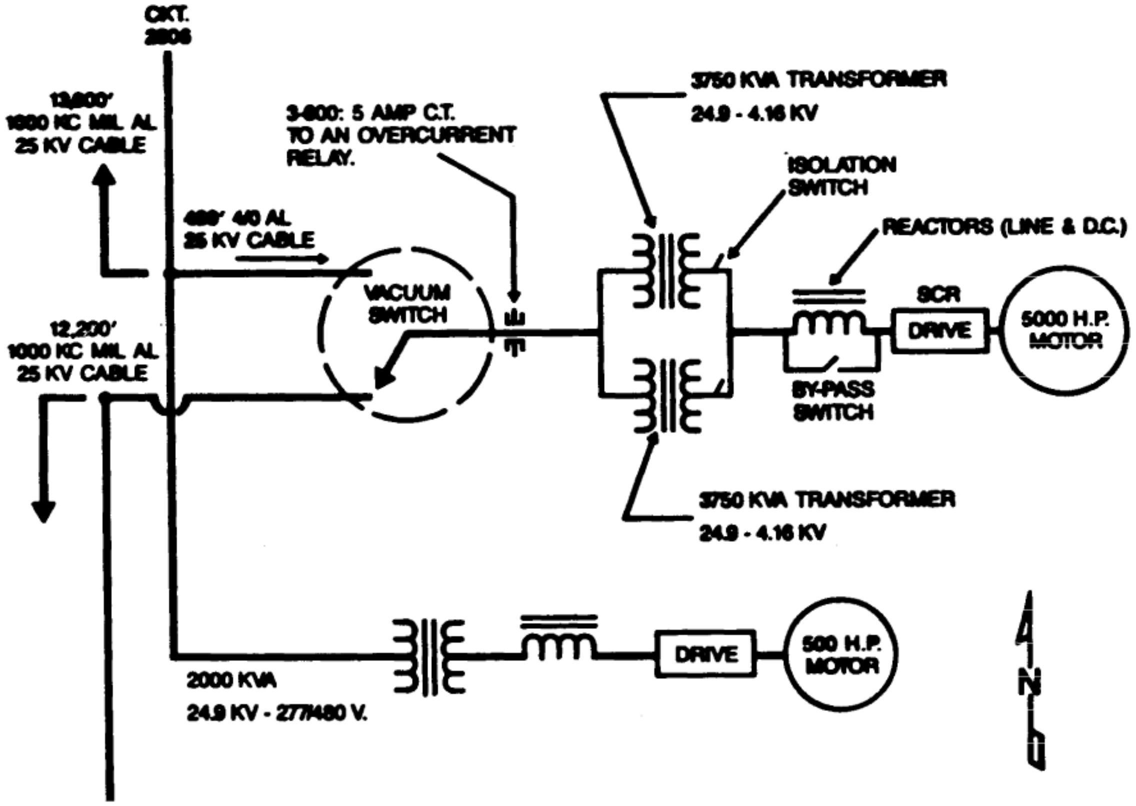


Figure 5-21
Local Connections for 5000Hp Chiller Motor ASD

Two parallel 3750kVA transformers, totaling 7500kVA, serve the ASD. Even though the 5000Hp motor draws less than 5000kVA, the parallel transformers overheat. Thus, Case 1 contains the following three classic symptoms of a harmonics problem:

1. Resonance
2. Nuisance tripping of sensitive loads
3. Overheating of transformers that cannot be explained by kVA load alone

By making voltage distortion measurements at the substation while the ASD is turned off and on, electric utility engineers confirm that the ASD is the source of the harmonics problem.

The unusual feature of this case is that there is a resonance problem even though no power factor correction capacitors are installed. Capacitors are not needed because the underground cables provide considerable power factor correction, especially during low-load periods.

To examine the impact of cables, consider the perfect coaxial case, where each meter has capacitance

$$C = \frac{2\pi\varepsilon_o\varepsilon_r}{\ln\left(\frac{r_o}{r_i}\right)} \approx \frac{2\pi \bullet 8.854 \bullet 2.25}{1} = \textit{125pF/meter/phase,}$$

and where ε_o is the permittivity of free space, ε_r is the relative permittivity of the cable dielectric, and r_i, r_o are the coaxial inner and outer radii of each phase. For three phases, the corresponding kVA at 25kV is

$$Q_{3\phi} = 3V_{LN}^2\omega C = 3 \bullet \left(\frac{25000}{\sqrt{3}}\right)^2 \bullet 120\pi \bullet 125 \bullet 10^{-12} = 29.5 \text{ VAr (three-phase)/meter.}$$

The net cable charging of the 16.27 miles of three-phase cables is then 0.772MVAr.

However, a review of the cable manufacturer's data (Table 5.4) gives the following values per meter for the three types of 25kV cables used in the system:

Table 5-4
Electrical Characteristics of 25kV Underground Cables

25kV Cable	R+	X+	C	kVAr
1/0 Al	0.696	0.1581	161	37.9
4/0 Al	0.352	0.1447	202	47.6
1000 kcmil Al	0.0827	0.1148	354	83.4

R+, X+: Positive sequence resistance and inductive reactance, 0 per meter

C: Capacitance, pF per meter per phase

KVAr: Cable kVAr (three-phase) per meter

Thus, the actual cable capacitance, which takes into account ground effects, is considerably higher than that of the ideal coaxial formula.

It is important to note that the above range of C, 161–354 pF/meter/phase, is very large compared to the 10 pF/meter/phase for overhead distribution feeders. The capacitance of overhead distribution feeders can usually be ignored in harmonics studies, especially if the feeders have power factor correction capacitors.

The subsystem contains 6.37 miles of 1000 kcmil Al, 5.40 miles of 1/0 Al, and 4.50 miles of 4/0 Al cables. Thus, the total cable charging is 1.53MVAr. Based on the substation P and *dpf* , the P and *dpf* of the converter, and the 1.53MVAr of cable charging, the *dpf* of the conventional load is estimated to be 0.770 (ignoring reactive power losses).

Simulations. Both the S.W. and N.W. systems are measured and simulated, and the comparisons for both systems match quite well. For brevity, only the results for the S.W. system are described here.

A study of the feeder blueprints shows there are 29 major load and circuit branch busses, plus the ASD bus. This set of 30 busses becomes the “retained” load busses for the study. Loads and cable charging for non-retained busses are lumped onto the nearest retained load bus. Retained busses are connected with line segments having the per meter characteristics shown in Table 5.4. The 5.60MW, 4.67MVAr of conventional load is distributed over the retained load busses (excluding the ASD) in proportion to net load transformer rating.

The ASD bus is connected to the feeder by the parallel 3750kVA transformers. Each transformer has impedance 0.79 + j5.69% on its own base, and has connection type high-side grounded-wye, low-side delta. The impedance of S.W. Transformer#1 is 1.803 + j40.8% on a 100MVA base, and the connection is high-side delta, low-side grounded-wye. The short circuit impedance on the 138kV side of S.W. Transformer#1 is 0.277 +j1.588% on a 100MVA base. The 138kV bus is assumed to have voltage 1.025pu. One-half of the line charging of the 138kV lines connected to the substation bus is 4.97MVAr.

Other nonlinear loads in the subsystem are ignored. For harmonics purposes, conventional loads are modeled as resistive elements, sized according to their active power. The ASD injection current waveform employed is that shown in Section 3, Figure 3-1.

An impedance scan (i.e., Thevenin equivalent impedance) at the 25kV converter bus, shown in Figure 5-22 as "No KVAr added," predicts strong parallel resonance at the 12th harmonic.

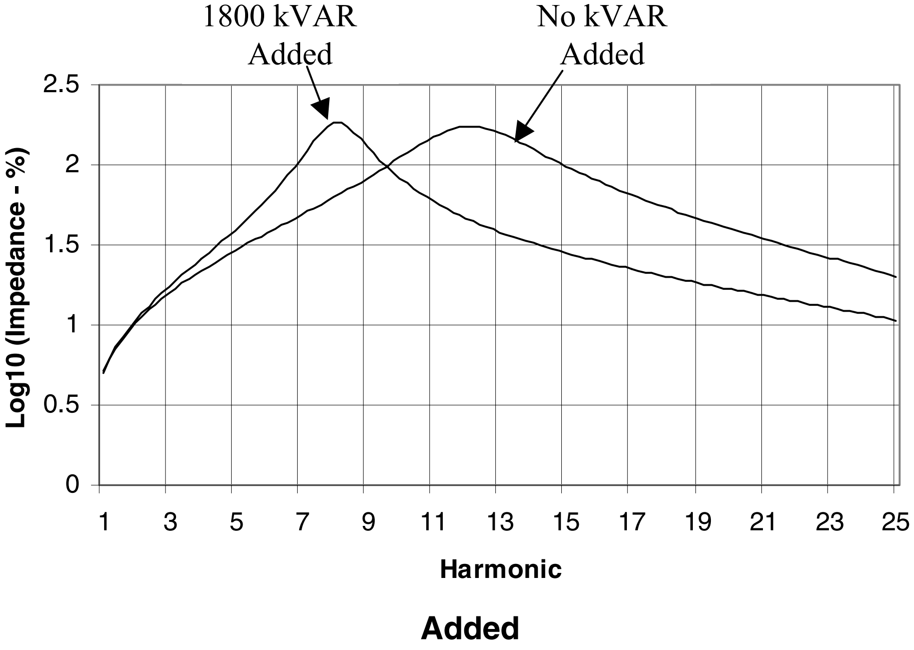


Figure 5-22
Thevenin Equivalent Impedance vs. Frequency at 25kV Converter Bus, with no kVAr Added, and with 1800kVAr

The corresponding simulation results show voltage distortions in the 25kV subsystem to be in the narrow range of 8.8 – 9.2%. Simulated voltage distortion at the 4160V ASD bus, behind the additional impedance of the parallel 25kV/4160V transformers, is 13.9%.

A comparison with measurements at the S.W. #1 25kV substation bus is given in Tables 5-5 and 5-6. Simulations and field measurements match reasonably well.

Table 5-5
Measured and Simulated Harmonic Voltages at S.W. #1 25kV Substation Bus

Harmonic	No kVAr Added. Measured V %	No kVAr Added. Simulated V %	1800 kVAr Added. Measured V %	1800 kVAr Added. Simulated V %
5	2.6	2.9	3.2	3.9
7	1.7	2.0	3.0	4.5
11	5.8	5.8	3.1	2.3
13	7.2	5.0	1.3	1.2
17	2.0	2.0	0.6	0.7
THD_V	9.9	8.7	5.6	6.5

Table 5-6
Measured and Simulated Harmonic Currents Through S.W. #1 25kV Substation Transformer

Harmonic	No kVAr Added. Measured I %	No kVAr Added. Simulated I %	1800 kVAr Added. Measured I %	1800 kVAr Added. Simulated I %
5	9.3	13.9	13.0	19.5
7	5.0	6.7	9.7	15.7
11	12.0	12.4	5.9	5.2
13	11.0	9.1	2.0	2.3
17	2.6	2.7	0.8	1.0
THD_I	19.6	22.0	17.4	25.7

In an attempt to reduce the resonance problem by detuning the feeder, 1800kVAr of capacitors are switched on at the converter 25kV bus. The simulated resonant curve shifts, as shown in

Figure 5-22, and the predicted voltage distortions across the 25kV system lower somewhat to the 6.5-7.4% range. Individual harmonics at the S.W. #1 25kV substation bus are shown in Tables 5-5 and 5-6. Unfortunately, detuning provides only a partial solution because the 5th and 7th harmonic injection currents are strong, and moving the resonant curve too close to them will only make the situation worse.

The major uncertainties in this modeling effort are:

- ASD injection current
- conventional load level and model
- cable capacitance
- cumulative effect of other nonlinear loads that are not included in the study

Case Study #10 2000HP Oil Pipeline Pumping Station ASD on 12.5kV System

Overview. There are no serious harmonics problems. Simulations compare favorably with field measurements. A 2000Hp six-pulse line-commutated ASD is connected to Bus 5 on the 12.5kV distribution system shown in Figure 5.23. The three-phase trunk portions of the two feeders connected to the substation transformer are entirely overhead construction and consist of

- 1.87 miles of 477 ACSR armless construction,
- 2.02 miles of 4/0 ACSR armless construction,
- 4.90 miles of 4/0 ACSR arm construction,
- 0.57 miles of 1/0 ACSR arm construction.

Harmonic measurements are taken on a hot summer day. The transformer load is 10.08MW, 5.47MVAr (i.e., $dpf = 0.879$), which includes 1.5MW ASD with assumed $dpf = 0.83$ (i.e., 1.05MVAr). Subtracting the ASD load from the transformer load leaves 8.58MW, 4.42MVAr for the conventional load plus capacitors. The uncorrected power factor of the conventional load is estimated to be 0.800, or 6.44MVAr. Thus, there are likely about $6.44 - 4.42 = 2.02$MVAr of shunt capacitors (plus enough to overcome line and transformer reactive power losses) in operation when the measurements are taken.

The two feeders have nine shunt capacitor banks, totaling 7.95MVAr. 5.10MVAr of the capacitors are time-controlled or time-temperature controlled, and 2.85MVAr are regulated by either voltage, current, or power factor. At the time of the measurements, time-controlled and time-temperature controlled capacitors are supposed to be on, and the regulated capacitors are most likely off due to good voltage and power factor levels. For purposes of comparing simulations to measurements, it is assumed that all of the 5.10MVAr of time and time-temperature capacitors are on-line. In relation to Figure 5-23, these are:

Case Studies

- 600kVAr at Bus 3
- 600kVAr at Bus 4
- 600kVAr at Bus 7
- 600kVAr at Bus 20
- 1200kVAr at Bus 21
- 600kVAr at Bus 24
- 900kVAr at Bus 25

Simulations. The connected load transformer kVA information is not readily available. As an approximation, it is assumed that the 8.58MW, 4.42MVAr of conventional load is uniformly distributed over all 12.5kV busses except the substation transformer buss. The conventional loads are modeled for harmonic purposes as shunt resistors. Single-phase laterals, underground cable segments from distribution poles to service transformers, and overhead line capacitances are ignored. The ASD is modeled as a 1/k-rule harmonics injector.

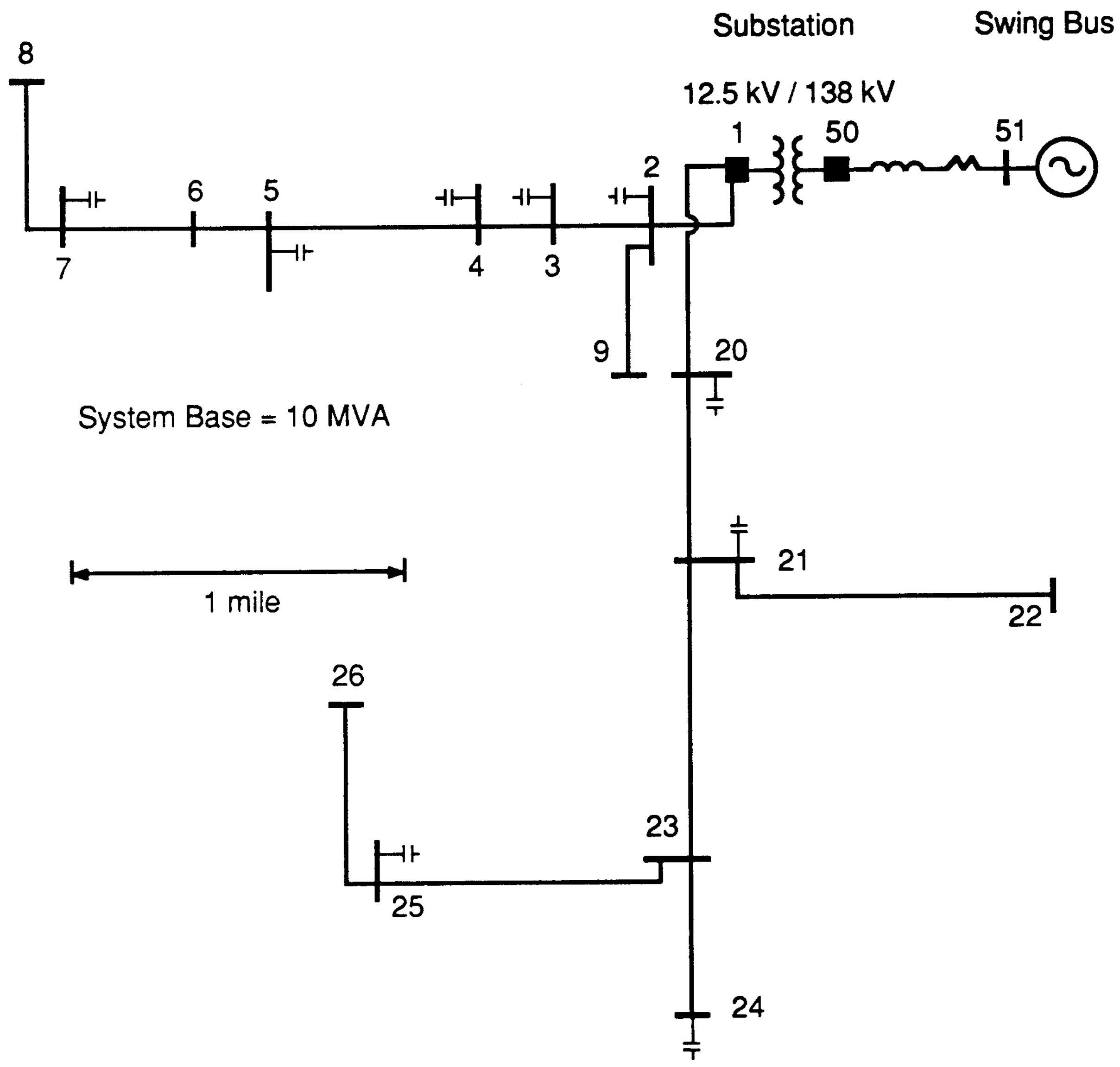


Figure 5-23
12kV System Serving 2000Hp Pipeline ASD

A 10MVA base is chosen. The positive/negative sequence Thevenin equivalent of the 138kV system (excluding the substation transformer) is 0.05 + j0.344%, with voltage 1.04pu. A shunt capacitance equal to one-half of the combined line charging of the 138kV transmission lines connected to the transformer (i.e., 24% on 10MVA base) is placed as a shunt element on the transformer 138kV bus. The substation transformer has positive/negative sequence impedance 0.312 + j6.75%.

Voltage distortion measurements are taken at the substation 12.5kV transformer bus and at the ASD. A comparison of measurements and simulations is given in Table 5.7

Table 5-7
Measured and Simulated Voltage Distortion Levels in Oil Pipeline Distribution Feeders

Measured at ASD Bus. THD_V - %	Simulated at ASD Bus. THD_V - %	Measured at Substation Transformer. THD_V - %	Measured at Substation Transformer. THD_V - %
3.3	3.6	2.1	1.9

The highest simulated THD_V for this case is 4.0% at Busses 8 and 26. It is interesting to note that Bus 26 is the most distant bus from the converter and is on an adjacent feeder served by the same substation tranformer.

Two other cases are simulated. When all capacitors are on, the highest THD_V is 4.3% at Bus 7. When only the regulated capacitors are on, the highest THD_V is 5.7% at the ASD bus. Hence, when a feeder has switched shunt capacitors:

- the highest voltage distortion may be at a remote point from the harmonics source
- the highest distortion case may be a situation when only a subset of the capacitors are on-line

Since the voltage distortions are not objectionable, no additional work is needed in this case.

Case Study #11. Television Broadcast Station on 25kV System

Overview. There is a serious problem where the broadcast picture wobbles due to interaction of a constant-voltage transformer with a distribution system that was upgraded from 12.5kV to 25kV. Simulations support a quickly-implemented field solution.The policy of this electric utility is to avoid 25kV delta, grounded-wye transformers because of potential ferroresonance problems. When a metropolitian area overhead distribution system is upgraded from 12.5kVto 25kV, all delta, grounded-wye service transformers are replaced with grounded-wye, grounded-wye transformers.

In this case, the voltage upgrade and transformer replacement coincides with the appearance of an annoying flicker on the broadcast signal of a television station. The problem is traced to fluctuations on the output of a 480V/480V saturable reactor transformer that is supposed to maintain constant 480V (± 1%) voltage to the transmitter rectifier. Measurements show that the neutral current on the primary of the saturable transformer rises from 30A before the upgrade to 325A after the upgrade, and that the neutral current is primarily 3rd harmonic. Furthermore, the primary phase current rises to 500A, while the load current remains 380A. The saturable transformer hums loudly after the upgrade.

Utility engineers suspect that the problem is harmonics-related. Several capacitor banks on the feeder are switched off, and the situation improves but does not disappear. In an attempt to solve the problem quickly, a special-ordered 25kV/480V delta, grounded-wye service transformer is installed in place of the new grounded-wye, grounded-wye transformer, and the problem disappears. Thus, it is speculated that the problem is due to harmonics, and specifically to the zero-sequence 3rd harmonic.

Simulations. At this point, simulations are performed to confirm that the "quick fix" transformer replacement can be explained. While there is no easy way to determine how the control system of the saturable transformer reacts with 3rd harmonic voltages, it is relatively easy to show with simulations that the Thevenin impedance of the 480V bus is

- not affected by the 25kV upgrade, but
- greatly affected by the replacement of the service transformer.

With the delta, grounded-wye transformer, the impedance "seen" by the saturable transformer is simply the grounded impedance of the 25kV/480V service transformer. However, with the grounded-wye, grounded-wye service transformer, the impedance is the service transformer impedance plus system impedance.

The study system has three feeders served by a substation transformer. The total load is 17.8MW, 11.0MVAr, *dpf* = 0.85. There are 15 power factor correction capacitor banks, totaling 9.3MVAr. The Thevenin equivalent impedance on the 138kV side of the substation transformer is 0.0376 + j0.2547% for positive/negative sequence, and 0.094 + j0.6368% for zero sequence, on a 10MVA base. The transformer impedance is 0.354 + j6.92% on a 10MVA base, and it is connected delta on the 138kV side, and grounded-wye on the 25kV side. The retained 25kV system has 109 busses. One-half of the combined line charging on the 138kV side of the substation transformer is 13.5MVAr.

Plots of the positive/negative and zero sequence impedances at the television 25kV bus are shown in Figure 5-24. It is clear that the 25kV system has parallel resonance for zero sequence near the 3rd harmonic. With the delta, grounded-wye service transformer, the saturable transformer does not "see" this 3rd harmonic resonance, but rather the relatively low impedance of the transformer to ground.

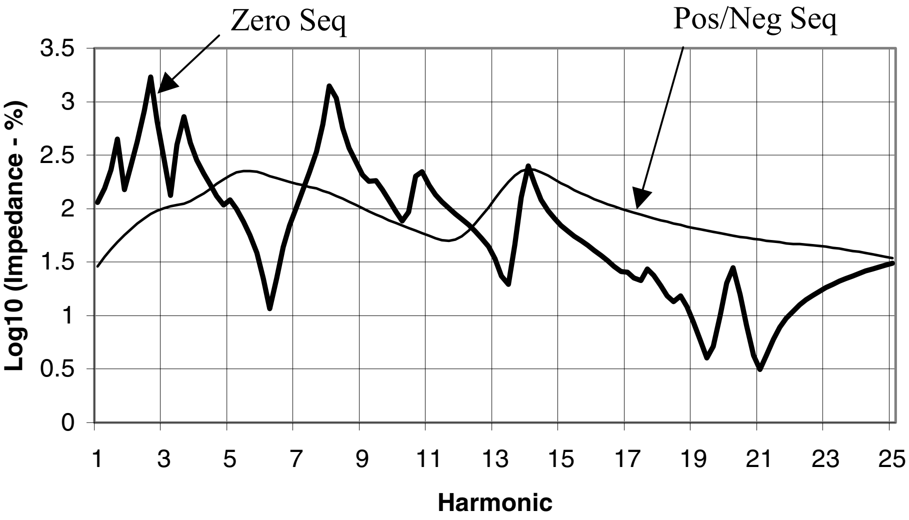


Figure 5-24
Thevenin Equivalent Impedance vs. Frequency at 25kV Television Station Bus

Summarizing, while the control instability problem is not explained, the simulations do confirm that 3rd harmonic resonance coincides with the appearance of the problem, and that by using a grounded-wye, grounded-wye transformer, the situation can be returned to normal.

Case Study #12. 12.5kV Ski Area with 5150HP of Distributed Lift Motor ASDs

Overview. This is a planning study where simulations are used to design a harmonics mitigation strategy. This case illustrates the effectiveness of phase cancellation and passive filters.This case deals with the proposed expansion of a ski area. The 12.5kV underground system will eventually have eight ski lifts powered by DC motor drives, totaling 5150Hp. The DC motors will be driven by six-pulse line-commutated ASDs so that the lifts will have soft-start, soft-stop operation. Measurements of the proposed system are, or course, not possible. Thus, the harmonics situation must be analyzed in advance using simulations.

Simulations. A diagram of the ski area is shown in Figure 5-25. In addition to the ASD loads, the ski area has 6 MVA of linear load. The ASDs are modeled using the 1/k rule for harmonics through the 25th, with no phase angle diversity. The *dpfs* of the ASDs and linear load are assumed to be 0.85. Cable capacitance is assumed to be 125pF/m/phase.

The point of common coupling (PCC) is Bus #20, Substation 138 kV. I_{sc} and I_{load} at the PCC are 34.4 pu and 1.054 pu, respectively, on a 10MVA base. Twelve-month average I_{load} is estimated to be 0.75 • 1.054 = 0.791 pu, so I_{sc}/I_{load} at the PCC is 43.5, and the corresponding IEEE 519 limit for TDD of current is 8.0%.

The three cases studied are

Case 4A. No Corrections.

Case 4B. 30° phase shifting transformers added at Apollo and BigBoss ASDs.

Case 4C. Case 4B, plus 1800kVAr of filters.

Bracketed values in Figure 5.25 give solved THD_V s for [Case 4A, Case 4B, Case 4C], except at the substation transformer, where THD_I is given directly under Z.

The results for Case 4A are shown in Figures 5-26 through 5-30. The highest voltage distortion is an unacceptable 13.2% at Bus #12, Apollo.

For Case 4B, wye-delta transformers are added at approximately one-half of the ASD HP, so that a net twelve-pulse operation for the entire ski area is approximated. Results are shown in Figures 5-31 – 5-33. The highest voltage distortion reduces to 8.9% at Bus #12, Apollo.

Case 4C builds upon Case 4B by adding the following passive filters:

- 300kVAr of 5th at Bus#6, Base.

- 300kVAr of 5th at Bus#10, Taylor.
- 300kVAr of 7th at Bus#10, Taylor.
- 300kVAr of 11th at Bus#12, Apollo.
- 300kVAr of 11th at Bus#15, BigBoss.
- 300kVAr of 13th at Bus#13, Jupiter.

Filter X/R equals 50. The 5th and 7th harmonics have only one-half of the dedicated kVArs because the two wye-delta transformers have already reduced 5th and 7th harmonic voltages. Some 5th and 7th filtering is still needed in case one or both of the wye-delta transformers are out of service (simulations for this contingency were made but are not presented here).

Results for Case 4C are shown in Figures 5-34 through 5-37. The highest feeder voltage distortion level falls to 2.5%, occurring at Bus #14, WipeOut.

A side benefit of the filters is that they correct the ski area power factor from 0.82 to 0.90, thus providing both a harmonics and power factor solution.

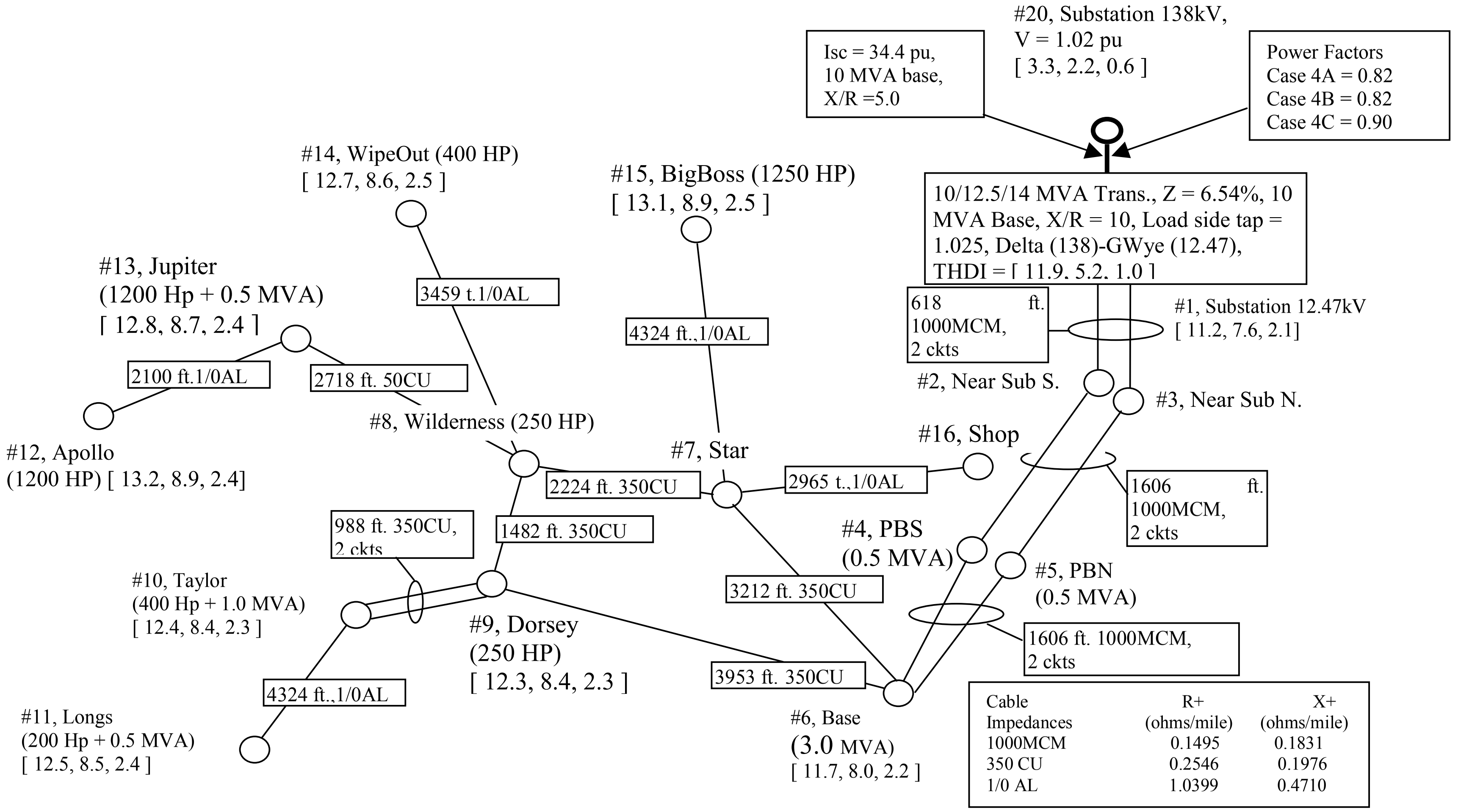
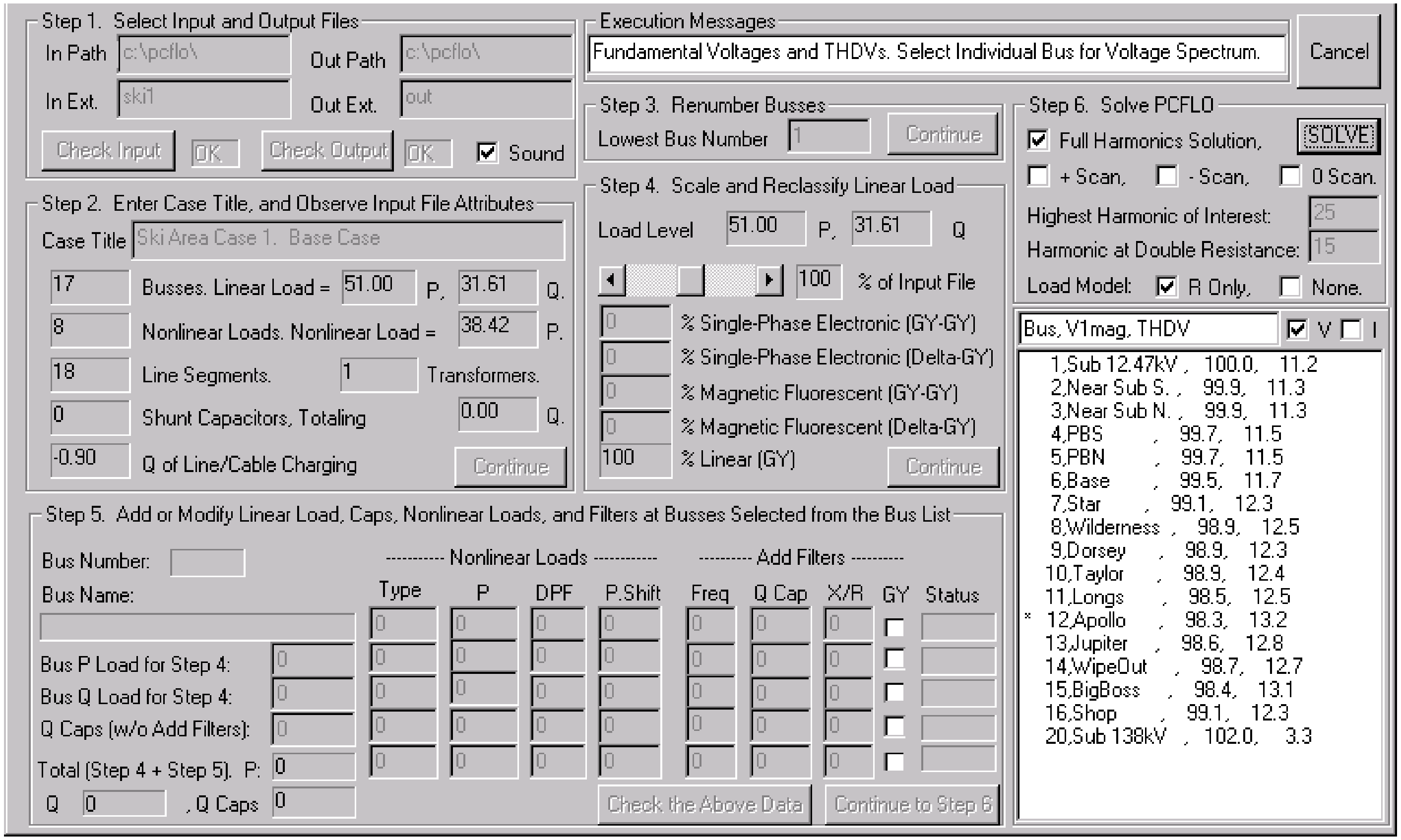


Figure 5-25
Case 4, Ski Area



Step 1. Select Input and Output Files
In Path: c:\pcflo\
Out Path: c:\pcflo\
In Ext.: ski1
Out Ext.: out
☑ Sound

Step 2. Enter Case Title, and Observe Input File Attributes
Case Title: Ski Area Case 1. Base Case
17 Busses. Linear Load = 51.00 P, 31.61 Q.
8 Nonlinear Loads. Nonlinear Load = 38.42 P.
18 Line Segments. 1 Transformers.
0 Shunt Capacitors, Totaling 0.00 Q.
-0.90 Q of Line/Cable Charging

Execution Messages: Fundamental Voltages and THDVs. Select Individual Bus for Voltage Spectrum.

Step 3. Renumber Busses
Lowest Bus Number: 1

Step 4. Scale and Reclassify Linear Load
Load Level: 51.00 P, 31.61 Q
100 % of Input File
0 % Single-Phase Electronic (GY-GY)
0 % Single-Phase Electronic (Delta-GY)
0 % Magnetic Fluorescent (GY-GY)
0 % Magnetic Fluorescent (Delta-GY)
100 % Linear (GY)

Step 5. Add or Modify Linear Load, Caps, Nonlinear Loads, and Filters at Busses Selected from the Bus List
Bus P Load for Step 4: 0
Bus Q Load for Step 4: 0
Q Caps (w/o Add Filters): 0
Total (Step 4 + Step 5). P: 0
Q 0, Q Caps 0

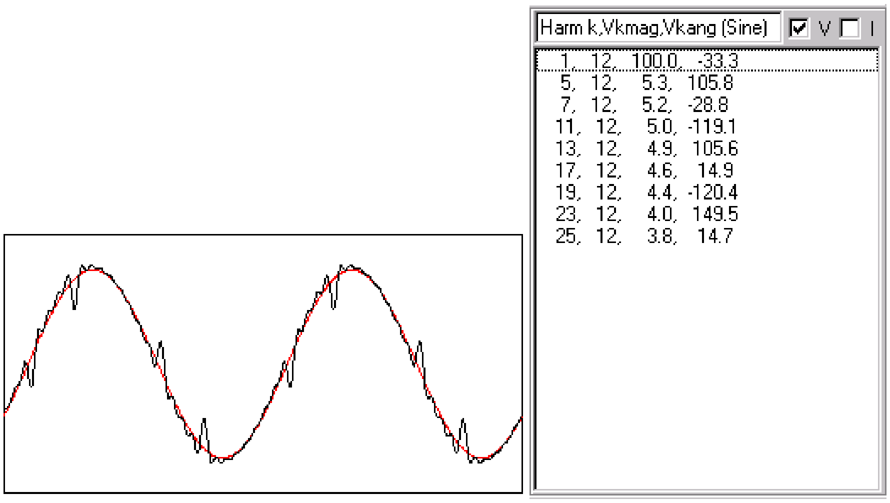
Step 6. Solve PCFLO
☑ Full Harmonics Solution,
☐ + Scan, ☐ - Scan, ☐ 0 Scan.
Highest Harmonic of Interest: 25
Harmonic at Double Resistance: 15
Load Model: ☑ R Only, ☐ None.

Bus, V1mag, THDV ☑ V ☐ I

```
  1,Sub 12.47kV ,  100.0,  11.2
  2,Near Sub S. ,   99.9,  11.3
  3,Near Sub N. ,   99.9,  11.3
  4,PBS         ,   99.7,  11.5
  5,PBN         ,   99.7,  11.5
  6,Base        ,   99.5,  11.7
  7,Star        ,   99.1,  12.3
  8,Wilderness  ,   98.9,  12.5
  9,Dorsey      ,   98.9,  12.3
 10,Taylor      ,   98.9,  12.4
 11,Longs       ,   98.5,  12.5
* 12,Apollo     ,   98.3,  13.2
 13,Jupiter     ,   98.6,  12.8
 14,WipeOut     ,   98.7,  12.7
 15,BigBoss     ,   98.4,  13.1
 16,Shop        ,   99.1,  12.3
 20,Sub 138kV   ,  102.0,   3.3
```

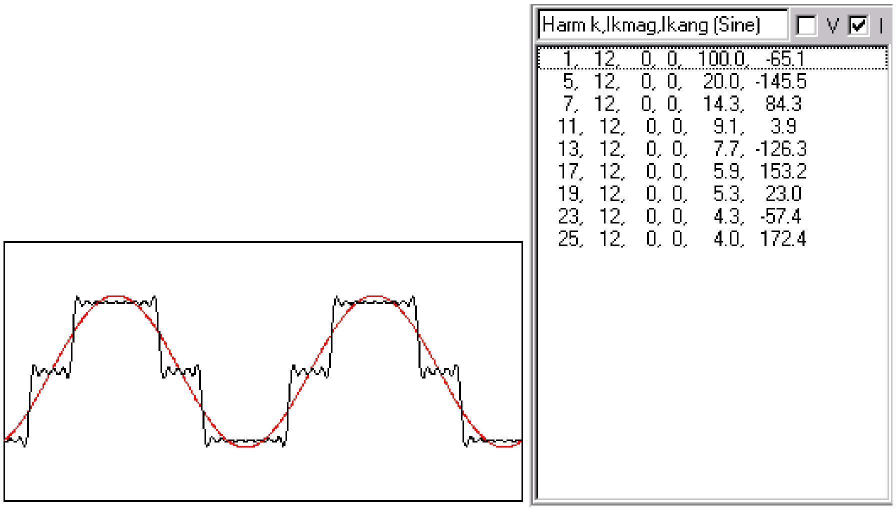
Figure 5-26
Case 4A Interface Screen

Note - the highest harmonic of interest is manually changed from 49 to 25. Solved THD_V s are shown. The highest THD_V , 13.2% at Bus #12, Apollo, is identified by the asterisk.



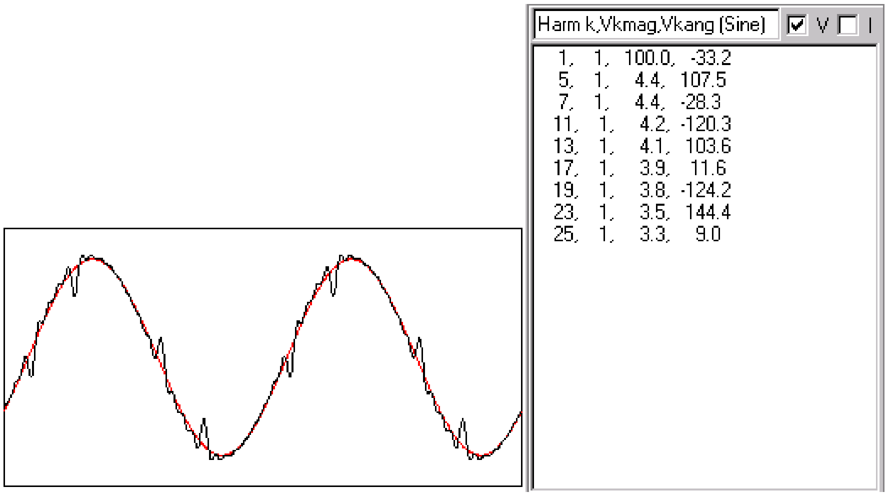
```
 1,  12,  100.0,  -33.3
 5,  12,    5.3,  105.8
 7,  12,    5.2,  -28.8
11,  12,    5.0, -119.1
13,  12,    4.9,  105.6
17,  12,    4.6,   14.9
19,  12,    4.4, -120.4
23,  12,    4.0,  149.5
25,  12,    3.8,   14.7
```

Figure 5-27
Case 4A, Voltage Waveform and Spectrum at Bus #12, Apollo
(THD_V = 13.2%)



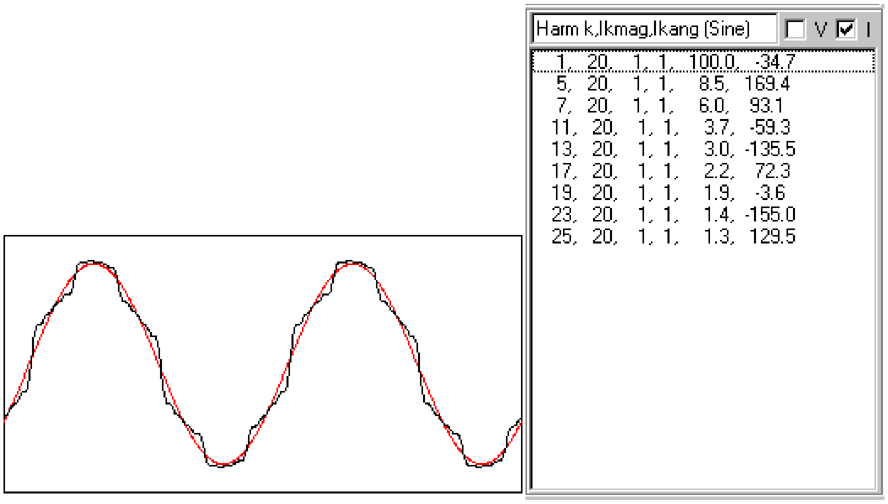
```
 1,  12,  0, 0,  100.0,  -65.1
 5,  12,  0, 0,   20.0, -145.5
 7,  12,  0, 0,   14.3,   84.3
11,  12,  0, 0,    9.1,    3.9
13,  12,  0, 0,    7.7, -126.3
17,  12,  0, 0,    5.9,  153.2
19,  12,  0, 0,    5.3,   23.0
23,  12,  0, 0,    4.3,  -57.4
25,  12,  0, 0,    4.0,  172.4
```

Figure 5-28
Case 4A, Current Injection Waveform and Spectrum at Bus #12, Apollo
(THD_I = 29.0%)



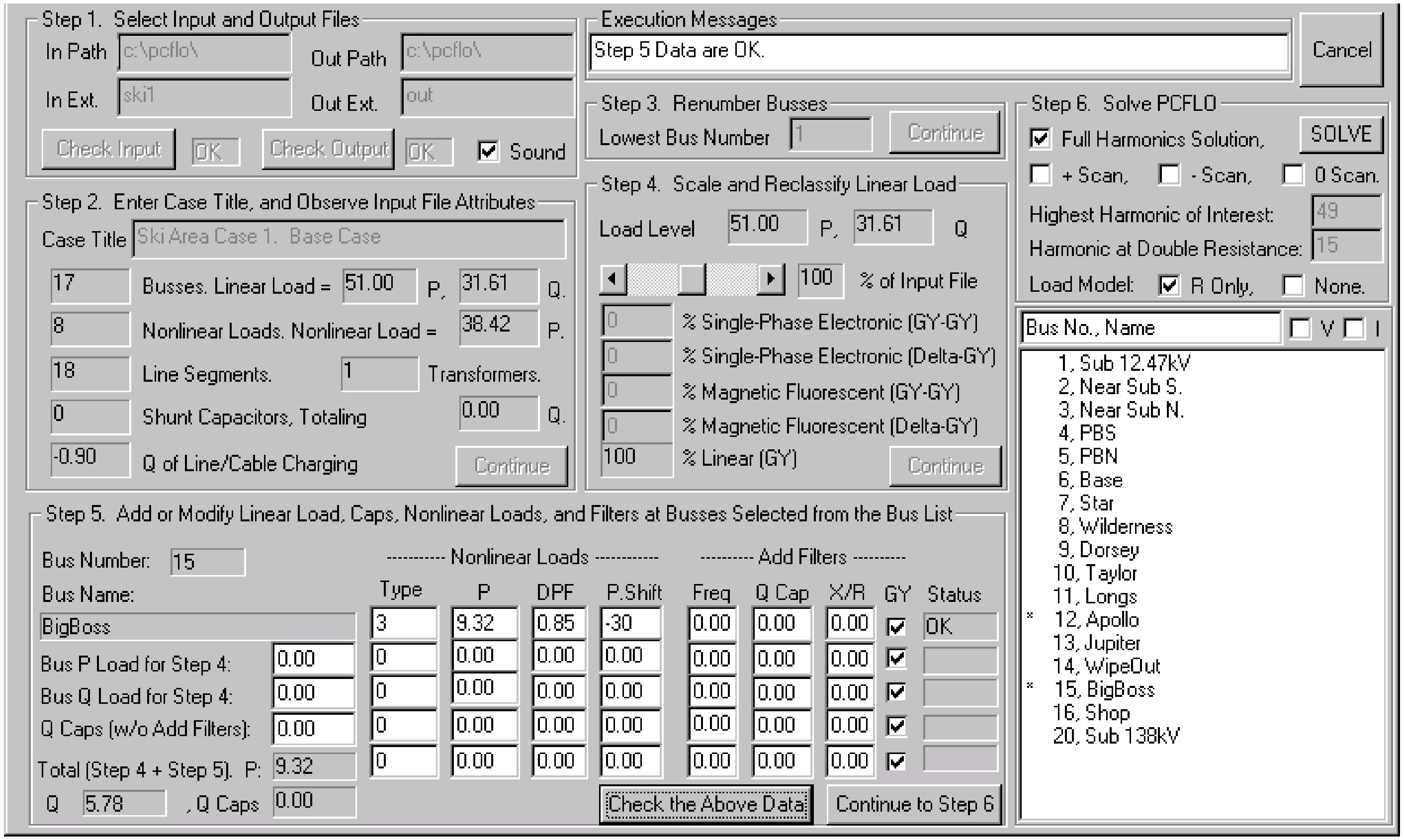
```
Harm k,Vkmag,Vkang (Sine)  ☑ V ☐ I
  1,   1,  100.0,  -33.2
  5,   1,    4.4,  107.5
  7,   1,    4.4,  -28.3
 11,   1,    4.2, -120.3
 13,   1,    4.1,  103.6
 17,   1,    3.9,   11.6
 19,   1,    3.8, -124.2
 23,   1,    3.5,  144.4
 25,   1,    3.3,    9.0
```

Figure 5-29
Case 4A, Voltage Waveform and Spectrum at Bus #1, Substation 12.5 kV (THD_V = 11.2%)



```
Harm k,Ikmag,Ikang (Sine)  ☐ V ☑ I
  1,  20,  1,  1,  100.0,  -34.7
  5,  20,  1,  1,    8.5,  169.4
  7,  20,  1,  1,    6.0,   93.1
 11,  20,  1,  1,    3.7,  -59.3
 13,  20,  1,  1,    3.0, -135.5
 17,  20,  1,  1,    2.2,   72.3
 19,  20,  1,  1,    1.9,   -3.6
 23,  20,  1,  1,    1.4, -155.0
 25,  20,  1,  1,    1.3,  129.5
```

Figure 5-30
Case 4A, Substation Transformer Current Waveform and Spectrum on 138 kV side (THD_I = 11.9%)



Execution Messages: Step 5 Data are OK.

Step 1. Select Input and Output Files
In Path: c:\pcflo\
Out Path: c:\pcflo\
In Ext.: ski1
Out Ext.: out
Check Input: OK
Check Output: OK
☑ Sound

Step 2. Enter Case Title, and Observe Input File Attributes
Case Title: Ski Area Case 1. Base Case
17 Busses. Linear Load = 51.00 P, 31.61 Q.
8 Nonlinear Loads. Nonlinear Load = 38.42 P.
18 Line Segments. 1 Transformers.
0 Shunt Capacitors, Totaling 0.00 Q.
-0.90 Q of Line/Cable Charging

Step 3. Renumber Busses
Lowest Bus Number: 1

Step 4. Scale and Reclassify Linear Load
Load Level: 51.00 P, 31.61 Q
100 % of Input File
0 % Single-Phase Electronic (GY-GY)
0 % Single-Phase Electronic (Delta-GY)
0 % Magnetic Fluorescent (GY-GY)
0 % Magnetic Fluorescent (Delta-GY)
100 % Linear (GY)

Step 5. Add or Modify Linear Load, Caps, Nonlinear Loads, and Filters at Busses Selected from the Bus List
Bus Number: 15
Bus Name: BigBoss
Bus P Load for Step 4: 0.00
Bus Q Load for Step 4: 0.00
Q Caps (w/o Add Filters): 0.00
Total (Step 4 + Step 5). P: 9.32
Q: 5.78, Q Caps: 0.00

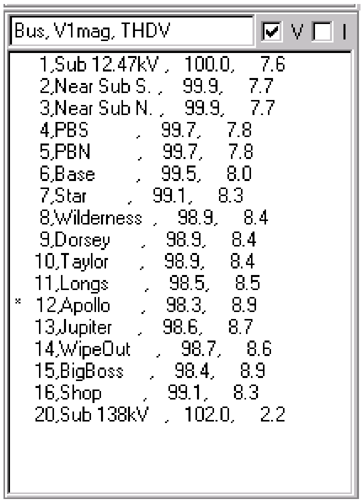
Nonlinear Loads				Add Filters				
Type	P	DPF	P.Shift	Freq	Q Cap	X/R	GY	Status
3	9.32	0.85	-30	0.00	0.00	0.00	☑	OK
0	0.00	0.00	0.00	0.00	0.00	0.00	☑	
0	0.00	0.00	0.00	0.00	0.00	0.00	☑	
0	0.00	0.00	0.00	0.00	0.00	0.00	☑	
0	0.00	0.00	0.00	0.00	0.00	0.00	☑	

Step 6. Solve PCFLO
☑ Full Harmonics Solution,
☐ + Scan, ☐ - Scan, ☐ 0 Scan.
Highest Harmonic of Interest: 49
Harmonic at Double Resistance: 15
Load Model: ☑ R Only, ☐ None.

Bus No., Name ☐ V ☐ I
1, Sub 12.47kV
2, Near Sub S.
3, Near Sub N.
4, PBS
5, PBN
6, Base
7, Star
8, Wilderness
9, Dorsey
10, Taylor
11, Longs
* 12, Apollo
13, Jupiter
14, WipeOut
* 15, BigBoss
16, Shop
20, Sub 138kV

Figure 5-31

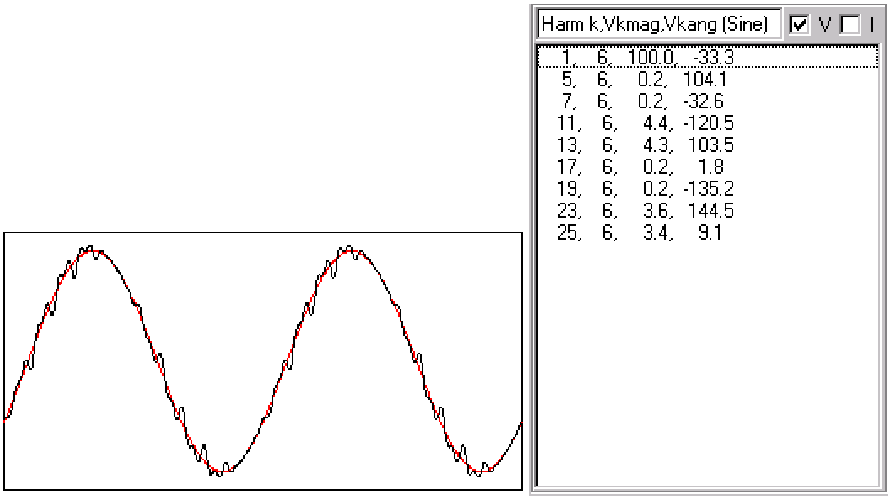
Case 4B, Interface Screen Showing 30^{O} Phase Shift Being Added at Bus #15, BigBoss (Note – 30^{O} is also added at Apollo)



Bus, V1mag, THDV ☑ V ☐ I

```
   1,Sub 12.47kV ,  100.0,    7.6
   2,Near Sub S. ,   99.9,    7.7
   3,Near Sub N. ,   99.9,    7.7
   4,PBS       ,   99.7,    7.8
   5,PBN       ,   99.7,    7.8
   6,Base      ,   99.5,    8.0
   7,Star      ,   99.1,    8.3
   8,Wilderness ,   98.9,    8.4
   9,Dorsey    ,   98.9,    8.4
  10,Taylor    ,   98.9,    8.4
  11,Longs     ,   98.5,    8.5
* 12,Apollo    ,   98.3,    8.9
  13,Jupiter   ,   98.6,    8.7
  14,WipeOut   ,   98.7,    8.6
  15,BigBoss   ,   98.4,    8.9
  16,Shop      ,   99.1,    8.3
  20,Sub 138kV ,  102.0,    2.2
```

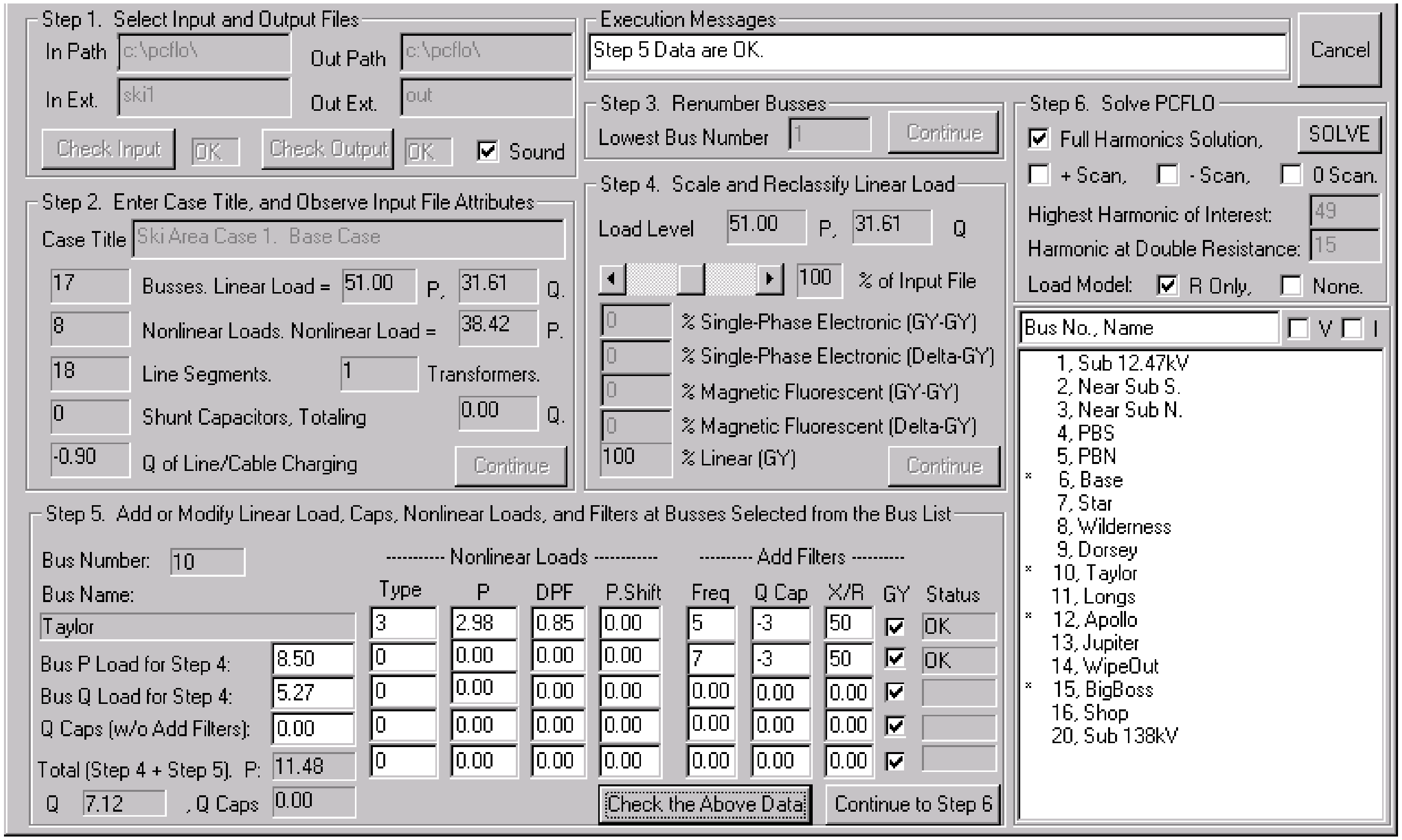
Figure 5-32
Case 4B, THD_V **s**



Harm k,Vkmag,Vkang (Sine) ☑ V ☐ I

```
  1,  6,  100.0,  -33.3
  5,  6,    0.2,  104.1
  7,  6,    0.2,  -32.6
 11,  6,    4.4, -120.5
 13,  6,    4.3,  103.5
 17,  6,    0.2,    1.8
 19,  6,    0.2, -135.2
 23,  6,    3.6,  144.5
 25,  6,    3.4,    9.1
```

Figure 5-33
Case 4B, Voltage Waveform and Spectrum at Bus #6, Base (THD_V **= 8.0%)**



Step 1. Select Input and Output Files
In Path: c:\pcflo\
Out Path: c:\pcflo\
In Ext.: ski1
Out Ext.: out

☑ Sound

Execution Messages
Step 5 Data are OK.

Step 2. Enter Case Title, and Observe Input File Attributes
Case Title: Ski Area Case 1. Base Case
17 Busses. Linear Load = 51.00 P, 31.61 Q.
8 Nonlinear Loads. Nonlinear Load = 38.42 P.
18 Line Segments. 1 Transformers.
0 Shunt Capacitors, Totaling 0.00 Q.
-0.90 Q of Line/Cable Charging

Step 3. Renumber Busses
Lowest Bus Number: 1

Step 4. Scale and Reclassify Linear Load
Load Level: 51.00 P, 31.61 Q
100 % of Input File
0 % Single-Phase Electronic (GY-GY)
0 % Single-Phase Electronic (Delta-GY)
0 % Magnetic Fluorescent (GY-GY)
0 % Magnetic Fluorescent (Delta-GY)
100 % Linear (GY)

Step 6. Solve PCFLO
☑ Full Harmonics Solution,
☐ + Scan, ☐ - Scan, ☐ 0 Scan.
Highest Harmonic of Interest: 49
Harmonic at Double Resistance: 15
Load Model: ☑ R Only, ☐ None.

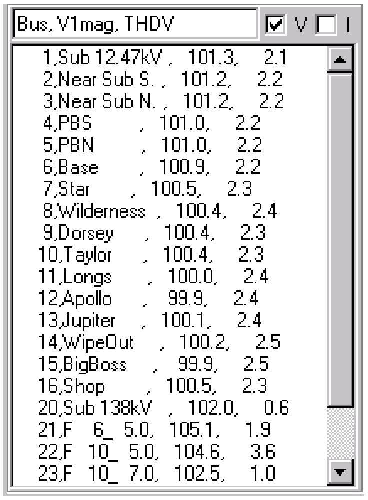
Bus No., Name ☐ V ☐ I
1, Sub 12.47kV
2, Near Sub S.
3, Near Sub N.
4, PBS
5, PBN
* 6, Base
7, Star
8, Wilderness
9, Dorsey
* 10, Taylor
11, Longs
* 12, Apollo
13, Jupiter
14, WipeOut
* 15, BigBoss
16, Shop
20, Sub 138kV

Step 5. Add or Modify Linear Load, Caps, Nonlinear Loads, and Filters at Busses Selected from the Bus List
Bus Number: 10
Bus Name: Taylor
Bus P Load for Step 4: 8.50
Bus Q Load for Step 4: 5.27
Q Caps (w/o Add Filters): 0.00
Total (Step 4 + Step 5). P: 11.48
Q 7.12 , Q Caps 0.00

Nonlinear Loads				Add Filters				
Type	P	DPF	P.Shift	Freq	Q Cap	X/R	GY	Status
3	2.98	0.85	0.00	5	-3	50	☑	OK
0	0.00	0.00	0.00	7	-3	50	☑	OK
0	0.00	0.00	0.00	0.00	0.00	0.00	☑	
0	0.00	0.00	0.00	0.00	0.00	0.00	☑	
0	0.00	0.00	0.00	0.00	0.00	0.00	☑	

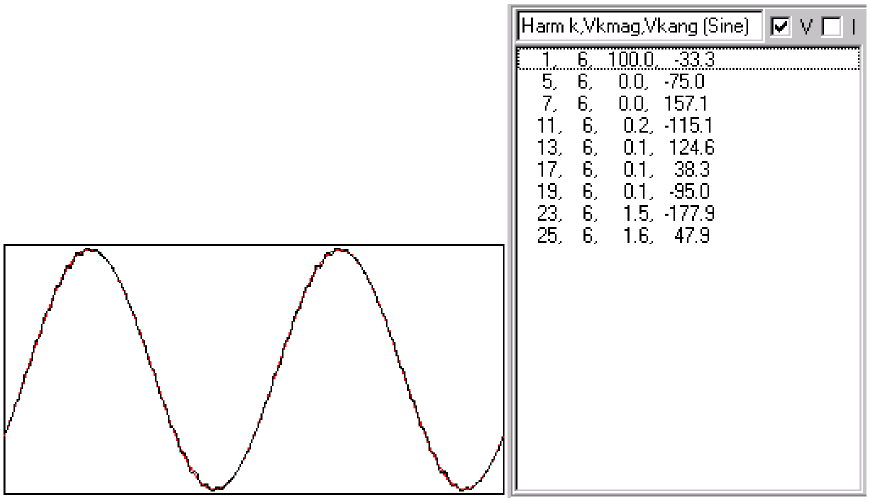
Figure 5-34
Case 4C, Interface Screen Showing 300 kVAr 5th and 7th Harmonic Filters Being Added at Bus #10, Taylor

(Note – 300 kVAr corresponds to 3% on a 10 MVA base. Negative 3% signifies capacitive VARs.)



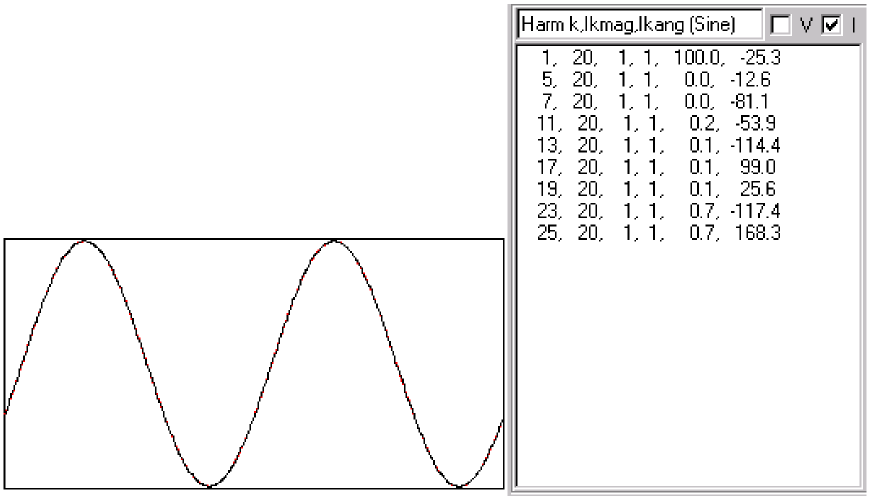
```
 1,Sub 12.47kV ,   101.3,    2.1
 2,Near Sub S. ,  101.2,    2.2
 3,Near Sub N. ,  101.2,    2.2
 4,PBS        ,  101.0,    2.2
 5,PBN        ,  101.0,    2.2
 6,Base       ,  100.9,    2.2
 7,Star       ,  100.5,    2.3
 8,Wilderness ,  100.4,    2.4
 9,Dorsey     ,  100.4,    2.3
10,Taylor     ,  100.4,    2.3
11,Longs      ,  100.0,    2.4
12,Apollo     ,   99.9,    2.4
13,Jupiter    ,  100.1,    2.4
14,WipeOut    ,  100.2,    2.5
15,BigBoss    ,   99.9,    2.5
16,Shop       ,  100.5,    2.3
20,Sub 138kV  ,  102.0,    0.6
21,F   6_ 5.0,  105.1,    1.9
22,F  10_ 5.0,  104.6,    3.6
23,F  10_ 7.0,  102.5,    1.0
```

Figure 5-35
Case 4C THD_V s



```
 1,  6, 100.0,  -33.3
 5,  6,   0.0,  -75.0
 7,  6,   0.0,  157.1
11,  6,   0.2, -115.1
13,  6,   0.1,  124.6
17,  6,   0.1,   38.3
19,  6,   0.1,  -95.0
23,  6,   1.5, -177.9
25,  6,   1.6,   47.9
```

Figure 5-36
Case 4C Voltage Waveform and Spectrum at Bus #6, Base (THD_V = 2.2%)



```
  1,  20,   1, 1,  100.0,  -25.3
  5,  20,   1, 1,    0.0,  -12.6
  7,  20,   1, 1,    0.0,  -81.1
 11,  20,   1, 1,    0.2,  -53.9
 13,  20,   1, 1,    0.1, -114.4
 17,  20,   1, 1,    0.1,   99.0
 19,  20,   1, 1,    0.1,   25.6
 23,  20,   1, 1,    0.7, -117.4
 25,  20,   1, 1,    0.7,  168.3
```

Figure 5-37
Case 4C, Substation Transformer Current Waveform and Spectrum on 138 kV side (THD_I **= 1.0%)**

Case Study # 13 1500HP Pumping Station ASD on 13.2kV System

Note: This case study is provided by Mr. Ramon Saenz, Central and South West Corporation, and Mr. Harry Simpson, Public Service Company of Oklahoma.

Overview. Serious voltage resonance causes fast digital clocks. This case illustrates the use of field measurements to propose and implement a field solution. A small community in Southwestern Oklahoma experiences problems with clocks gaining time. The telephone company tries many solutions, including filters, to maintain quality voice signals. In addition, Public Service Company of Oklahoma (PSO) personnel reconfigure the distribution system in an attempt to correct the problem. The PSO Power Quality Team becomes involved after others have exhausted their options.

The Power Quality Team consulted with local PSO personnel, telephone company personnel, the CSW Power Quality Team, and some of the customers who are impacted. All of them suspect that a pumping station in the area is the source of the problem. Rather than going directly to the pumping station first, the PQ Team begins an investigation, knowing that proof will be needed.

Measurements. The one-line diagram of the affected system is shown in Figure 5-38. The substation transformer is a 7.5MVA, 69kV-13.8kV, with two feeders connected. Waveforms for both feeders are observed at the substation, and from these observations, the industrial feeder is positively identified as having the problem load. From the voltage and current waveforms shown in Figure 5-39 and described in Table 5-8, Figure 5-40, and Figure 5-41, it is apparent why the customers are upset. These waveforms are taken while the capacitors are on-line.

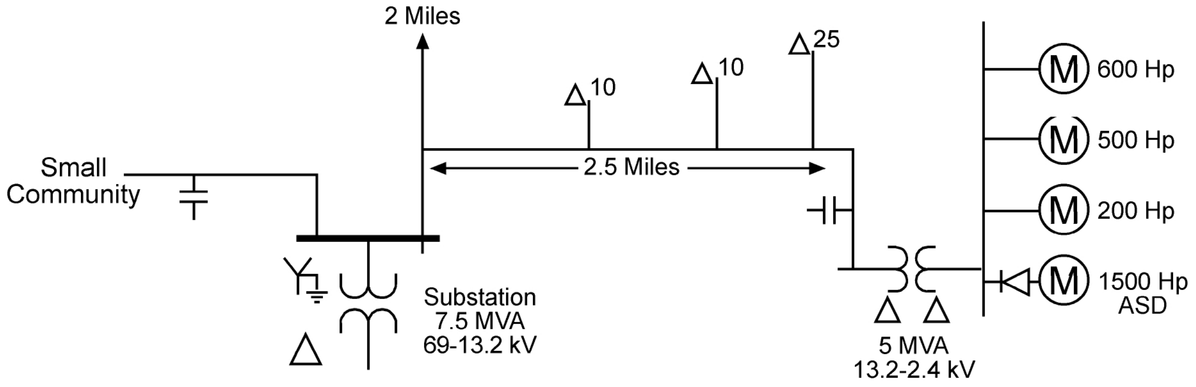


Figure 5-38
Distribution System One-line Diagram

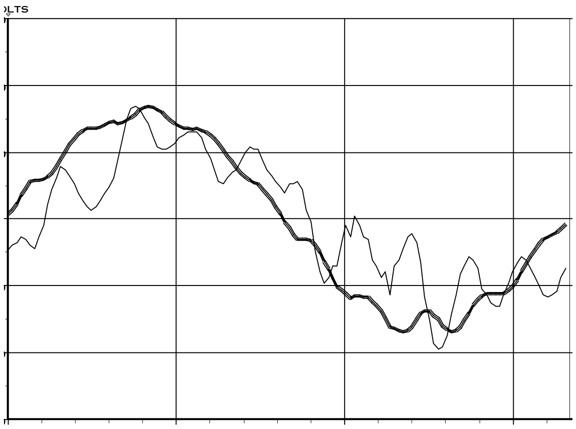


Figure 5-39
13.2kV Substation Voltage and Current for Industrial Feeder

$$THD_V = \mathbf{7.5\%},\ THD_I = \mathbf{40.1\%}$$

Table 5-8
Harmonic Components for Figure 5-39

Harmonic	V - %	I - %
3	0.4	0.9
5	0.9	20.2
7	0.8	6.7
8	2.2	13.5
10	6.0	26
11	3.0	12

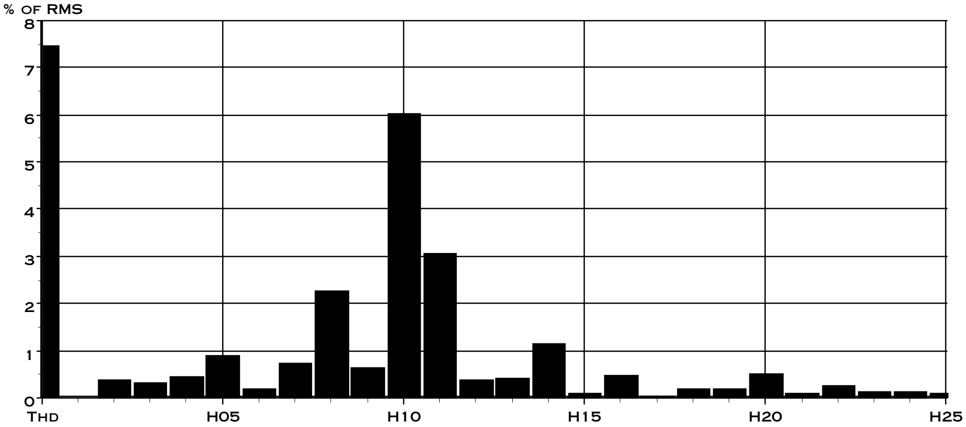


Figure 5-40
13.2kV Voltage Spectrum for Figure 5-39

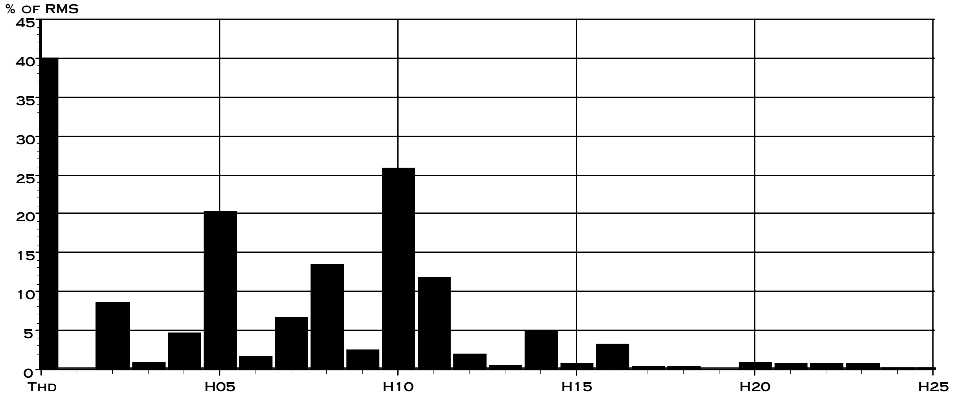


Figure 5-41
13.2kV Current Spectrum for Figure 5-39

The PSO serviceman opens the line capacitor on the industrial feeder in an attempt to reduce current distortion. Figure 5-42 shows the voltage and current waveform captured at the substation with the line capacitor off. With the minimal amount of current distortion present, the team is able to obtain the current magnitudes (Table 5-9) and associated spectra (Figures 5-43 and 5-44). The current spectrum is used to establish a pattern of frequencies that can be tracked.

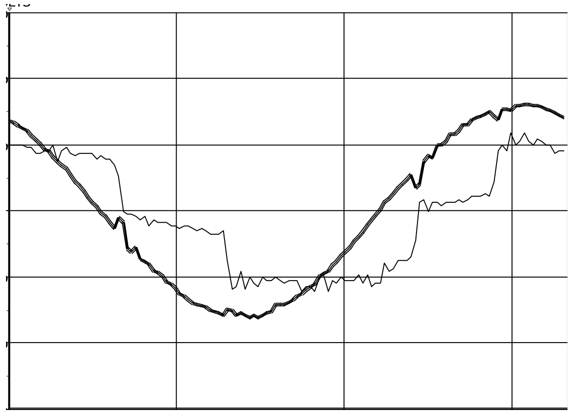


Figure 5-42
13.2kV Substation Voltage and Current for Industrial Feeder, with Capacitor Off

$$THD_V = \mathbf{4.7\%},\ THD_I = \mathbf{23.9\%}$$

Table 5-9
Harmonic Components for Figure 5-42

Harmonic	V - %	I - %
3	0.6	2.7
5	1	14.7
7	1.3	9.7
8	1.1	
10	1	3.7
11	0.9	4

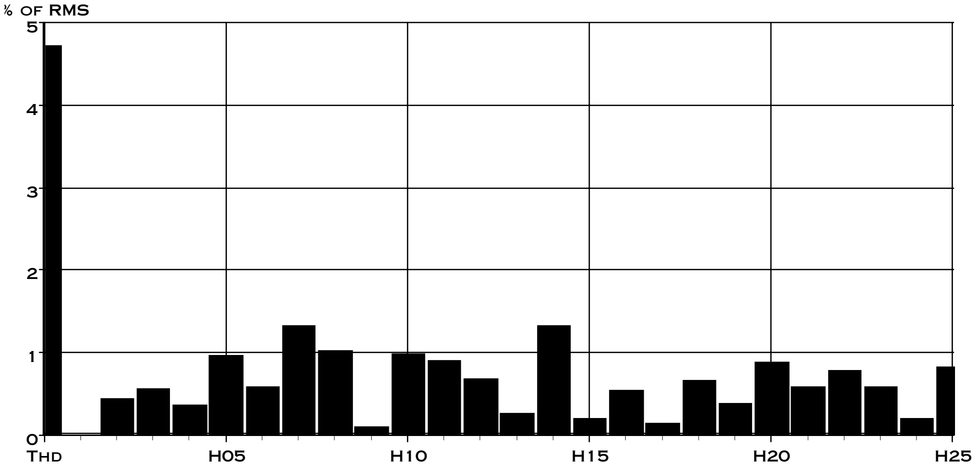


Figure 5-43
Voltage Spectrum for Figure 5-42

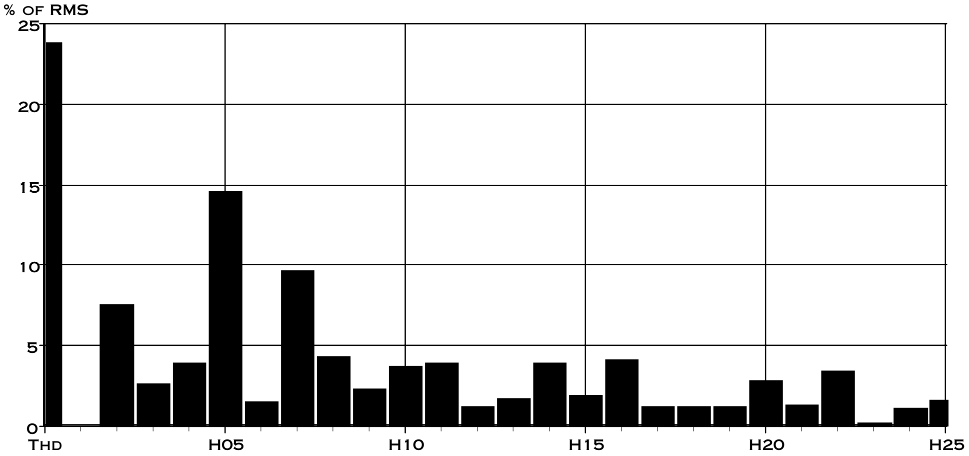


Figure 5-44
Current Spectrum for Figure 5-42

With a spectrum analyzer connected to a loop-antenna, it is possible to drive to the offending source using the data collected at the substation as the reference. The loop-antenna couples with the magnetic field produced by the distribution feeder current.

When the PQ Team arrives at the offending source, the 5MVA transformer at the customer site is making an abnormal noise, as if it is ready to fail. Data are collected at the metering point to determine if the harmonic currents injected into the distribution system exceed IEEE 519 limits. These data are shown in Figures 5-45, 5-46, and 5-47.

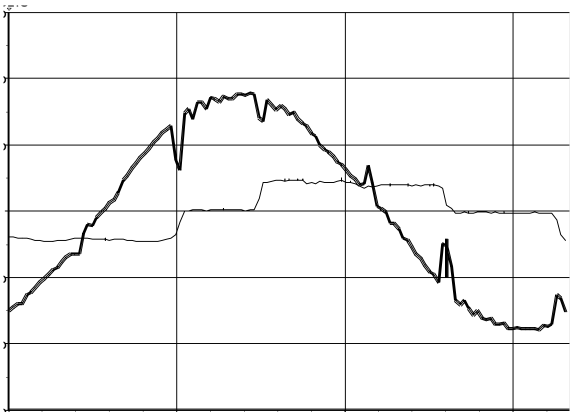


Figure 5-45
Current and Voltage Waveforms at the Meter

$$THD_V = 11.3\%,\ THD_I = 30.5\%$$

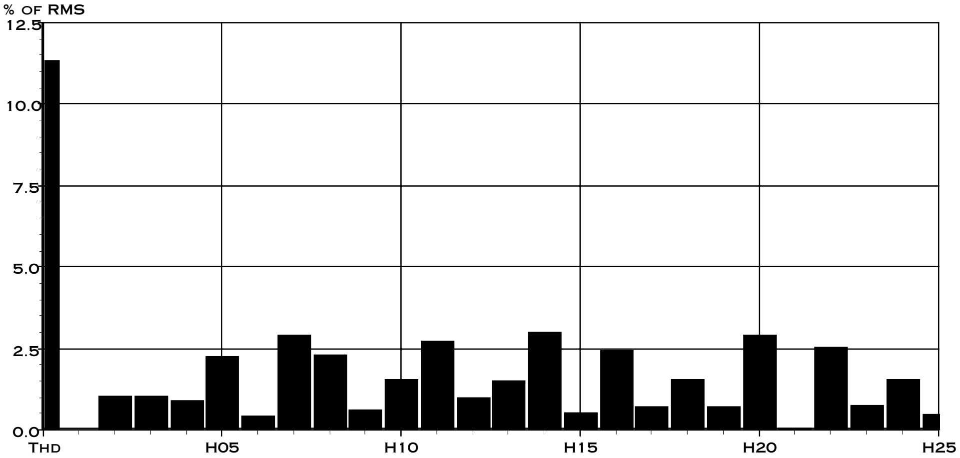


Figure 5-46
Voltage Spectrum for Figure 5-45

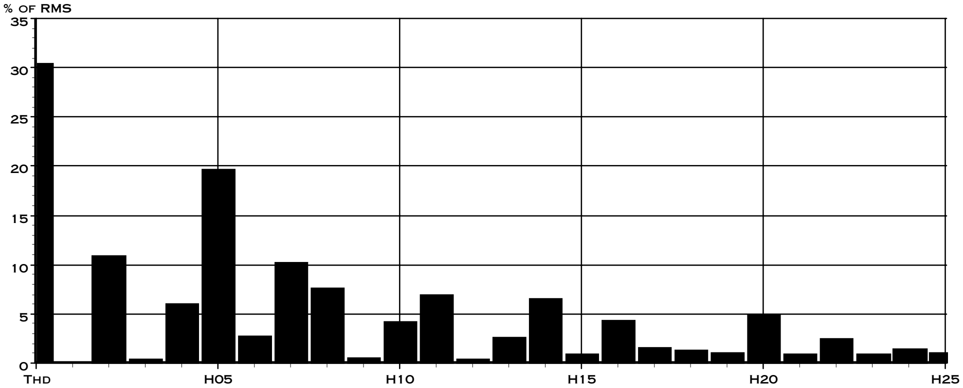


Figure 5-47
Current Spectrum for Figure 5-45

The allowable amount of harmonic current injection is determined by the ratio of short circuit to load current. In this case, the ratio is 38:22. The allowable individual limit for odd harmonics below the 11th is 7%. The allowable individual limit for even-ordered harmonics below the 11th is 1.7%. The percent distortion of each harmonic below the 11th that exceeds IEEE-519 is listed in Table 5.10.

Table 5-10
Harmonic Currents that Exceed IEEE 519 in Figure 5-45

Odd	%	Even	%
3	11.0	4	6.2
5	19.7	6	2.8
7	7.6	8	7.2

No doubt, the pumping station equipment is the source of the problem. The problem loads are determined to be

- a 1500 horsepower, six-pulse, pulse-width modulated (PWM) ASD,
- a half-wave rectifier used for pipeline cathodic protection.

Thus, prior to meeting with the customer, the source is clearly identified and the necessary documentation is obtained. PSO Account Representatives then meet with the customer to request cooperation in resolving the problem. The customer agrees to do what is needed, but does not know what action should be taken. The customer asks PSO to provide guidance in the matter.

The customer is directed toward the drive manufacturer, who is surprised that the drive causes such a significant problem. One comment by the manufacturer is that "we have yet to have anyone complain."

Solutions. The solutions agreed upon are:

1. Tune up the ASD.
2. Install shunt filters to trap the 5th, 7th, and 11th harmonic currents.
3. Install a grounding zigzag transformer to trap the 3rd harmonic current.
4. Install a grounding grid for the entire pumping station.
5. Replace the half-wave rectifier with a full-wave rectifier.

In addition to the above long-term solutions, immediate action is needed so that the pumping station can continue to operate while the filter work is commencing. Under testing, it is determined that the load current can be diversified to allow the pumping station to operate without exceeding current distortion limits. Diversifying the linear and nonlinear currents helps to damp and dilute the harmonic currents. Station operation is modified to allow the operator to run one induction motor while using the ASD as a jockey pump. Meanwhile, PSO stays in contact with the customer's engineering staff and the drive manufacture's representatives throughout the project.

After the solutions are installed, PSO revisits the substation to take measurements. Figure 5-48 is the resulting waveform. The harmonic spectra are given in Table 5-11 and Figures 5-49 and 5-50.

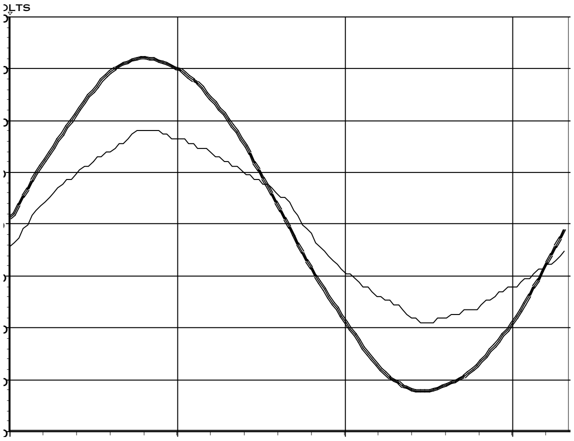


Figure 5-48
13.2kV Substation Voltage and Current for Industrial Feeder

Solutions Installed. ASD and Capacitors On

THD_V **= 1.2%,** THD_I **= 6.7%**

Table 5-11 Harmonic Components for Figure 5-48

Harmonic	V - %	I - %
3	0.115	4.3
5	1.1	4
7	0.29	1.9
8	0.02	0.1
10	0	0.2
11	0.316	1.3

By comparing the before-solution and after-solution waveforms captured at the substation, (i.e., Figure 5-39 before, and Figure 5-48 after), significant improvement in the quality of the voltage and current waveforms can be observed. THD_V reduces from 7.48% to 1.2%, and THD_I reduces from 40.1% to 6.7%.

The ASD continues to produce harmonic currents, but through load diversification, the harmonic currents have little impact on the electric distribution system.

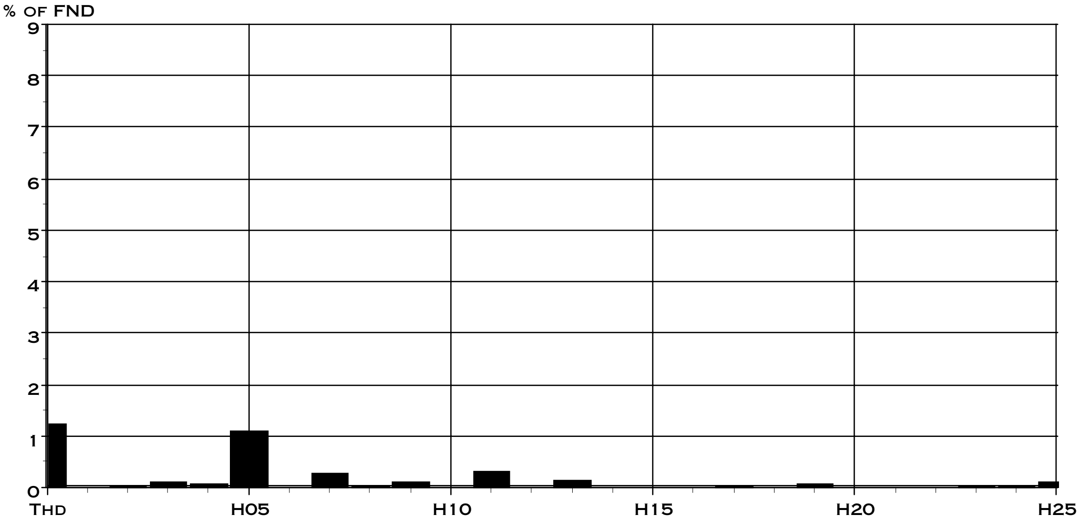


Figure 5-49
13.2 kV Substation Voltage Spectrum for Figure 5-48

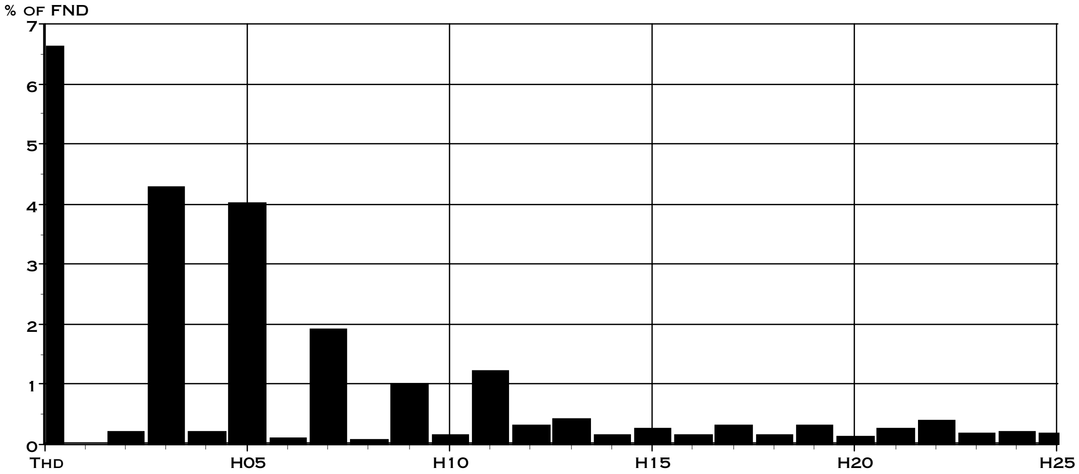


Figure 5-50
13.2 kV Substation Current Spectrum for Figure 5-48

This case study proves that harmonic resonance problems are challenging and may require a list of solutions on both the utility and customer electric systems. The incompatibility of end-use nonlinear loads and the electric distribution system can have a profound impact on system equipment and loads. Because harmonics are not commonly understood, one of the best strategic actions for electric utilities is to educate their personnel and their customers on the topic. Without education, end-users and utilities will continue to spend excessive dollars to correct problems due to nonlinear loads, and possibly without due consideration for lost production. Inevitably, more distorting loads will be connected to the electric distribution system as new nonlinear load types emerge.

Conclusion. As progress is made, electric utilities and their customers will continue to modify their systems to maximize equipment use. When power factor correction capacitors are added, resonant frequency should be considered. When nonlinear loads are added, special consideration should be given to managing harmonic currents. Electric system modifications or additions should be evaluated using sound engineering practices.

6

RESOURCES FOR HARMONIC MITIGATION TECHNOLOGY DEMONSTRATION

Introduction

The EPRI power quality business area and other EPRI targets have developed numerous tools that enable utilities to more effectively conduct a harmonic mitigation demonstration project. These tools include market research, technology development, software, and other information resources in the area of power quality, power electronics, and energy storage. The purpose of this chapter is to provide an overview of EPRI tools that will help utilities better manage a harmonic mitigation technology demonstration project.

EPRI Software Resources

EPRI Online Power Conditioning Database

http://pcdatabase.epriweb.com

The EPRI Online Power Conditioning Database is a web-based tool that analyzes a specific power quality problem and suggests solutions. Solutions are made available in a timely manner, as needed and when needed. Moreover, the information about the solution is based on EPRI know-how, acquired through years of equipment testing and customer site investigation experience. The online power conditioning database site is password-protected for utility members who are funders of the power conditioning database project.

Users can search the database for specific power conditioning equipment. Results not only include which manufacturers to contact and how to contact them but also provide detailed, objective, and expert information about the specific device the user is interested in. The database offers two additional search engines based on expert know-how. The first searches for equipment to handle power disturbances specified by the user, and the second searches for equipment to protect specific loads.

The database currently includes approximately 100 manufacturers and 250 products for initial market testing. Starting January 1, 2000, only companies with products that have been tested by EPRI PEAC Corporation are listed in the database. Manufacturers will be informed about this requirement and asked to contact EPRI PEAC directly. The main factor that will differentiate the database from competing products is EPRI's commitment to provide an objective, thorough, and expert evaluation of power conditioning equipment that cannot be easily obtained elsewhere.

Some of the main features of the database are:

- Provides 24/7 online access to power quality and power conditioning information, providing on-demand “self-help.”
- Offers 3 power and user friendly search engines, which novice and expert users will find easy to use.
- Contains objective, detailed information about power conditioning products.
- Provides in-depth, expert know-how in the form of test protocols and installation guidelines.

Power Quality Database

AP-106028, Version 1.0

The Power Quality Database™ (PQ Database™) System is a database management system used to store and retrieve information related to power quality investigations. The database contains results from numerous power quality projects and evaluations conducted by the Electric Power Research Institute (EPRI). It is designed to help evaluate power quality problems on electric utility systems and within end-use facilities. It provides examples of power quality case studies in a variety of different categories, along with a variety of additional reference information to facilitate the investigation and reporting process.

The PQ Database is intended to

- Serve as a training tool for new engineers dealing with power quality problems.
- Reduce the investigation time required for a power quality problem by providing background information on all types of power quality problems, equipment characteristics, actual examples from other investigations, and descriptions of standards that apply to the solutions.
- Provide alternatives for solving the problem, including information on power-conditioning technologies.
- Facilitate reporting on power quality investigations by providing general information on similar problems and solutions that can be cut and pasted directly into standard reports.
- Provide up-to-date information on the latest developments in power-conditioning technologies, equipment characteristics, and problems experienced by customers nationwide.
- Provide a vehicle for utilities to maintain their own power quality information.

Power Quality Toolbox: Wiring and Grounding Analysis Tool

Production Version 1.0, CD-109128

The Power Quality (PQ) Toolbox Wiring and Grounding Analysis Tool provides an easy-to-use framework for collecting information for commercial and light industrial power systems. This information, including equipment nameplate data, panel wiring practices, and voltage and current measurements, provides a database that can be automatically searched to detect conditions that can degrade equipment power quality. The software runs on a PC computer and helps engineers perform wiring and grounding power quality analysis for their customers.

The PQ Tool Box Wiring and Grounding Tool includes basic applets such as K-Factor Applet, Neutral Applet, and Ampacity Applet. These applets assist field service personnel with performing site surveys. Each applet is a stand-alone, one-screen program. Each applet can be run from the PQ Tool Box Wiring and Grounding Tool using the keyboard or mouse. The tool also has a detailed, on-line help system that contains wiring and grounding reference information. The application is on a CD-ROM that also contains sample data files and a user's manual.

Power Quality Diagnostic System

Version 1.1

The Power Quality Diagnostic System (PQDS) is a complete system of tools designed to help engineers and technicians develop optimal solutions to power quality problems. System capabilities include data collection from measurement equipment, data processing, database management, waveform recognition technology to identify disturbance causes, libraries of example cases to identify previous similar cases, analytical tools to verify causes and develop possible technical solutions, economic analysis to identify optimum solutions, and report writing. The following sections provide a functional overview of the harmonic simulation tool and other related tools in the power quality diagnostic system software that will help utilities to conduct a harmonic mitigation technology demonstration project:

Analysis and Simulation Module, Harmonic Simulator

The harmonic analysis application will calculate voltage and current harmonic levels in a facility and at the interface with the electricity supplier, based on the characteristics of the facility and the nonlinear loads that are being used. A simple two-bus representation is used for the facility model, with a step down transformer from the electricity supplier. Usually, this two-bus representation will be used to evaluate the 480-volt and 120-volt systems within a facility.

The application will evaluate the impact of nonlinear loads within the facility. A library of nonlinear load characteristics will be maintained with typical harmonic-producing characteristics. Alternatively, the user can supply known harmonic current characteristics for specific systems or loads (such as from actual measurements). The program evaluates the following concerns:

- Harmonic current injection into the utility system vs. IEEE 519 limit
- Voltage THD at each bus
- Transformer loading versus maximum permissible loading after transformer is de-rated in accordance with IEEE C57.110

- Neutral conductor overloading in systems supplying computers and other single-phase electronic power supplies
- Capacitor kV, kVAR, and current duties versus IEEE Std 18 limits
- Filter reactor current duties

The program will also allow the evaluation of the system frequency response with and without power factor correction to identify possible resonance problems. Frequency scans are used for this purpose.

Analysis and Simulation Module, EMTP Simulation Support

The simplified analysis applications included in the Analysis and Simulation Module of the Power Quality Diagnostic System are designed to help evaluate a number of the most common power quality problems. There are many problems that cannot be conveniently fit into one of these categories. However, simulations are still very useful in evaluating the problems and evaluating different solutions to help identify the optimal approach. These more detailed simulations will often be performed using either the Electromagnetic Transients Program (EMTP) or a specialized harmonic analysis program, like the HarmFlo+ Workstation.

Although it is beyond the scope of the Analysis and Simulation Module to actually embed these sophisticated analysis tools within the system, they can be used in conjunction with the PQDS to complete a more sophisticated analysis. The Analysis and Simulation Module's help file provides an overview of a number of modeling and simulation subjects:

1. Modeling guidelines for system representation in transient studies.
2. Modeling guidelines for system representation in harmonic studies.
3. Example representations for different types of nonlinear loads.
4. Guidelines for solutions to evaluate for typical problems.
5. Example cases (transients and harmonics) for different types of problems.

The module also provides an overview and guidelines for transient modeling and simulation using a digital computer program. The introduction to the EMTP Simulation Support section includes an overview of the Electromagnetic Transients Program (EMTP), including examples of program inputs and outputs, and a suggested study procedure.

The Modeling and Simulation Guidelines section summarizes the computer simulation process, and provides guidelines regarding the following system aspects of modeling and simulation:

1. Computer Simulation Process
2. Developing a System Model

3. Data Collection and Initial Model Development
4. Time Step and Simulation Time Selection
5. Frequency Ranges for EMTP Simulations
6. Simulation Model Verification
7. Suggested Study Procedure
8. Evaluation and Presentation of Results

The transient analysis section includes several of the more common transient concerns, including capacitor switching and the low-side current surge phenomena. Finally, case studies are provided to illustrate several of the more important transient events. The case studies are intended to involve the user in an active learning process. This document is not intended to replace other EMTP-related literature and documentation, but rather to be used as a supplement to this reference library.

Analysis and Simulation Module, Case Study Investigator

The Case Study Investigation Processor (CSI) was designed to assist the power quality field investigator in determining or assessing problems. This module guides you to other PQDS modules and simulators based on power quality symptoms. These modules, in turn, provide the investigator with different solutions to power quality problems.

The CSI module of the PQDS provides an interface that guides you through a power quality case study. CSI is a driver module that leads you to other PQDS modules, which represent investigation steps in a case study, and that prints the investigation results.

A case study investigation will consist of a series of standard steps for a given event. An event can be a power quality problem such as a flicker or a power quality assessment such as a customer-site survey or a compliance evaluation.

CSI will provide a block diagram that correlates to each step in a given event investigation. This block diagram will direct you through each step and launch the appropriate PQDS module for related data entry. The first step of an investigation will gather background information and therefore will be the responsibility of CSI.

Each investigation step block in the diagram will have a status. The status of each investigation step block will have its status indicated by color. The possible states for an investigation step block are not applicable, not started, in-progress, and complete.

CSI provides a printable case study report that will become part of the PQDS's Power Quality Database (PQDB). The case study is a set of reports, structured for consistency with PQDB, which correspond to each completed step in an investigation.

Additionally, CSI provides a free-text dialog to allow you to record interpretations of the case study report (that is, causes of problems, impacts on facility, possible solutions, and recommendations) prior to running the report for the PQIT.

HARMFLO -- Harmonic Power Flow Program Version 5.0 and HARMFLO Plus Version 1.0 EL-4920-CCMV5

AP-014920

HARMFLO (Harmonic Power Flow Program) is a computer program to calculate the magnitude and propagation of harmonics in balanced power systems. This program is useful for predicting or diagnosing design or operating problems, such as resonance detection and prevention, insulation coordination and protection, and HVDC filter design operation.

Harmonic voltages and currents that occur at frequencies above 60 hertz cause distortion of the standard sine wave. They are caused by non-linear loads such as rectifiers, DC drives, saturated transformers, and HVDC terminals. Harmonics in power systems cause higher losses, and if severe, can cause insulation degradation, flashover, and equipment overheating and failure.

HARMFLO is a significant improvement over other methods used for harmonic analysis because loads are stated by power demand levels. Thus harmonic levels need not be known before the study. Moreover, the solution does not depend upon assumed linear superposition. Input format is similar to that of existing power flows. The recommended frequency range is from 60 to 11430 hz (19th harmonic), thus overcoming the limitations of the models and impedance representation currently implemented. Nonlinear impedance and 6 or 12 pulse convertors can be modeled. A 3-phase analysis is not performed, although transformer connections must be specified.

HARMFLO Plus -- PC/DOS acts as an application launcher for the following harmonic analysis tools: EPRI HarmFlo, SuperHarm, TOP, Spreadsheets&Other Tools, User Program, and Data File Editor.

Wavelet Theory

The wavelet transform has emerged as a technique to allow analysis of non-steady-state, non-stationary processes. Traditionally, Laplace or Fourier transforms are used for steady state analysis, and do a good job of showing all the frequency content in a time-based waveform. This is effective if the signature waveform is periodic, or steady state, but if the important information is localized in time on the waveform, these traditional methods may be unable to detect that information. This is where wavelet transforms can be of use. By allowing the user to analyze short term waveform events, the inabilities of the traditional methods can be overcome.

Wavelet transforms are accomplished in a similar fashion to the Laplace or Fourier transforms, in that an integration is carried out on the product of the original time-based function and some basis function, or transformation kernel. This integration is also referred to as the inner product. This operation yields a new function in a new domain that represents the original time domain function.

A classic example of an inner product yielding a transform operation is the Fourier transform, in which the integrand includes the product of the time-based function and an exponential function with a complex exponent. Since this transform cannot provide any information contained in the time domain, a variation of this transform has been used for non-stationary signals, and is known as the Short Time Fourier Transform, or STFT. This transform multiplies the original non-stationary signal with a windowing function. The signal is then assumed stationary within the window, and Fourier transformed. Now the result can provide both time and frequency information about the signal. Note that the width of the window is constant, although the frequency of the windowing function can vary.

The wavelet transform is performed using a transformation kernel based on time and scale instead of time and frequency. This is accomplished through a windowing procedure as with the STFT, but now the width of the window is variable, and the frequency of the windowing function is constant.

The wavelet transform can yield information about the signal in the time domain, and is especially useful if the information is localized on the time scale. This means short term events can be detected and analyzed, while long term steady state events will be ignored. In fact, there is a property of this transform called a vanishing moment that results in an interesting characteristic of the transform- it only reacts to the first and higher derivatives of the signal in question. Therefore, wavelet transforms are best suited for analysis of fast-changing transient events.

Wavelet transforms are a fascinating mathematical tool, and in fact have been referred to as a mathematical microscope, since they allow the user to “zoom in” on a short-lived waveform characteristic. While these methods may allow analysis of certain burst type phenomena of power frequency harmonics, by and large the harmonics in power systems are steady state conditions better treated with Fourier transforms.

EPRI Technical Document Resources

1. Written-Pole Motor Generator Technologies Application Guide TR-111036
2. Assessment of Active Power Line Conditioning Technologies TR-102026
3. Power Quality Workbook for Utility and Industrial Applications TR-105500
4. Power Quality for Electrical Contractors, Application Guide, Volume 1: Power Quality Fundamentals, TR-111762-V1

5. Technology Assessment and Business Planning for Power Conditioning Technologies TR-109896
6. Active Power Line Conditioning Technologies Applications Guide TR-106525
7. An Assessment of Distribution System Power Quality (Vols. 1-3) TR-106294
8. Active Power Line Conditioning Methods – A Literature Survey TR-105168
9. Active Power Line Conditioning Technologies Application Guide TR-106535
10. Power Quality Market Assessment TR-104372
11. Assessment of Active Power Line Conditioning Technologies TR-102026
12. Power Quality in Commercial Buildings BR-105018
13. Power Quality Considerations for Power Factor Correction Applications BR-105017
14. Hybrid Filters for Power System Harmonics TR-105009
15. Adjustable Speed Drive: Harmonic Effects on Induction Motors: Volumes 1 and 2 TR-105323-V1
16. Improved Motors for Utility Applications, Volume 4: Impact of Harmonics EL-4286-V4
17. Harmonics and Electrical Noise in Distribution Systems, Volume 1: Measurements and Analyses EL/EM-4290-V1
18. Error Correction Methods for Measuring Harmonics in Power Systems TR-105215
19. Western Resources Uses EMTP Workstation to Analyze 12-KV Distribution Fifth Harmonic Filter IN-105930
20. Performance and Design Evaluation of Switch-Mode Power Supplies -- AC Interface Issues TR-107925
21. Roadmap for Power Quality Mitigation Technology Demonstration Projects at Commercial Customer Sites

Applicable Standards

1. ANSI C84.1-1989, American National Standard for Electric Power Systems and Equipment—Voltage Ratings (60 Hz).
2. ANSI/NFPA 70-1993, National Electrical Code.
3. ANSI/NFPA 75-1992, Protection of Electronic Computer/Data Processing Equipment.
4. ANSI/NFPA 77-1988, Recommended Practice on Static Electricity.
5. ANSI/NFPA 780-1992, Lightning Protection Code.
6. IEEE Std C57.12.00-1987, IEEE Standard General Requirements for Liquid-Immersed Distribution, Power, and Regulating Transformers (ANSI).
7. IEEE Std C57.12.01-1989, IEEE Standard Requirements for Dry-Type Distribution and Power Transformers Including Those with Solid Cast and/or Resin-Encapsulated Windings.
8. IEEE Std C62.41-1991, IEEE Recommended Practice on Surge Voltages in Low-Voltage AC Power Circuits (ANSI).
9. IEEE Std 142-1991, IEEE Recommended Practice for Grounding of Industrial and Commercial Power Systems (IEEE Green Book).
10. IEEE Std 446-1987, IEEE Recommended Practice for Emergency and Standby Power Systems for Industrial and Commercial Applications (IEEE Orange Book).
11. Federal Information Processing Standards Publication 94: Guideline on Electrical Power for ADP Installations, Sept. 21, 1983.1[1]
12. CFR (Code of Federal Regulations), Title 29, Part 1910: Occupational Safety and Health Standards (OSHA).
13. CFR (Code of Federal Regulations), Title 29, Part 1926: Safety and Health Regulations for Construction (OSHA).
14. IEEE Std 81-1983, IEEE Guide for Measuring Earth Resistivity, Ground Impedance, and Earth Surface Potentials of a Ground System.
15. IEEE Std 449-1990, IEEE Standard for Ferroresonant Voltage Regulators (ANSI).
16. IEEE Std C57.110-1986, IEEE Recommended Practice for Establishing Transformer Capability When Supplying Nonsinusoidal Load Currents (ANSI).

17. IEEE Std C62.36-1991, IEEE Standard Test Methods for Surge Protectors Used in Low-Voltage Data, Communications, and Signaling Circuits.

18. IEEE Std C62.41-1991, IEEE Recommended Practice on Surge Voltages in Low-Voltage AC Power Circuits (ANSI).

19. IEEE Std 141-1986, IEEE Recommended Practice for Electric Power Distribution for Industrial Plants (Red Book) (ANSI).

20. IEEE Std 399-1990, IEEE Recommended Practice for Industrial and Commercial Power Systems Analysis (Brown Book) (ANSI).

21. IEEE Std 519-1992, IEEE Guide for Harmonic Control and Reactive Compensation of Static Power Converters (ANSI).

22. IEEE P519A IEEE Guide for Applying Harmonic Limits on Power Systems-Unpublished Draft

23. IEC 1000-3-2, “Limits for Harmonic Current Emissions”

24. IEC 1000-3-6, “Limitation of Emission of Harmonic Currents for Equipment Connected to Medium and High Voltage Power Supply Systems”

25. ANSI/IEEE C37.20.2 Standards for Metal-Enclosed Switchgear

26. FCC Part 15 Class B Electromagnetic Interference Emission Level

27. ANSI C63.12 – 1987 Electromagnetic Compatibility Limits – Recommended Practice

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A

HARMONICS BASICS

A1. Introduction

Power systems are designed to operate at frequencies of 50 or 60Hz. However, certain types of loads produce currents and voltages with frequencies that are integer multiples of the 50 or 60 Hz fundamental frequency. These higher frequencies are a form of electrical pollution known as power system harmonics.

Power system harmonics are not a new phenomenon. In fact, a text published by Steinmetz in 1916 devotes considerable attention to the study of harmonics in three-phase power systems. In Steinmetz's day, the main concern was third harmonic currents caused by saturated iron in transformers and machines. He was the first to propose delta connections for blocking third harmonic currents.

After Steinmetz's important discovery, and as improvements were made in transformer and machine design, the harmonics problem was largely solved until the 1930s and 40s. Then, with the advent of rural electrification and telephones, power and telephone circuits were placed on common rights-of-way. Transformers and rectifiers in power systems produced harmonic currents that inductively coupled into adjacent open-wire telephone circuits and produced audible telephone interference. These problems were gradually alleviated by filtering and by minimizing transformer core magnetizing currents. Isolated telephone interference problems still occur, but these problems are infrequent because open-wire telephone circuits have been replaced with twisted pair, buried cables, and fiber optics.

Today, the most common sources of harmonics are power electronic loads such as adjustable-speed drives (ASDs) and switching power supplies. Electronic loads use diodes, silicon-controlled rectifiers (SCRs), power transistors, and other electronic switches to either chop waveforms to control power, or to convert 50/60Hz AC to DC. In the case of ASDs, DC is then converted to variable-frequency AC to control motor speed. Example uses of ASDs include chillers and pumps.

Power electronic loads offer tremendous advantages in efficiency and controllability. However, they draw nonsinusoidal currents from AC power systems, and these currents react with system impedances to create voltage harmonics and, in some cases, resonance. Studies show that harmonic distortion levels in distribution feeders are rising as power electronic loads continue to proliferate.

Unlike transient events such as lightning that last for a few microseconds, or voltage sags that last from a few milliseconds to several cycles, harmonics are steady-state, periodic phenomena that produce continuous distortion of voltage and current waveforms. These periodic nonsinusoidal waveforms are described in terms of their harmonics, whose magnitudes and phase angles are computed using Fourier analysis.

Fourier analysis permits a periodic distorted waveform to be decomposed into a series containing dc, fundamental frequency (e.g. 60Hz), second harmonic (e.g. 120Hz), third harmonic (e.g. 180Hz), and so on. The individual harmonics add to reproduce the original waveform. The highest harmonic of interest in power systems is usually the 25th (1500Hz), which is in the low audible range. Because of their relatively low frequencies, harmonics should not be confused with radio-frequency interference (RFI) or electromagnetic interference (EMI).

Ordinarily, the DC term is not present in power systems because most loads do not produce DC and because transformers block the flow of DC. The even-ordered harmonics are generally much smaller than odd-ordered harmonics because most electronic loads have the property of half-wave symmetry, and half-wave symmetric waveforms have no even-ordered harmonics.

The current drawn by electronic loads can be made distortion-free (i.e., perfectly sinusoidal), but the cost of doing this is significant and is the subject of ongoing debate between equipment manufacturers and electric utility companies in standard-making activities. Two main concerns are

1. What are the acceptable levels of current distortion?
2. Should harmonics be controlled at the source, or within the power system?

A2. Fourier Series

Any physically realizable periodic waveform can be decomposed into a Fourier series of DC, fundamental frequency, and harmonic terms. In sine form, the Fourier series is

$$i(t) = I_{dc} + \sum_{k=1}^{\infty} I_k \sin(k\omega_o t + \theta_k)\,, \tag{A2.1}$$

where I_{dc} is the DC value, I_k are peak magnitudes of the individual harmonics, ω_o is the fundamental frequency (in radians per second), and θ_k are the harmonic phase angles. The time period of the waveform is $T = \dfrac{2\pi}{\omega_o}$. Sine terms in (2.1) can be converted to cosine terms by subtracting 90° from each θ_k.

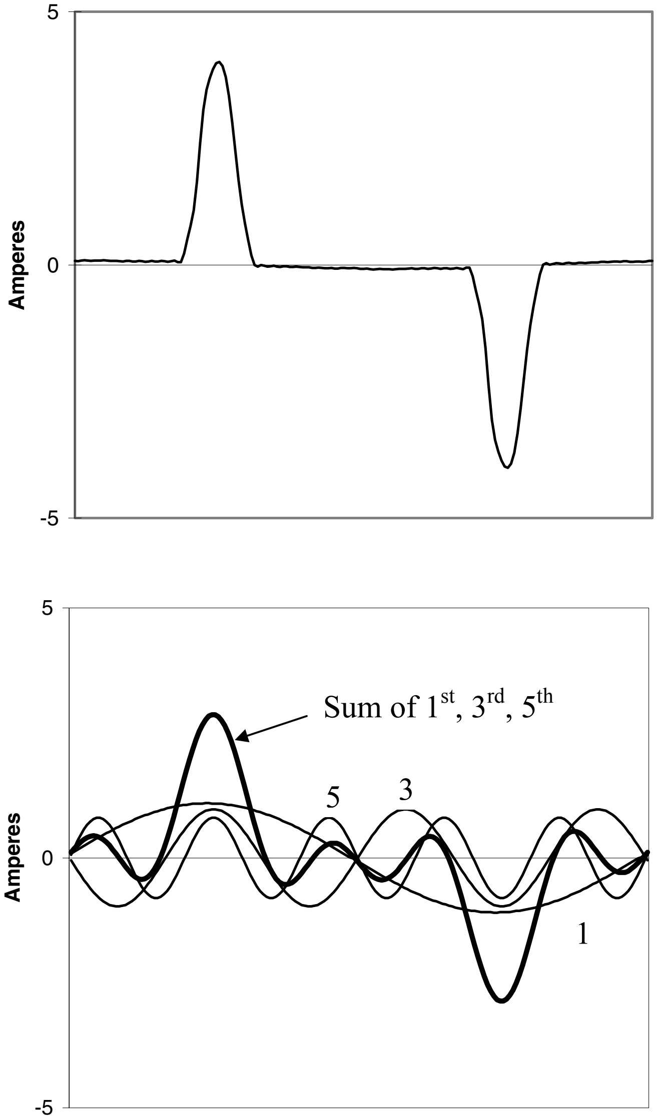
The formulas for computing I_{dc}, I_k, θ_k are well-known and can be found in any undergraduate electrical engineering textbook on circuit analysis.

Figure A-1 shows a desktop computer (i.e., PC) current waveform. The figure illustrates how the actual waveform can be approximated by summing only the fundamental, 3rd, and 5th harmonic components. If higher-order terms are included (i.e., 7th, 9th, 11th, and so on), then the PC current waveform will be perfectly reconstructed. A truncated Fourier series is actually a least-squared error curve fit. As higher frequency terms are added, the error is reduced.

Fortunately, a special property known as half-wave symmetry exists for most power electronic loads. Have-wave symmetry exists when the positive and negative halves of a waveform are identical but opposite, i.e.,

$$i(t) = -i(t \pm \frac{T}{2})\,,$$

where T is the period. Waveforms with half-wave symmetry have no even-ordered harmonics. It is obvious that the television current waveform is half-wave symmetric.



PC Current Waveform, and its 1st, 3rd, and 5th Harmonic Components

Figure A-1
PC Current Waveform, and its 1st, 3rd, and 5th Harmonic Components

A3. Definitions

A3.1. RMS

The rms value of a sinusoidal voltage or current is simply the peak value divided by $\sqrt{2}$. When harmonics are present, the squared rms values of all harmonic components, including the fundamental, add so that

$$I_{rms}^2 = I_{1,rms}^2 + I_{2,rms}^2 + I_{3,rms}^2 + \cdots . \tag{A3.1}$$

Each rms harmonic current is related to its own peak value by $\sqrt{2}$ so that

$$I_{rms} = \sqrt{\sum_{k=1}^{\infty}\left(\frac{I_k}{\sqrt{2}}\right)^2} = \sqrt{\frac{1}{2}\sum_{k=1}^{\infty} I_k^2} . \tag{A3.2}$$

Equation (3.2) ignores any DC that may be present.

A3.2. THD

The most commonly used measure of harmonics is total harmonic distortion (THD), also known as distortion factor. It is applied to both voltage and current. THD is defined as the rms value of the harmonics above fundamental, divided by the rms values of the fundamental. DC is ignored. Thus,

$$THD_I = \frac{\sqrt{\sum_{k=2}^{\infty}\left(\frac{I_k}{\sqrt{2}}\right)^2}}{\frac{I_1}{\sqrt{2}}} = \frac{\sqrt{\sum_{k=2}^{\infty} I_k^2}}{I_1} . \tag{A3.3}$$

Because line losses are proportional to the square of rms current (and sometimes increase more rapidly due to the resistive skin effect), then line losses always increase when harmonics are present. For example, many PCs have a current distortion near 1.0 (i.e., 100%). Thus, the wiring losses incurred while supplying a PC are twice what they would be in the sinusoidal case.

While current distortion in loads vary from a few percent to more than 100%, voltage distortion is generally less than 5%. Voltage THDs below 0.05, i.e. 5%, are considered acceptable, and those greater than 10% are definitely unacceptable and will cause problems for sensitive equipment and loads.

THD and rms are directly linked. By manipulating (A3.1) – (A3.3), it can be shown that

$$I_{rms} = I_{1,rms}\sqrt{1+THD_I^2}\ . \tag{A3.4}$$

A3.3. Average Power

Harmonic powers (including the fundamental) add and subtract linearly to produce total average power. If the voltage and current at a measuring point are

$$v(t) = \sum_{k=1}^{\infty} V_k \sin(k\omega_o t + \delta_k)\ ,\ i(t) = \sum_{k=1}^{\infty} I_k \sin(k\omega_o t + \theta_k)\ ,$$

the average power is the sum of the individual harmonic powers

$$P_{avg} = \sum_{k=1}^{\infty} \frac{V_k I_k}{2} \cos(\delta_k - \theta_k) = P_{1,avg} + P_{2,avg} + P_{3,avg} + \cdots\ . \tag{A3.5}$$

The harmonic power terms $P_{2,avg}, P_{3,avg}, \cdots$ are mostly losses and are usually small in relation to fundamental power. However, harmonic losses may be substantial when compared to fundamental frequency loss.

Equation (A3.5) is important in explaining who is responsible for harmonic power. Electric utility generating plants produce sinusoidal terminal voltages. According to (A3.5), if there is no harmonic voltage at the terminals of a generator, then the generator produces no harmonic power. However, due to nonlinear loads, harmonic power does indeed exist in power systems and causes additional losses. Thus, it is accurate to say that

- Harmonic power is parasitic and is due to nonlinear equipment and loads.

- The source of most harmonic power is power electronic loads.

- By chopping the 60 Hz current waveform and producing harmonic voltages and currents, power electronic loads convert some of the “60 Hz” power into harmonic power, which in turn propagates back into the power system, increasing system losses and impacting sensitive loads.

A3.4. True Power Factor

To examine the impact of harmonics on power factor, it is important to consider the true power factor, which is defined as

$$pf_{true} = \frac{P_{avg}}{V_{rms} I_{rms}} . \tag{A3.6}$$

In sinusoidal situations, (3.6) reduces to the familiar displacement power factor

$$dpf_1 = \frac{P_{1,avg}}{V_{1,rms} I_{1,rms}} = \frac{\frac{V_1 I_1}{2}\cos(\delta_1 - \theta_1)}{\frac{V_1 I_1}{2}} = \cos(\delta_1 - \theta_1) .$$

When harmonics are present, (3.6) can be expanded as

$$pf_{true} = \frac{P_{1,avg} + P_{2,avg} + P_{3,avg} + \cdots}{V_{1,rms}\sqrt{1+THD_V^2} \bullet I_{1,rms}\sqrt{1+THD_I^2}} .$$

In most instances, the harmonic powers are small compared to the fundamental power, and the voltage distortion is less than 10%. Thus, the following important simplification is usually valid:

$$pf_{true} \approx \frac{P_{1,avg}}{V_{1,rms} I_{1,rms}\sqrt{1+THD_I^2}} = \frac{dpf_1}{\sqrt{1+THD_I^2}} . \tag{A3.7}$$

It is obvious in (A3.7) that the true power factor of a nonlinear load is limited by its THD_I. For example, the true power factor of a PC with THD_I = 100% can never exceed 0.707, no matter how good its displacement power is.

A3.5. Phase Sequence

When a three-phase power system is balanced, harmonics fall into the following predictable phase shift pattern:

Table A-1
Phase Sequence of Harmonics in a Balanced Three-Phase System

Harmonic	Phase Sequence
1	*+*
2	–
3	0
4	+
5	–
6	0
…	…

If a system is not balanced, then each harmonic can have positive, negative, and zero sequence components. However, in most cases, the pattern in Table A-1 can be assumed to be valid.

Since "triplen" harmonics (i.e., multiples of three) in a balanced system are zero sequence, they cannot flow in three-wire systems or loads. Thus, a delta – grounded wye transformer at the entrance of an industrial customer effectively blocks the flow of triple harmonic load currents into the power system, provided that the load is reasonably balanced. Unfortunately, the transformer does nothing to block the flow of non-triplen harmonics.

Only the triplen harmonic currents are affected by grounding paths. The other harmonics are either positive or negative sequence, which sum to zero at neutral points and do not flow in neutral wires or ground connections.

Another interesting observation can be made concerning Table A-1. Line-to-line voltages never have zero sequence components because, according to Kirchhoff's voltage law, they always sum to zero. For that reason, line-to-line voltages in commercial buildings are missing the 3rd harmonic that dominates line-to-neutral voltage waveforms.

A3.6. K Factor

Losses in transformers increase when harmonics are present because

1. harmonic currents increase the rms current beyond what is needed to provide load power,
2. harmonic currents do not flow uniformly throughout the cross sectional area of a conductor and thereby increase its equivalent resistance.

Dry-type transformers are especially sensitive to harmonics. The K factor was developed to provide a convenient measure for rating the capability of transformers, especially dry types, to serve distorting loads without overheating. The K factor formula is

$$K = \frac{\sum_{k=1}^{\infty} k^2 I_k^2}{\sum_{k=1}^{\infty} I_k^2} \ . \tag{A3.8}$$

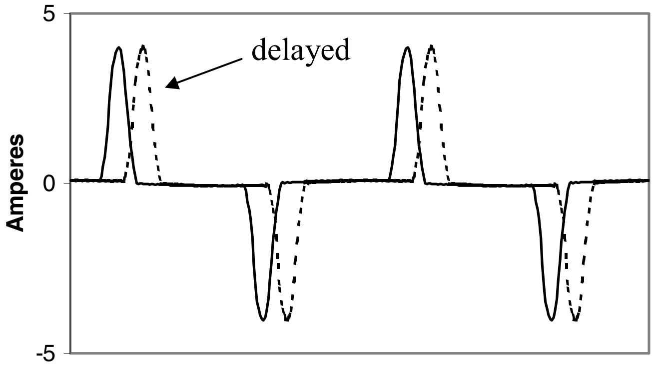
In most situations, $K \le 10$.

A3.7. Phase Shift

There are two types of phase shifts pertinent to harmonics. The first is a shift in time, e.g. the $\pm\frac{2T}{3}$ among the phases of balanced a-b-c currents. If the PC waveform in Figure A-2 is delayed by ΔT seconds, the modified current is

$$\begin{aligned} i(t-\Delta T) &= \sum_{k=1}^{\infty} I_k \sin(k\omega_o(t-\Delta T)+\theta_k) = \sum_{k=1}^{\infty} I_k \sin(k\omega_o t - k\omega_o \Delta T + \theta_k) \\ &= \sum_{k=1}^{\infty} I_k \sin(k\omega_o t + (\theta_k - k\omega_o \Delta T)) = \sum_{k=1}^{\infty} I_k \sin(k\omega_o t + \theta_k - k\theta_o), \end{aligned} \tag{A3.9}$$

where θ_o is the phase lag of the fundamental current corresponding to ΔT. The last term in (3.9) shows that individual harmonics are delayed by $k\theta_o$.



PC Current Waveform Delayed in Time

Figure A-2
PC Current Waveform Delayed in Time

The second type of phase shift is in harmonic angle, which occurs in wye-delta transformers. Wye-delta transformers shift voltages and currents by $\pm 30^o$. ANSI standards require that, regardless of which side is delta or wye, the a-b-c phases must be marked so that the high-voltage side voltages and currents lead those on the low-voltage side by 30^o for positive-sequence, and lag by 30^o for negative sequence. Zero sequences are blocked by the three-wire connection so that their phase shift is not meaningful.

Since harmonics in a balanced system fall into the predictable phase sequences shown in Table A-1, it is clear that a wye-delta transformer will advance some harmonics by 30^o and delay other harmonics by 30^o. This property makes it possible to cancel half of the harmonics produced by ASDs (most importantly the 5th and 7th) through a principle known as phase cancellation. The result is illustrated in Figure A-3, where two parallel six-pulse converters combine to yield a net twelve-pulse converter with much less current distortion.

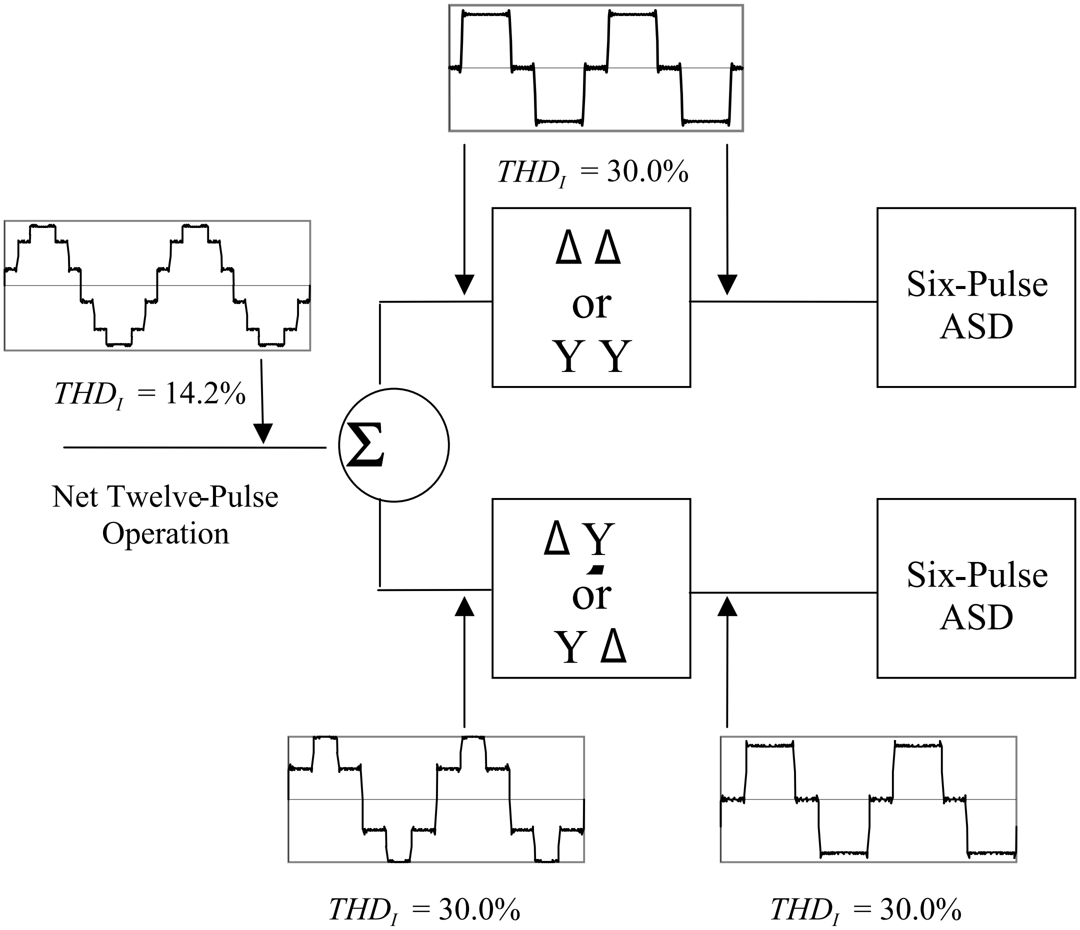


Figure A-3. Current Waveforms of Identical Parallel -Pulse Converters
Yield a Net Twelve-Pulse Converter

Figure A-3
Current Waveforms of Identical Parallel – Pulse Converters Yield a Net Twelve-Pulse Converter

B

GUIDELINES FOR PROJECT MANAGMENT

Establishing Roles and Responsibilities, and Preparing the MOU

As discussed in Sections 2 and 3, the first step in any power quality mitigation technology project is to conduct a power quality audit to identify the power quality problem that potentially can be solved using the power quality mitigation equipment and to clearly state the problem in a clear concise format. For example, a problem statement might be, “We are experiencing random system disturbances associated with voltage sags that result in sensitive electronic equipment shutting down.” After defining the problem, the next step is to assemble the project team that will be responsible for identifying all the feasible alternatives for solving the power quality problem.

The management of the power quality mitigation project should be based on the project team concept. Normally, a project team is organized by a project manager, identified early in the problem-definition and budget-formulation phases, when it appears certain that a specific project is required to meet a corporate power quality objective. All team members report functionally to the project manager, who is assigned the responsibility, accountability, and authority for the overall management of the project. Team member assignments are typically documented on a project team roster. The project team roster shows typical functional areas assigned to project team members. Many projects will not require full-time participation of the identified team members, while other projects may require full-time support of specialized team members for short periods. As a minimum, the project team should include the equivalent roles of a project manager, project analyst, finance officer, scheduler, and cost estimator. In some cases, the team member may fill multiple roles.

Before project initiation, the project manager should divide the project into a series of more detailed tasks called the “work breakdown structure” (WBS). The WBS defines lower-level elements and more detailed scopes of work required to solve the identified problem. Once the WBS is developed, more detailed planning is possible because uncertainties and assumptions used to develop the forecast baseline during the program-development phase are resolved through studies and decisions made during the intervening period. The project manager, along with other members of the project team, should ensure that the WBS is product-oriented and structured in accordance in which the work is managed and the individual responsibilities.

Once the project team has been assembled and the feasible power quality mitigation alternatives have been selected, the project manager should prepare a memorandum of understanding (MOU). The purpose of the MOU is to define the roles and responsibilities of all parties involved in the project. The following elements of the MOU may be used as an example.

Memorandum of Understanding

Definitions

- Project Management defines the role of an individual or organization in coordinating overall work activities, combining and analyzing data and findings, and issuing monthly and final reports and minutes of all meetings.
- System Analysis defines the process of reviewing the application of the power quality mitigation device from the standpoint of its impact on connected and connecting elements, the process product, and the operating system as a whole.
- Steering Committee - The purpose of the steering committee is to overview and provide direction and council to the project team. The committee will review and approve all major decisions. Any member of the steering committee will have the right of veto in regard to a decision. All decisions must have unanimous approval of the steering committee. The steering committee will consist of a representative from all parties involved including the EPRI project manager.
- System Integration defines the process of effectively applying the power quality mitigation device as part of an overall cost/benefit, reliability, and performance enhancement project goal. System integration considers overall system process impacts as well as process benefits.
- Project Team defines the member organizations and individuals comprising the team. The team should include participation by all stakeholder organizations including the end user, conditioning equipment manufacturer, installation team, and EPRI.

Purpose

The purpose of this memorandum is to describe the roles and responsibilities of the project team members. The team is charged with bringing together the required expertise and resources to provide and install the power quality mitigation device. The project will identify issues and benefits that occur from using the power quality mitigation device, thereby promoting market transformation for the technology introduction.

The cooperation is to include non-confidential information exchange on equipment operation before and after the installation of the power quality mitigation device. Measurements will be taken to determine the degree of effectiveness in avoiding production process impact due to power quality events.

The represented parties have mutual interest in the successful application of energy storage to protect manufacturing processes. The energy storage will permit the process to continue operating through brief voltage sags and voltage interruptions.

Understanding

To accomplish the desired cooperation, each party will have a specific role in completing tasks as outlined by the defined statement of work. The objective of the work is to demonstrate the performance of the power quality mitigation device under monitored field conditions. The roles defined for each team member are as follows:

Member Utility

The member utility will provide project funding for monitoring equipment, site coordination management, and EPRI services through an EPRI tailored collaboration (TC) project agreement and will provide an individual to serve on the project team and steering committee. Details of the project activities to be completed by the member utility are as follows:

- Provide system information.
- Identify the host demonstration site.
- Provide site coordination management.
- Gather information on the application that may be used in conjunction with the electrical performance measures.
- Contribute information for the EPRI report.
- Facilitate project workshop and production of an Innovators.

End-Use Customer Team

The end-use customer will provide an individual to serve on the project steering committee and provide a site for the installation of the new power quality mitigation device. Detailed contribution to the project will be as follows:

- Provide system information.
- Install the power quality mitigation device.
- Provide access to site for installation and service.
- Provide a data service telephone line.
- Provide local assistance with data collection.
- Allow reasonable access to the installation for interested observers.
- Assist with the economic information.
- Contribute to the project report.

Power Quality Mitigation Device Manufacturer

The power quality mitigation device manufacturer will provide the following information on the power quality mitigation equipment:

- Provide detailed specification.
- Supply equipment that meets the specification requirement
- Arrange witness testing at manufacturer's site.
- Assist with startup.
- Assist with information collection and review.
- Contribute specialized sections of the EPRI report covering the power quality mitigation device design.
- Contribute to the production of EPRI Publications.

EPRI Role

EPRI will act as overall project manager for the project and will maintain control of the project budget. EPRI will:

- Manage the project.
- Publish a report and Innovators.
- Facilitate a workshop.

Engineering Consulting Team

The engineering consulting team will be responsible for the overall technical project management, data collection, data analysis and facilitate project review meetings and provide meeting agendas and histories. The engineering consulting team will also be responsible for:

- Project schedules.
- Project budget monitoring.
- Ordering instruments.
- MOUs.
- Collect data before and after the power quality mitigation device installation.
- Data analysis.
- Writing the project final report and tech transfer documents.
- Integrate comments into the report.

Statement of Work

Background

- Discussion on the power quality problem impacting the customer.
- Overview of the proposed power quality mitigation device

Objectives

- To demonstrate the performance of the power quality mitigation device under controlled field conditions.
- To quantify the cost-benefit analysis associated with the retrofit of the power quality mitigation device to an existing industrial power system.
- To prepare a comparative analysis with competing solutions both at MV and LV.
- To demonstrate the benefits in terms of the reduced number of events at the chosen site.
- To identify broad and generic assessment of the site that can be published.
- To determine the system benefits from the power quality mitigation system:
- To establish a methodology for the demonstration of the new system.
- To provide transfer of technical information on the project to EPRI members through:
- One-day Workshop
- Project Innovator
- EPRI Technical Report

Tasks

- Task 1 : Project technical coordination.
- Task 2 : Preparing specification, RFP, bid evaluation, developing factory witness testing plan.
- Task 3 : Engineering instructions for installation and site preparation and coordinate system commissioning at the end-user facility.
- Task 4: Developing plan for pre- and post- monitoring for performance verification
- Task 5: Data collection and data analysis
- Task 6: Final report and associated EPRI tech transfer documents.

Agreement

Based on the operational needs of each team member, the team will establish and define a mutually agreeable schedule for completion of the work. The Agreement set forth in this Memorandum of Understanding is not binding on the parties, but every reasonable means will be used to carry out the intent of the Memorandum of Understanding.

Accepted this _____________ day of __________________ , 2000 by:

____[List Parties to this Agreement]____

Establishing Time Line and Schedule

The project schedule or timeline is based on the WBS and is a series of tasks with duration and interrelationships within a specified period. A baseline schedule is developed within the framework of the WBS and in a hierarchical manner such that those activities at the lowest level of the hierarchy can be summarized and traced through successively higher levels.

Along with a project timeline, the project costs are estimated at the lowest level of the WBS. The project team estimator, based upon the following information, should develop the cost estimates based on the (1) scope of work, (2) work breakdown structure, (3) schedule, (4) participants, and (5) project assumptions. The project manager should validate the schedule against the work breakdown structure and project deliverables.

The customer or end user should be part of the project planning team. Getting the end user involved in the decision process early in the planning stages will assure that all important issues involved in satisfying the project needs are meet. In addition, the end user should be involved in developing the WBS and the schedule to make sure the project is coordinated with the production requirements of the end user. Example project schedule milestone chart is shown in Table B-1.

Table B-1
Project Schedule Milestone Chart

Project Task Description	*Weeks From Start*	*Duration in Weeks*
1. Initial customer contact	1-2	2
2. Level 1 PQ Audit	3-4	2
3. Level II PQ Audit	5-8	4
4. Preparing Equipment Specification	9-10	2
5. Preparing RFP	11-12	2
6. Evaluating RFP and Awarding Bid	13-16	4
7. Equipment Manufacture	17-28	12
8. Factory Acceptance Testing	29-30	2
9. Installation, Commissioning and Start-up	31-35	5
10. Performance Verification	36- 60	25
11. EPRI Final Report and Tech Transfer	61- 68	8

Manpower Requirement

The manpower requirements identifies the resources required for each task as outlined in the work breakdown structure and the project milestone chart shown in Table B-1 and agreed to in the MOU. Each member of the project team identified in the MOU should determine the required resources necessary to accomplish the desired tasks given the project schedule. It may be necessary to refine the manpower requirements during the project lifecycle depending on the progress made toward accomplishing the tasks and schedule. The manpower requirements will also change depending on the task.

Finalizing Budget

Once the Work Breakdown Structure is finalized, the financial plan should be prepared that provides the monetary authorizations and allotment of funds for obligations by fiscal period. The Financial Plan authorizes project funding and work should not proceed until the Financial Plan is approved by all parties involved. The schedule of budget disbursements in the Financial Plan should correspond to the milestone task discussed earlier.

The Project Manager and the finance staff is responsible for preparing the funds status report for each task. The report shows amounts authorized for projects based upon the Financial Plan and all internal funding currently allocated through work orders. The work orders are budgeted based upon the control account plan for a project. The funds status report is a mechanism to help keep a project from becoming over-spent.

C

GENERIC CHECKLIST FOR ESSENTIAL SPECIFICATIONS AND APPLICATION ISSUES

This appendix provides a suggested checklist to ensure that the minimum points in planning a power quality mitigation installation have been addressed.

Defining and Selecting a PQ Mitigation Equipment

Output Power Characteristics

Power rating: ___kva.
Steady-state voltage: ___V RMS.
Voltage transient and recovery: +___%, - ___%, ___second.
Frequency limits: ___Hz, ± ___Hz.
Line-to-line voltage unbalance: ___%.
Load unbalance ratio: ___:1.
Voltage modulation: ___%.
Waveform deviation factor: ___%.
Total harmonic content: ___% RMS.
Phase angle: ± ___°.
Overload: ___%, ___ seconds.
High momentary loads: ___amperes, __-second.
Current limit.
External fault clearing.
Internal fault clearing.

Other Requirements

Audio noise level.
Growth provision to: ___kva.
Automatic bypass operation.
EMC.
Input voltage harmonics: ___% RMS.
Efficiency.
Reliability and maintainability.
___MTBF: _____ hours.
___MTTR: ___-hours.
Safety.

Determining Power Rating

Present system load: ___kva.
Planned additions: ___kva.
Long-range expansion: ___kva.
Critical lighting: ___kva.
Other critical loads: ___kva.

Optional Features

Remote console.
Emergency power-off interconnection.

Special EMC requirements.
Lighting and cooling during outage.
Nonstandard input power voltages.
Special acoustic or aesthetic requirements.
Automatic start of and transfer to E-G.
Smoke detectors.
Additional spare parts and test equipment.

Site Selection

Temperature: ___°C to ___°C (___°F to ___°F).
Relative humidity: ___% to ___%.
Altitude: ___meters (___ feet)
Ventilation and/or air conditioning.
Acoustics.
Safety.
Floor loading.
Space.
Accessibility.
Growth.
Lightning protection.
Earthquake conditions.

Power Distribution

Single-line electrical diagram.
Input power source impedance.
Connection diagram.
Independent mains bypass feeder.
Circuit Protection.
_____ Input .
_____ load.
_____ Energy Storage Device
_____ Input to load (bypass).

Requests for Proposals

Parameters and information in first four sections.
Reliability.
_____ Average utility failure rate: ____
_____ Average utility failure

duration: _______

Maintenance.

_____ Strategy 1 (all supplier provided) or

_____ Strategy 2 (all user-provided) or

_____ Strategy 3 (parts of 1 and 2).

_____ Time between notification and arrival of service personnel: _____________.

_____ Training.

_____ Maintenance documentation.

Operator training.

Single-point failures.

System ground constraints.

Warranties.

Electrical codes.

Structural codes.

Safety codes.

Contracts.

Schedules.

Input power.

_____ Maximum: _____kva.

_____ Power factor: ___.

_____ Voltage harmonics: ___% RMS.

Energy Storage

_____ Voltages.

    _____ Float: _____V.

    _____ Equalization: _____ V.

    _____ End: _____ V.

_____ Rated dc current at full load: _____ amperes.

_____ Maximum available dc short-circuit current: _____ amperes.

_____ Ride-through time at full load..

_____ Projected life: ___ years

_____ Operating temperature ___°C, ± ___°C (___°F, ± ___°F).

Proposed Evaluation

Compliance statements.

Deviation statements.

Visits.

Acceptance Tests

Output voltage regulation.

bypass switch.

PQ mitigation performance

Environment.

Instrumentation, controls, and indicators.

Installation

Compliance with codes, regulations, drawings, and specifications.

Total System Acceptance Tests

Dummy load tests.
_____ Output voltage regulation.
_____ Energy Storage.
_____ Static bypass switch.
_____ Instrumentation, controls, and indicators.
_____ System grounds.
_____ Serviceability.
Live load tests.
_____ Current distortion tests
_____ Output voltage regulation.
_____ Static bypass switch.
_____ Long-term run.
_____ Safety.

Performance Specifications		
	Necessary Specifications	***Comments***
1	Phase number	Single or three phase
2	Rated kVA of Load	Filter ratings vary based on filter technology
3	Nominal Voltage	System voltage. On passive traps, derate capacitor banks due to tuning inductors
4	Maximum RMS Current	On passive or active filters, capacitor and/or inverter duty must take into account load current plus any harmonic current from source
5	Nominal Tuned Frequency	For passive traps, or passive single phase filters, this is the frequency desired to be removed.
6	Blocking or Trapping	For single phase passive filters, this is the filter configuration
7	If Blocking, Phase voltage distortion limits	Blocking filters distort bus voltage. How much distortion can the filter be allowed to cause?
8	If trapping, Existing Background Harmonics	How much current will the filter sink from source? Capacitor must be rated for that current.
9	Load impedance- high or low relative to source	For active filters, shunt or series configuration depends on load impedance relative to source.
10	Di/dt requirements of compensator	For active filters, steep rising wavefronts are difficult for inverter to track
11	High frequency content of waveform to be compensated	For broad band filters and the passive interface filter used in active configurations, capacitor duty depends on this high frequency content.
12	Voltage transients	Transients can be magnified by interface filter, also can cause extra current in IGBT snubber diodes
13	Power Factor Correction Capacitors and System Resonance Conditions	Power factor correction capacitors can cause resonance

D
SURVEY DATA FROM VENDORS

Harmonic Filter Manufacturer Information

Table D-1 contains the 28 harmonic filter manufacturers that were contacted to determine if they would be interested in providing information and case studies for this EPRI report. Table D-2 provides a brief summary of the harmonic filter information collected from the manufacturers, based on currently available information.

Table D-1
Harmonic Filter Manufacturers

Manufacturers	**Web-Sites Available, www.**	**Information Available**	**Provided Information**
1. ABB Controls Inc.	abb.ca	X	X
2. Aim Energy		X	X
3. AIM Europe	aimeurope.mcmail.com	X	
4. Amecon Inc	ameconinc.com		
5. Commonwealth Sprague (CWS)	comsprague.com	X	
6. Control Transformer	control-transformer.com	X	
7. Current Technology	currenttechnology.com	X	X
8. Current Thinking Inc.	currentthinking.com	X	X
9. Electronic Power Conditioning Inc. (EPC)	accusine.com	X	X
10. GE	geindustrial.com	X	
11. Harmonics Limited	harmonicslimited.com	X	X
12. MESTA Electronics, Inc.	mesta.com	X	
13. MGE UPS Systems	mgeups.com	X	
14. MTE Corporation	mtecorp.com	Y	X
15. Myron Zucker, Inc.	myronzuckerinc.com	X	
16. Northeast Power Systems (NEPSI)	nepsi.com	X	
17. PFC Engineering Ltd.	pfc-engineering.com	X	X
18. Powell Electrical MFG. CO.	powellncd.com	X	
19. Power Correction Systems Inc. *(Active Harmonic Filters)*	activeharmonicfilters.com	X	X
20. Power Quality Inc.	powerqualityinc.com	X	
21. Power Quality Systems, Inc. (PQS)	pwrqualitysys.com	X	X
22. PowerSmiths International Corp.	powersmiths.com	X	X
23. Siemens Power Transmission and Distribution	siemenstd.com	X	
24. Soft Switching Technologies	softswitch.com	X	
25. SquareD	squared.com	X	
26. Steelman Industries	steelman.com		
27. Trans-Coil, Inc. (TCI)	transcoil.com	X	
28. Versatex	versatexonline.com	X	

Table D-2
Summary of Harmonic Filter (HF) Manufacturer Information.

(This table indicates what *is* available as opposed to being all inclusive, i.e. it is based on information currently available)

Manufacturers	**Filter Type, *Offers: C, I, U**	**Voltage Ratings Offered**	**Power Ratings Offered**
1. ABB Controls Inc.	Active, I	400 – 600 V	up to 1 MVA
2. Aim Energy	Active	208 – 600 V	50, 100, 200 A
3. AIM Europe	Active, C, I	110 – 600 V, 690 V	up to 1000 A
4. Amecon Inc			
5. Commonwealth Sprague (CWS)	Passive, I	Low Voltage	
6. Control Transformer	HF Inductor, I		
7. Current Technology	Active, C, I	120/208 V, 220/380 V 277/480 V	up to 400 A
8. Current Thinking Inc.	Passive, I	208 – 600V	100 – 1200 kVAR
9. Electronic Power Conditioning Inc. (EPC)	Active, C, I	208 – 480 V (600, 2400, 4160V with transformer)	50, 100, 300 A
10. GE	Passive, I	240, 480, 600 V	25 – 2400 kVAR
11. Harmonics Limited	Passive, C, I	208, 480, 600 V	15 – 500 kVA
12. MESTA Electronics, Inc.	Active, I	See Section	See Section
13. MGE UPS Systems	Active, C, I		10 – 2000 kVA
14. MTE Corporation	Passive, C, I	120 – 600 V	5 – 15 A, 3 - 1000 hp
15. Myron Zucker, Inc.	Passive, I	240, 480, 600 V	10 – 800 A
16. Northeast Power Systems (NEPSI)	Passive, U	2.4 – 34.5 kV	300 – 15,000 kVAR
17. PFC Engineering Ltd.	Passive, I	Variable, See Section	Variable, See Section
18. Powell Electrical MFG. CO.	Passive, I, U	240, 480, 600V, 15kV	
19. Power Correction Systems, Inc. *(Active Harmonic Filters)*	Active,Hybrid,C, I, U	120,208,230,460,575V 4.16 – 21 kV	1 – 1000 A 0.7 – 1000 kVA
20. Power Quality Inc.	Passive, C, I	208, 480 V	5 – 125 kVA
21. Power Quality Systems, Inc. (PQS)	Passive, U	4.16, 13.8,15, 25kV	Variable, See Section
22. PowerSmiths International Corp.	Passive, Active, C, I, U	120/208 V to 4160 V	10 – 5000 kVA
23. Siemens Power Transmission and Distribution	Active, I		20 – 5000 kVA
24. Soft Switching Technologies (SST)	Active,Hybrid, I	460 V	30 A, 150 A
25. SquareD	Passive, I	up to 600 V	up to 1200 kVAR
26. Steelman Industries			
27. Trans-Coil, Inc. (TCI)	Passive, I	208 to 600 V	3 to 2000 kVAR
28. Versatex	Passive, I	208 to 600 V	200 to 900 kVAR

**C = Harmonic Filters Designed for Single-Phase* Commercial/Computer-Type *Loads*

*I = Harmonic Filters Designed for Three-Phase *Industrial* Load Applications

*U = Harmonic Filters Designed for *Utility* Grid Distribution Level Applications

D-1. Passive Harmonic Filters

Passive harmonic filters are classified here as filters using inductors (reactors) and capacitors to form frequency dependent networks that reduce harmonic currents in electrical systems. What follows is a compilation of passive harmonic filter manufacturer information and case studies where available.

D-1.1 Commonwealth Sprague (www.comsprague.com)

Commonwealth Sprague manufactures two primary harmonic filters: The Autovar ® Filter and the Unipak ® Filter, as described below. Fig. D-1 shows an example of these systems.

Figure D-1
Example Commonwealth Sprague Harmonic Filter Systems.

Autovar Filter

The Autovar Filter is an automatically switched harmonic filter/power factor correction system. It is designed to be used in three-phase, 6-pulse, high harmonic environments. The Autovar Filter is situated in two cabinets. Reactors and optional disconnect are placed in one cabinet, which is isolated from the controller and heat-sensitive capacitors in the other cabinet. UL-recognized, 200,000 A fuse interrupting capacity is provided on all three phases of each bank.

Unipak Filter

The Unipak Filter is a fixed harmonic filter bank for low-voltage, heavy-duty applications. This filter reduces harmonics and corrects power factor, and is tuned for maximum efficiency in reducing harmonic currents associated with 6-pulse drive environments. The Unipak Filter is designed with two separate enclosures, to isolate capacitors from reactors.

D-1.2 Control Transformer (www.control-transformer.com)

Control Transformer offers three-phase, open and enclosed, CT Harmonic Filter Inductors for harmonic filtering networks to neutralize unwanted harmonics (see Fig. D-2). The filtering network prevents the harmonics from getting back into the supply line circuits. Designed to the specific application, CT Harmonic Filter Inductors are tuned to the capacitor used for a given (desired) frequency. Typically, Harmonic Filter Inductors will feature a low temperature rise with a 220 degree C (Class H) insulation system; and a distributed-gap core construction technique which reduces gap losses, fringing flux and magnetic fields.

Figure D-2
Control Transformer Harmonic Filter Inductor

D-1.3 Current Thinking Inc. (www.currentthinking.com)

The Current Thinking filter products are manufactured for industrial and commercial three-phase applications. Their systems utilize traditional passive filter techniques (i.e. capacitors and reactors) and come in the following configurations:

- Static Capacitor Banks (pre-manufactured units from Commonwealth-Sprague and Power Survey Inc.) for use at service panels or on individual motor loads.

- Manufactured-to-Order Switched Capacitor Banks in two configurations; un-tuned (capacitors only), or de-tuned to reduce harmonic current magnification in high harmonic environments. These systems are usually installed at the service entrance or feeder switch-board.
- Manufactured-to-Order Shunt and Band-Pass Filters. These systems are usually installed at the service entrance or feeder switch-board.

Current Thinking Inc. are the designated specialists for the complete line of Commonwealth Sprague capacitor and filter products. They are application specialists of custom manufactured units for Power Survey Inc. in Ontario, which are branded as "Current Thinking" units. They are also resellers of the complete line of Trans-Coil Inc. (TCI) reactors and drive-applied filters. Current Thinking Inc. provides site measurements, design support, sizing data, preliminary modeling data, installation, service and support. Their units are manufactured per their site recommendations by the companies noted above (see Fig.D- 3).

Figure D-3
Typical Current Thinking LV Filtered Unit (Manufactured to Order by Power Survey Inc.)

Filter Description, Topology and Method of Operation

The Current Thinking LV filter is a passive device utilizing capacitors and iron core reactors, switched by adequately rated contactors as necessary. Voltage, current, kVA, kVar and harmonic content is monitored by a microprocessor based control unit. These units vary with the model, type and manufacturer of the capacitor unit but include Alstom Novar and Roederstein controllers, among others.

Available Ratings and Dimensions

Filters are available in sizes from 100 kVAR and up, voltages from 208 V to 600 V @ 60 Hz (supplying only the North American market at this time). Systems for demagnification and power correction are typically tuned in the 3.8-4.7th harmonic range, however this can vary with the site requirements. Dimensions vary with the size of filter, number of reactors, contactor requirements etc., however particular size limitations on site can be accommodated with the use of custom cabinetry. Nominal sizes of stock capacitor units are 60"x36"x20" for 80 to 360 kVAR, 60"x48"x20" for 360 to 480 kVAR and 60"x60"x24" for 480 to 600 kVAR. Nominal sizes for units at 480-600 V, utilizing caps and reactors are as follows.

Table D-3
Nominal Sizes for Units at 480-600 V Utilizing Capacitors and Reactors

KVAR	50 KVAR STEPS	100 KVAR STEPS
100	72H 36W 24D	To Order
200	72H 36W 36D	*To Order*
300	72H 48W 36D	90H 48W 24D or 90H 36W 36D
400	72H 48W 36D	90H 48W 24D or 90H 36W 36D
500	90H 60W 36D	90H 60W 24D or 90H 48W 36D
600	90H 72W 36D	90H 72W 24D or 90H 48W 36D
700	To Order	90H 60W 36D
800	To Order	90H 72W 36D
900	To Order	90H 72W 36D
1000	To Order	90H 84W 36D
1200	To Order	90H 96W 36D

D-1.4 GE (www.geindustrial.com)

GE offers the Aerovox Demand Line Plus for power factor correction and harmonic reduction (Fig.D-4). The GE Aerovox Demand Line Plus multi-step power factor control equipment automatically maintains desired power factor levels, adjusting to the system load requirements in selected kVAR steps, with the flexibility of including harmonic filter reactors, typically tuned to the 4.7th harmonic.

Available Ratings:

240 volt	up to 600 kVAR
480 volt	up to 2400 kVAR
600 volt	up to 2400 kVAR

Figure D-4
GE Aerovox Demand Line Plus Auto Switched LV Power Factor Correction and Harmonic Filter

GE also offers the Aerovox HSICS, a line of fixed capacitor and harmonic suppression units for nonlinear load applications.

Available Ratings:

240 volt	25-50 kVAR
480 volt	25-200 kVAR
600 volt	25-200 kVAR

D-1.5 Harmonics Limited (www.harmonicslimited.com)

Harmonics Limited provides the "Neutralizer Series" of harmonic suppression systems in several configurations. These are harmonic blocking filters, designed to block lower order harmonics. The PlugMax and RackMax devices are designed to be located directly at the harmonic load and are available in models of 3-30 A. The SysteMax device is designed to be located at the 208V secondary distribution transformer or at a dedicated panel and is available from 15 to 500 kVA. A harmonic filter with TVSS is also available (SysteMaxPlus). Harmonics Limited also offers combinations of filter/transformer (PowerMax) and filter/transformer/TVSS with high frequency noise filtering (PowerMaxPlus) available from 15 kVA to 500 kVA (600, 480, or 208V primary). These products have the same footprint and ease of installation as a standard transformer while providing protection to the electrical distribution system from the transformer to the furthest outlet. Examples of filters available from Harmonics Limited are shown in Fig. D-5.

Figure D-5
Examples of Filters available from Harmonics Limited

Filter Description, Topology and Method of Operation

The "Neutralizer Series" blocking filter is an LCR circuit, tuned to have its maximum impedance at the 3rd harmonic (180Hz for 60Hz distribution systems.) The main circuit consists of reactors and capacitors connected in a parallel-resonant tank, with the Thevenin-equivalent circuit shown in Fig. D-6.

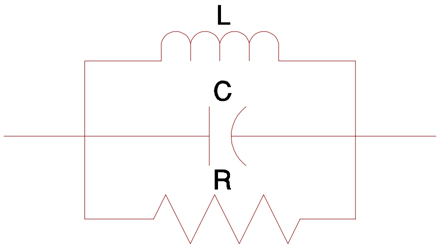


Figure D-6
Thevenin-Equivalent Circuit for Harmonics Limited Blocking Filters

The parallel-resonant tank circuit is characterized by an infinite impedance at the tuning frequency and a relatively low impedance at all other frequencies. In the neutralizer filter the circuit is used to prevent the flow of 3rd-harmonic currents, thus protecting the electrical distribution system.

Table D-4
Available Ratings and Dimensions.

Size kVA	Neutralizer Dimensions	Weight	PowerMax Dimensions	Weight
15	16x20x9	60	38x17x14	230
30	24x20x9	120	45x22x20	500
45	24x20x9	130	45x22x20	550
75	30x24x13	210	55x26x21	755
112	36x30x13	300	57x30x24	1150
150	36x30x13	325	57x30x24	1325
225	60x25x23	750	68x40x30	2400
300	60x25x23	775	68x40x30	2495
500	60x50x23	1450	87x49x46	4600

D-1.6 MTE Corporation (www.mtecorp.com)

MTE Corporation offers Harmonic Filter (HF) series single-phase harmonic filters which are designed primarily to block the flow of third harmonic currents, with the best filter location being as close as possible to the non-linear load. The 3rd HF reduces each of the individual harmonics from 3rd through 9th, with typical reduction of the 3rd harmonic often as much as 80%-90%.

Figure D-7
Example MTE 3rd Harmonic Filter

Filter Description, Topology and Method of Operation

The HF series filters are 3rd harmonic filters. They incorporate series connected blocking filter technology which is designed to block the 3rd harmonic. In addition they also reduce the 5th, 7th and 9th harmonics. The general topology is shown in Fig. D-8.

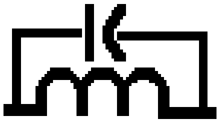


Figure D-8
General Topology for the MTE HF Series Harmonic Filters

Available Ratings and Dimensions

The HF series are available as either 120 V or 240 V filters, in ratings of 5, 10 and 15 A (50 Hz or 60 Hz available). The styles of filter available include hardwire and plug-in, with the specifications given in Tables D-5 and D-6 respectively.

Table D-5
Hardwire Style Filter Specifications

Model	Amps	Volts	VA	Width (in./mm)	Depth (in./mm)	Height (in./mm)
5PHF	5	120	600	8.66/220	8.5/216	5/127
10PHF	10	120	1200	11.25/285	8.5/216	5/127
15PHF	15	120	1800	11.25/285	8.5/216	5/127
5HF2	5	240	1200	8.66/220	8.5/216	5/127
10HF2	10	240	2400	11.25/285	8.5/216	5/127
15HF2	15	240	3600	11.25/285	8.5/216	5/127

Table D-6
Plug-In Style Filter Specifications

Model	Amps	Volts	VA	Width (in./mm)	Depth (in./mm)	Height (in./mm)
5HF	5	120	600	7.5/191	8.5/216	5.9/150
10HF	10	120	1200	10.25/260	8.5/216	5.9/150
15HF	15	120	1800	10.25/260	8.5/216	5.9/150
5HF2	5	240	1200	7.5/191	8.5/216	5.9/150
10HF2	10	240	2400	10.25/260	8.5/216	5.9/150
15HF2	15	240	3600	10.25/260	8.5/216	5.9/150

Harmonic Filters Designed for Three-Phase Industrial Load Applications

MTE also offers Broad Band Harmonic Filters (Fig. D-9), designed for use at the input of variable frequency drives (VFDs), for variable torque applications. The broad band harmonic filter uses a low pass filter topology with an interposing transformer to prevent overvoltage conditions. As a low pass filter, it filters out each individual harmonic frequency and offers guaranteed performance levels of either 12% current THD or 8% current THD.

Figure D-9
MTE Broad Band Harmonic Filters

Broad band harmonic filters are available in all voltage ratings form 208 to 600 V, are available in either 50Hz or 60Hz designs and in ratings from 3hp to 1000hp. They are available either as separate components for customer mounting or as a complete NEMA 1 assembly.

D-1.7 Myron Zucker Inc. (www.myronzuckerinc.com)

Myron Zucker Inc. offers the Caltrap^{TM} and Autocapacitrap^{TM} series of harmonic filters. The Caltrap^{TM} "RIM-H" series is a tuned LC filter trap designed to improve power factor and reduce harmonics generated at the source. The Caltrap^{TM} with Line Reactor is the "RIM-L" series, which reduces harmonics while isolating the load. They are available in 10 to 132 A ratings, at 240, 480 and 600V. The Caltrap^{TM} "CIM-H" series is a tuned LC filter trap designed for mounting at a distribution center or service entrance to reduce harmonics and improve the power factor. They are available in 150 to 800 A ratings, at 240, 480 and 600V.

Myron Zucker Inc. also offers the Autocapacitrap^{TM} harmonic filter series "ACIM-H", that is a tuned LC filter trap designed for mounting at a distribution center or service entrance. The Autocapacitrap^{TM} is designed to reduce harmonics, improve power factor, and maintain the electrical system power factor at a pre-selected value. It is also available in 150 to 800 A ratings, at 240, 480 and 600 V.

D1.8 Northeast Power Systems, Inc. (NEPSI) (www.nepsi.com)

NEPSI offers metal enclosed capacitor banks and harmonic filter banks for indoor and outdoor substation applications for power factor correction and harmonic filtering (Fig. D-10). The range is from 300 kVAR to 15,000 kVAR, and 2.4kV through 34.5kV.

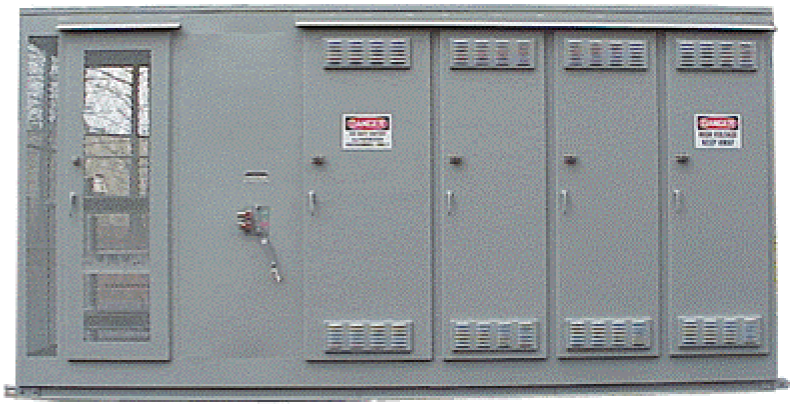


Figure D-10
NEPSI Metal Enclosed Capacitor Banks and Harmonic Filter Banks for Substation Applications

NEPSI also offers pad-mounted capacitor banks and harmonic filter banks for placement in publicly accessible areas for power factor correction and harmonic filtering (Fig. D-11). The range is also from 300 kVAR to 6,000 kVAR, and 2.4kV through 34.5kV.

Figure D-11
NEPSI Pad-Mounted Capacitor Banks and Harmonic Filter Banks for Placement in Publicly Accessible Areas

D-1.9 PFC Engineering Ltd. (www.pfc-engineering.com)

PFC Engineering Ltd. offers three types of filter systems using reactor connected capacitors which are designed to prevent resonance and to reduce the level of harmonics. An Example harmonic filter available from PFC Engineering Ltd. is shown in Fig. D-12. The three available types of harmonic filters are described below.

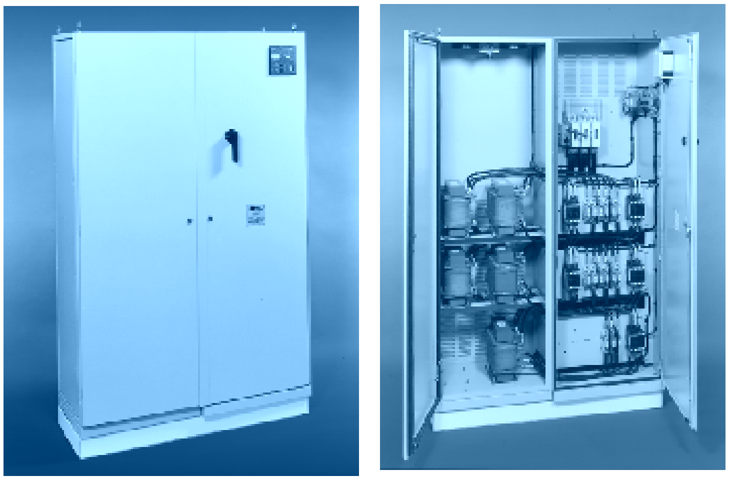


Figure D-12
Example of Filter available from PFC Engineering Ltd.

Blocking Reactor system - This reactor connected capacitor combination is designed to have a resonant frequency of 189 Hz. In this case system resonances are avoided and between 17% and 20% of the 5th harmonic is absorbed. This is suitable for variable loads.

Partial Filter System - Here the reactor capacitor combination is designed to resonate at a frequency of 210 Hz. Again system resonances are avoided and between 40% and 50% of the 5th Harmonic is absorbed. Suitable for variable loads where harmonic reduction is also required.

Full Filter System - In this system the capacitor/reactor legs are tuned to a given harmonic frequency, producing almost zero impedance to that harmonic current. Therefore, most of the current is absorbed by the filter. This type of filter can realistically reduce the harmonic current flowing in the supply network by up to 90%. Ideally suited for constant loads.

Available Ratings - PFC Engineering Ltd. states that they offer the de-tuned harmonic filters to any size and specification, most of which are individually designed specifically to customer requirements.

D-1.10 Powell Electrical Mfg. Co. (www.powellncd.com)

Powell offers Harmonic Filter Systems for either low or medium voltage networks to reduce harmonics and correct power factor. The LIFEGUARD Harmonic Filter Systems are available in 240, 480, and 600 V, NEMA 1 enclosures (Fig. D-13). Powell also offers 15kV Harmonic Filter Systems.

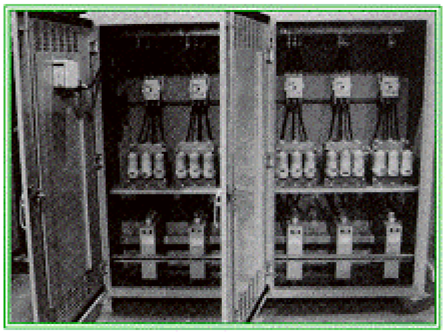


Figure D-13
Powell LIFEGUARD Harmonic Filter Systems

D-1.11 Power Quality, Inc. (www.powerqualityinc.com)

Power Quality Inc. offers the BIDHISS I™ single-phase, low-impedance power conditioners in the 70 VA to 10 kVA, 120V range, and the BIDHISS III™ three-phase, low-impedance power conditioners in the 5 kVA to 125 kVA, 208 and 480V range. The BIDHISS systems (Fig.D-14) combine a bidirectional harmonic filter with an isolating series low-impedance power conditioner. They protect the load from electrical power disturbances and protect the power system from load-generated harmonics. BIDHISS power conditioners also provide load regulation to maintain output voltage during sudden changes in load currents.

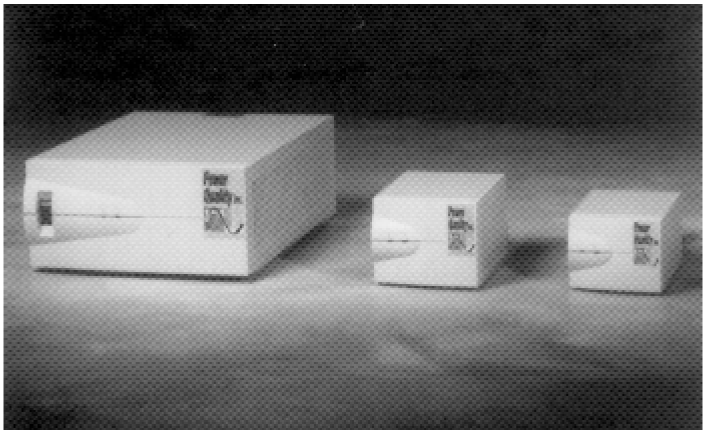


Figure D-14
Power Quality Inc. BIDHISS Low-Impedance Power Conditioners

D-1.12 Power Quality Systems, Inc. (PQS) (www.pwrqualitysys.com)

Power Quality Systems provides the IntelliHarmonic™ line of custom harmonic filters. The filters are typically applied with static VAR compensators:

- when system studies show that the added shunt capacitance could create resonant frequencies
- to abate existing harmonic problems on the system

The harmonic filters can also be applied in stand-alone applications to abate existing harmonic problems. Fig. D-15 shows a four-stage single-phase harmonic filter.

Figure D-15
Power Quality System's Four-Stage Single-Phase Harmonic Filter

The filters utilize oil-cooled magnetics and standard commercial capacitors to provide a compact package that can be pole mounted on distribution systems. The filters are custom designed and include tuned and detuned filters.

Detuned filters are typically designed to compliment added capacitor banks when the added capacitance could generate harmonics with the existing system impedances. They are tuned to just below the lowest harmonic that the added capacitance would generate, for instance at the 2.7th harmonic.

Tuned filters are used to abate existing harmonic problems, and are typically tuned to the 3rd to 7th harmonic frequency.

Filter Description

The "IntelliHarmonic" filters use series LC elements in either a WYE or Delta configration. The passive filters are tuned to the existing harmonic frequencies occurring on a system.

Available Ratings

The "IntelliHarmonic" filters are available in 4.16 kV, 15 kV class (e.g. 12.47 kV,13.2 kV,13.8 kV) and 25 kV class. Single phase filters are typically the size of distribution transformers. A three phase filter has a typical foot print of 12 square feet, depending on the rating. The filters are designed for the frequency and energy requirements of the system. Power Quality Systems offer a full range of kVAR ratings, dependent on the power system requirements. Typically, a stand-alone harmonic filter is sized to provide unity PF correction of the nominal load.

D-1.13 PowerSmiths International Corp. (www.powersmiths.com)

PowerSmiths offer the PowerStar^{TM} series of harmonic reduction equipment as described here. The N1000 is a modified zig-zag reactor optimized to remove excessive 3rd harmonic, neutral current and neutral-ground voltage where it is connected to an electrical system. It is connected in parallel at the 3-phase 4-wire electrical panel feeding the circuits with the single-phase electronic equipment, e.g. personal computers. This product is ideally suited for 3-phase 4-wire systems that have excessive current flowing in the neutral conductor. When connected at the 3-phase electrical panel close to the loads, it provides an alternate path for the neutral current and removes it from flowing upstream. This product can be used in conjunction with the PowerStarTM PS0507or N1000 PLUS to address the 5th & 7th harmonic currents flowing in the system in addition to neutral current. The PowerStarTM N1000 is typically sized according to the panel amp rating at 120/208V and other voltages, at 50 and 60Hz.

The PowerStarTM PS0507 and the PS1113 harmonic conditioners are designed to cancel 5th, 7th and 11th, 13th harmonics respectively. These products introduce a phase-shift so that a single product is able to cancel two or more harmonic sources. Their high efficiency (>99%) ensures minimal losses and their low impedance design (Z=1%) ensures that minimal voltage drop is introduced to the system. These products can be used to phase-shift one load against another similar load, one group of loads against another group of similar loads, or one large load against a group of smaller loads. For optimum performance the PS series products should be placed in-line with roughly half the harmonic-producing load on a kVA basis. The PowerStarTM PS0507 and PS1113 are available from 15 to 5000kVA, from 120/208V to 4160V, at 50 and 60Hz.

The PowerStarTM VFD0507 is used in conjunction with 6-pulse drives, and the VFD1113 with 12-pulse drives to reduce harmonic currents and voltage distortion. The VFD0507 and VFD1113 are also available from 15 to 5000kVA, from 120/208V to 4160V, at 50 and 60Hz.

D-1.14 SquareD (www.squared.com)

SquareD offers the REACTIVAR® passive harmonic filter systems (AV7000) for harmonic reduction and power factor correction in industrial networks (Fig. D-16). The units rate up to 1200 kVAR, 600V. The AV7000 system is similar to anti-resonant systems with the exception that the capacitive/inductive components form a "harmonic trap".

Figure D-16
SquareD REACTIVAR® Passive Harmonic Filter Systems (AV7000)

D-1.15 Trans-Coil, Inc. (TCI) (www.transcoil.com)

Trans-Coil offers the HarmonicGuard^{TM} LC passive harmonic filters, which provide a low impedance path for the lower order harmonics generated by nonlinear loads (e.g. adjustable speed drives). The HarmonicGuard^{TM} comes standard with series 5% reactors (unless a reactor or isolation transformer already exists on-site). HarmonicGuard^{TM} is available in voltages from 208 to 600V and from 3 to 2000 kVAR.

D-1.16 Versatex (www.versatexonline.com)

Versatex offers three types of passive harmonic filters: The Non-Automatic H*Rack, the Automatic H*Pak and the Convertible Reactor Ready filters as described below.

Non-Automatic H*Rack Harmonic Filter

These units were designed for a fixed amount of capacitance in harmonic rich environments and include a kVAR monitor which gives a visual and electrical indication of proper operation (Fig. D-17). Each is designed to supply a fixed amount of reactive current and to avoid the problems that can otherwise occur from the interaction between harmonic generating loads and power factor capacitors. Models are available for distribution systems rated at 600 VAC, or less and are capable of supplying kVAR requirements ranging from 200 kVAR to 400 kVAR. Non-Automatic Harmonic Power Filters are continuously monitored and automatically taken off-line in the event performance falls outside normal parameters, or a total power outage occurs. This is to protect the system and connected equipment from unbalanced operating conditions.

Figure D-17
Versatex H*Rack Non-Automatic Harmonic Filter

Automatic H*Pak Harmonic Filter

This unit is designed to automatically adjust the amount of capacitance and supply the required amounts of reactive current in a harmonic rich environment to keep the power factor between a programmable set point and unity (Fig. D-18). Models are available for distribution systems rated at 208 to 600 VAC, and are capable of supplying kVAR requirements ranging from 200 kVAR to 900 kVAR. The performance of H*Pak Harmonic Power Filters is continuously monitored. In the event performance falls outside design parameters, selected components are automatically taken off line.

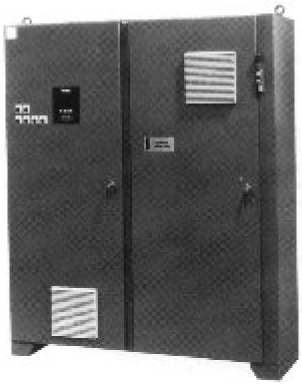


Figure D-18
Versatex H*Pak Automatic Harmonic Filter

Convertible Reactor Ready Non-Automatic Harmonic Filter

These units were designed for easy conversion to a harmonic power filter if the harmonic content exceeds a safe limit. Each is engineered to supply a fixed amount of reactive current. Models are available for distribution systems rated at 600 VAC or less, and are capable of supplying kVAR requirements ranging from 200 kVAR to 400 kVAR. Reactor-Ready Capacitor Assemblies are continuously monitored and automatically taken off-line in the event performance falls outside normal parameters, or a total power outage occurs.

D-2. Active and Hybrid Harmonic Filters

Active harmonic filters are classified here as filters employing power electronic switching devices to actively synthesize and cancel harmonic currents present in the load to reduce harmonic currents in electrical systems. Hybrid harmonic filters consist of both active and passive filters connected in different configurations to reduce system harmonics. What follows is a compilation of active and hybrid harmonic filter manufacturer information and case studies where available.

D-2.1 ABB Controls, Inc. (www.abb.ca)

ABB Controls Inc. provides an active filter (named PQFA) designed for discrete harmonic cancellation for three-phase systems in the 400-600 V range. The design is modular, with each module having a current rating of 155A, that can be stacked and rack mounted up to 1 MVA. ABB's active filter allows the user to select 15 different harmonics to filter, from the 2nd to the 50th harmonic.

D-2.2 Aim Energy

The Aim Energy active filter technology incorporates spectrum cancellation techniques and mitigates the full range of harmonics that the device senses. The active harmonic conditioners come in 50, 100, and 200 A modules (208 to 600 VAC). Aim Energy is located in Richmond Hill, Ontario, Canada, and also operates in the U.S. under Active Power Technologies in Signal Hills, CA.

D-2.3 AIM Europe (www.aimeurope.mcmail.com)

AIM's active harmonic current cancellation technology (Fig. D-19) offers the following:

- Harmonic current attenuation up to the 51st harmonic
- Parallel connection
- 'Real time' adaptive current injection
- Active Load balancing
- Not sensitive to network topology
- Electronic VAR current (14-216 kVAR)
- Current Limited

- 25 to 400 A harmonic current in a single unit, up to 1000 A in multi-parallel form
- 208V - 600V 3-phase 3-wire or 4-wire, 50/60Hz, 690V Available
- 110V - 240V. 1-phase 50H/60Hz (up to 25 Amps),

Figure D-19
AIM Europe's Active Harmonic Filter

D-2.4 Current Technology, Inc. (www.currenttechnology.com)

Current Technology, Inc. (in collaboration with Texas A&M University) has developed an Active Harmonic Cancellation System (Trademark: Harmonix) that cancels 100 A of zero-sequence harmonics from a three-phase four-wire distribution system. Fig. D-20 shows the topology of the active Harmonix cancellation system, with the schematic given in Fig. D-21. The three-phase active cancellation system is connected in parallel with the network and completely eliminates all zero-sequence harmonics from the phases and the neutral upstream in the distribution system. This design uses a full-bridge inverter and a closed-loop operation to cancel zero-sequence harmonics. The control scheme does not monitor the fundamental (60 Hz) current flowing in the neutral due to the load unbalance, but only accounts for the harmonic current. Also, the active cancellation system draws negligible 60Hz current from the distribution system as the filter does not consume any real power other than what is required for the losses.

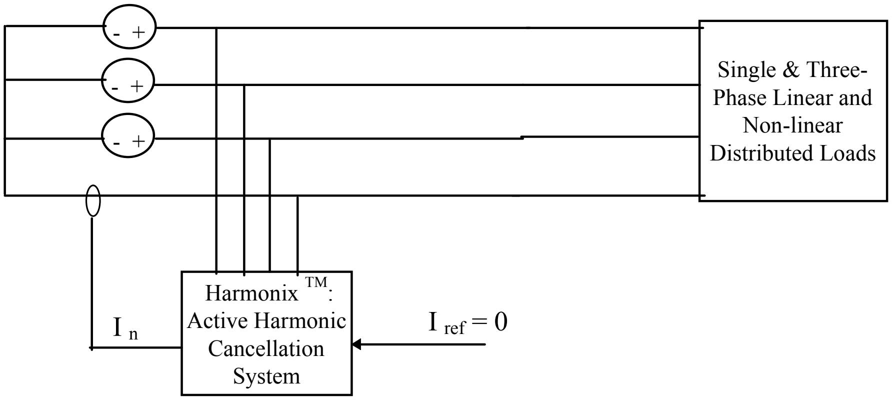


Figure D-20
Topology of the Current Technology Active Harmonix Filter

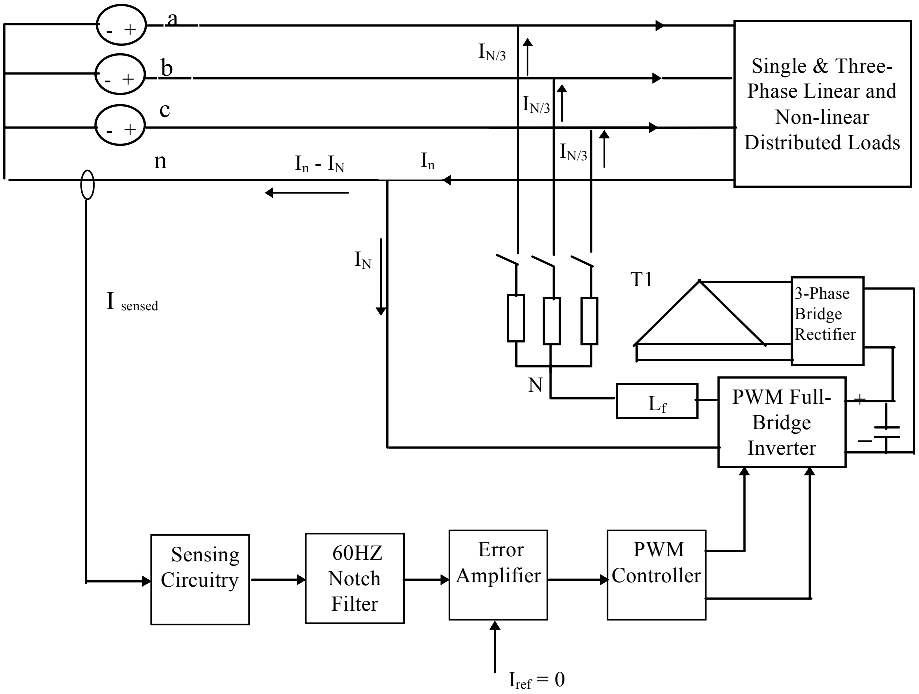


Figure D-21
Schematic of the Current Technology Active Harmonix Filter

Some of the features of the active Harmonix filter include:

- High harmonic cancellation effectiveness
- Performance independent of system impedance

- Cancellation of zero-sequence neutral current harmonics by measurement and closed-loop control
- No low-impedance path for zero-sequence 60Hz component
- Built-in current limit (No overloading)
- Significant improvement in Voltage and Current THD in the phases
- Fast-response characteristics and sufficient bandwidth to cancel several zero-sequence harmonics
- Compact and light in weight

Available Ratings and Specifications

- Input Voltage: 120/208V, 220/380V, 277/480V (3-phase, 4-wire)
- Rated Current: 100-Amps per module
- Power Frequency: 50/60Hz
- Cancellation Effectiveness:95%
- Power Efficiency: >90%
- Parallelability: Up to 4 units in parallel (400Amps) with active load sharing
- Protection: Pulse-pulse current protection, thermal shutdown, overcurrent protection, etc.
- Monitoring: LCD display for facility neutral current and filter current
- Status Indication: Indicator lights, audible alarm, dry contacts, etc.
- Enclosure size: 18H x 24W x 13D (Floor mount, stackable)

D-2.5 Electronic Power Conditioning, Inc. (EPC) (www. accusine.com)

Electronic Power Conditioning Inc. (EPC) provides the ‘AccuSine Power Correction Systems’ line of harmonic suppression and power factor correction systems (Fig. D-22). These are 3–phase systems designed to attenuate harmonics up to the 50th order and/or provide leading or lagging VARs for displacement power factor correction. These systems are designed to provide harmonic compensation for line harmonics (not neutral harmonics) in a 3-phase, 3-wire or 4-wire environment.

- Type of Filter: Shunt Active Filter
- Designed to be located at the utility point of common coupling (compensation for multiple loads) or at the individual load.
- The current sensors can be located on the load side or on the source side of the AccuSine connection.

Figure D-22
Filters Available from EPC (Stand-alone and MCC Installed Models Shown)

Filter Description

AccuSine is a complete power correction system that delivers Active Harmonic control, Total Power Factor Correction, Dynamic VAR compensation and Resonance Prevention in electrical distribution systems.

Method of Operation

Load current is measured using clamp-on type current sensors. A DSP-based controller determines the harmonic and/or reactive current compensation required. The 3-phase inverter produces this compensation current using pulse-width modulation (PWM). The filter section removes carrier frequency harmonics and passes the compensation current to the line.

Available Ratings and Dimensions

Three basic models are available rated as per Total Compensation Current: 50A, 100A and 300A

Voltage: 208-480VAC
Frequency: 50/60Hz
Dimensions (HxWxD inches)
    50A: 51.8x20.7x18.5
    100A: 68.7x20.7x18.5
    300A: 74.9x32.2x19.5
These dimensions are for NEMA1 models.
Chassis models are also available for installation in a Motor Control Center (MCC).

Also, 600V, 2400V and 4160V rated systems can be supplied. A specially designed transformer is used.

D-2.6 Mesta Electronics, Inc. (www.mesta.com)

Mesta offers the Digital Power Manager (DPM), an Active Harmonic Filter designed to effectively reduce harmonic distortion to less than 5%, while balancing the power, compensating for reactive currents, and improving the power factor to unity (Fig. D-23). The DPM acts as a parallel filter. When placed on a plant load, it reacts instantly to meet IEEE-519-1992 requirements, under constant or variable load conditions by continuously monitoring the load currents. The design of the MESTA DPM features both a microcontroller and DSP computer. The DPM also features an easy to install interface to the power system and zero downtime installation with the optional split core current sensors.

Figure D-23
Mesta Digital Power Manager (DPM) Active Harmonic Filter

DPMs are sized to a facility by looking at the harmonics and fundamental phase shift. The DPM current rating indicates the amount of correction current that the unit is capable of producing. As an example, a 125 Hp motor drive with 32% THD would have approximately 40 A of harmonic current. If there was also 25 A of reactive current to compensate for, the filter would generate a total of 48 A of correction current. Therefore, installing a 50 A DPM would correct the harmonics and reactive current, while the drive draws 130 amps of total current.

D-2.7 MGE UPS Systems (www.mgeups.com)

MGE UPS Systems produces the SineWave THM Active Conditioners for installations from 10 to 2000 kVA (see example in Fig. D-24). SineWave reduces harmonic currents by a factor of 10 which, depending on the type of loads, can rise to a factor of 20. Compensation covers 2nd to 25th order harmonics allowing a wide regulation span to cover every type of load. Additionally, two operating modes are available: global compensation, and pre-selected order of compensation. SineWave can also improve the power factor and save on energy costs.

Figure D-24
MGE SineWave 60 Amps (Model SW60)

These units are compact and allow easy integration on walls, in switchboards and in panelboards (dimensions given in Fig. D-25). SineWave units are compatible with every 3-phase power network and automatically handle single and three phase loads, data processing equipment, fluorescent lighting, variable speed drives, etc. To enhance compensation at a given point in the installation they can be connected in parallel. Up to four SineWave active conditioners can be installed in parallel or mounted in series if the system changes. The design also protects the unit from overloads. If the demand for harmonic compensation exceeds its rated capacity, conditioning continues up to the maximum limit.

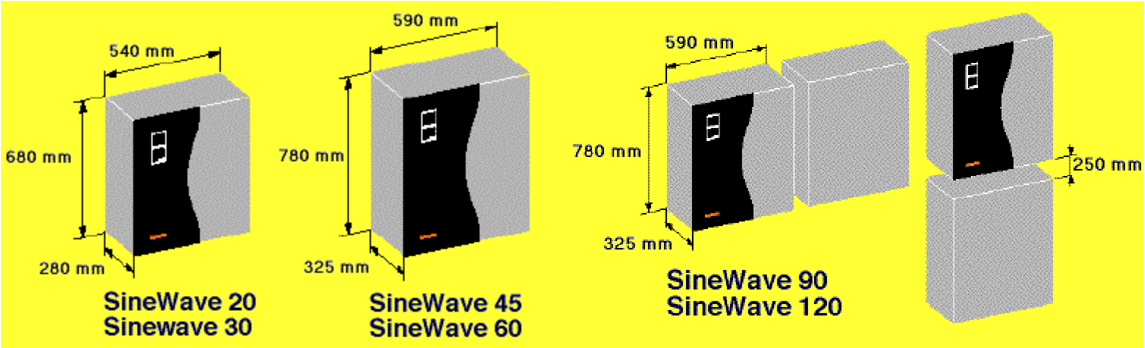


Figure D-25
Dimensions of the MGE SineWave Active Power Filter

The features of the MGE SineWave active power filter include:

- Compensation of the harmonics : global or selected harmonics
- Compensation of the displacement and true power factor
- Parameter control of load type : data processing, rectifier,...
- Remote control (lockable)
- Complies with IEC standards and EC marking
- Redundancy and parallel configuration
- Wide range of current transformers

D-2.8 Power Correction Systems, Inc. (www.activeharmonicfilters.com)

Power Correction Systems provides the TimesOne™ Series 1000 harmonic suppression systems, that are designed to reduce lower order harmonics, as described below.

Active Harmonic Filter

- Series
- Parallel

Location of installation

- Series Filter –The unit installation is preferred at the load. However, it may be placed anywhere in the System.
- Parallel Filter – The unit installation is preferable at the load. Again, it may be placed anywhere in the System.

Figure D-26
Power Correction Systems, Inc. Series 1000 Active Harmonic Filter

Filter Description, Topology and Method of Operation

The TimesOne™ Series 1000 filters are available for either a parallel or series installation. The series connected filter is an active/passive hybrid unit and carries the full load current. The parallel connected filter is a 6-pole inverter unit with feedback controls operating in time domain. A description of the topologies are given below.

For the **parallel topology**, control circuits and processors separate 60Hz from harmonics, and create a modulating signal that powers a 6-pole IGBT inverter. The power stage is coupled to a capacitor inductor network.

For the **series topology**, control circuits and processors separate 60Hz from harmonics, and create a modulating signal that selects taps on an inductor; the capacitor network is controlled by SCR's switching at zero crossing.

Available Ratings and Dimensions for Single-Phase Products:

	VOLTAGE	*CALCELATION*	*kW*	*kVA*	*DIMENSION*
	RANGE	*CURRENT*	*RATING*	*RATING*	*(H x D x W)*
Series	120/230VAC	10–30Amps	0.7 – 6	0.7 – 6	7" x 19" x 15"
Parallel	120/230VAC	10–30Amps	NA	NA	7" x 19" x 15"

Harmonic Filters Designed for Three-Phase Computer-Type Load Applications

Power Correction Systems provides the TimesOne™ Series 2000, Series 3000 and Series 4000 of harmonic suppression systems, designed to reduce lower order harmonics.

Active Harmonic Filter

- Series
- Parallel

Location of Installation:

- Series Filter –The unit installation is preferred at the Load. May be placed anywhere in the System.
- Parallel Filter – The unit installation is preferable at the Load. May be placed anywhere in the System.

Enclosures

Figure D-27
Power Correction Systems Series 2000, 3000 & 4000 Enclosures

Filter Description, Topology and Method of Operation

The TimesOne™ Series 2000, 3000 and 4000 of filters are available for either a Parallel or Series installation as with the Series 1000. The Series connected filter is an active/passive hybrid unit and carries the full load current. The Parallel connected filter is a 6-pole inverter unit with feedback controls operating in time domain. The topologies are similar to the 1000 Series filters described above.

Available Ratings and Dimensions for Three-Phase Products:

TimesOne™ Series 2000

Series

VOLTAGE	*LOAD*	*HARMONIC*	*kVA*	*HP*	*DIMENSION*
RANGE	*CURRENT*	*CURRENT*	*RATING*	*RATING*	*(H x D x W)*
208/230VAC	18–250Amps	10–200Amps	7–103	5–100	66” x 33” x 48”
460VAC	9–605Amps	5–500Amps	7–493	5–500	66” x 33” x 48”
575VAC	6–472Amps	4–400Amps	6–485	5–500	66” x 33” x 48”

Parallel

VOLTAGE RANGE	*LOAD CURRENT*	*HARMONIC CURRENT*	*kVA RATING*	*HP RATING*	*DIMENSION (H x D x W)*
208/230VAC	NA	3–120Amps	1–45	NA	23” x 27” x 16”
380/400/415/460VAC	NA	1–1,000Amps	1–750	NA	66” x 33” x 48”
575VAC	NA	1–900Amps	1–700	NA	66” x 33” x 48”

TimesOne™ Series 3000

Series

VOLTAGE RANGE	*LOAD CURRENT*	*HARMONIC CURRENT*	*kVA RATING*	*HP RATING*	*DIMENSION (H x D x W)*
2,300VAC	10–250Amps	10–250Amps	6–750	5–1,000	66” x 33” x 48”

Parallel

VOLTAGE RANGE	*LOAD CURRENT*	*HARMONIC CURRENT*	*kVA RATING*	*HP RATING*	*DIMENSION (H x D x W)*
2,300VAC	10–250Amps	10–250Amps	6–750	NA	66” x 33” x 48”

TimesOne™ Series 4000

Series

VOLTAGE RANGE	*LOAD CURRENT*	*HARMONIC CURRENT*	*kVA RATING*	*HP RATING*	*DIMENSION (H x D x W)*
4,160VAC	10–250Amps	10–250Amps	6–1,500	5–2,000	66” x 33” x 48”

Parallel

VOLTAGE RANGE	*LOAD CURRENT*	*HARMONIC CURRENT*	*kVA RATING*	*HP RATING*	*DIMENSION (H x D x W)*
4,160VAC	10–250Amps	10–250Amps	6–1,500	NA	66” x 33” x 48”

Harmonic Filters Designed for Utility Grid Applications

Power Correction Systems provide the TimesOne™ Series 5000 of harmonic suppression systems for 4,160 – 21kV voltage levels.

Active Harmonic Filter

- Series

Location of installation:

- Series Filter –The unit installation is preferred at the Load. May be placed anywhere in the System.

Enclosure

Figure D-28
Power Correction Systems Series 5000 Harmonic Filter

Filter Description, Topology and Method of Operation

- The TimesOne™ Series 5000 filters are available for series installation. The series connected filter is an active/passive hybrid unit and carries the full load current.
- The topology consists of control circuits & processors that separate 60Hz from harmonics, and create a modulating signal that selects taps on an inductor; the capacitor network is controlled by SCR's switching at zero crossing.

Available Ratings and Dimensions for Utility Grid Products:

VOLTAGE *RANGE*	*LOAD* *CURRENT*	*HARMONIC* *CURRENT*	*kVA* *RATING*	*DIMENSION* [1] *(H x D x W)*
4,160–21,000VAC	10–100Amps	10–100Amps	250–4,000	66" x 33" x 48"

NOTE: [1] Dimension per 1,000kVA module.

D-2.9 PowerSmiths International Corp. (www.powersmiths.com)

PowerSmiths offers the Contour active filter, in addition to their line of passive conditioners, for real-time broadband harmonic correction in parallel with loads. The rack-mount 120V configuration is available in 15 and 25 peak harmonic correcting amps, and multiple modules can be paralleled. The Contour active filter uses analog circuitry to measure the load current profile and generate a real-time error signal compared to the fundamental component. This error signal is then used to drive a bi-directional transistor bridge, so as to inject the appropriate corrective amps, essentially canceling the non-fundamental frequencies in the load profile. The electrical system then only supplies fundamental power (W) to the load instead of having to supply substantial distortion (VA). The Contour's analog design allows it to correct fast-changing loads in real time. The technology is not frequency dependent, thus the PowerSmiths Contour active filter removes even, odd and inter-harmonic currents.

D-2.10 Siemens Power Transmission and Distribution (www.siemenstd.com)

Siemens offers the SIPCON P active filter systems that are user configurable to cancel up to four lower order harmonics. They are available in ratings of 20 to 5000 kVA.

D-2.11 Soft Switching Technologies (SST) (www.softswitch.com)

SST has solid-state active and hybrid-active filters available for harmonic compensation in commercial and industrial applications. SST has developed a parallel active filter platform capable of reducing the total harmonic distortion in the supply to below 5% for most current source or adjustable speed drive type loads. The parallel active filter supplies the harmonic current required by the total load, allowing the source to supply only the fundamental component.

At the heart of SSTs active filter is a soft switching resonant dc link inverter, operating at 70kHz, providing the bandwidth necessary to eliminate high frequency harmonics. Due to the reduced transistor losses under soft switching, current control to beyond the 17th harmonic comes without the added cost of IGBT device derating. The inverter and filter are controlled by a high performance DSP platform, resulting in the following active filter features:

- Source current reduction to the 25th harmonic
- 5% THD achievable for current source type loads
- Efficiency above 97%

- Filter is current regulated, cannot be overloaded
- Does not cause resonance with other loads
- Operation in the presence of unbalanced loads
- Limited reactive power compensation capability
- Operation in conjunction with power factor correction capacitors and passive shunt filters

Active Filter Topology and Ratings

The parallel active filter consists of a resonant dc link inverter and filter section, controller and feedback signals. The filter inductor is used to convert the voltage source inverter output to a current source capable of injecting harmonic currents to the load and the filter capacitor is necessary to trap the switching frequency ripple from the inverter. Units available are rated at 30Arms and 150Arms of harmonic correction current for 460V service.

Target:
Power Quality for Improved Industrial Operations

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