

The Origin, Effect, and Suppression of Harmonics in Industrial Electrical Networks

INTRODUCTION

Traditionally, electrical loads have been characterized as inductive, capacitive and/or resistive. Excluding switching transients, none of these can be classed as particularly disruptive, either to utility networks, other consumers, or the network to which they are connected.

During the 1980s, electronic power conversion became commonplace in industrial, commercial, and institutional networks. These new loads, known as power converters, impact all electrical networks, usually in a negative manner. Power converters tend to be disruptive to the utility network and sometimes to other consumers. When power electronic loads are present, attempts to correct power factor in the traditional manner frequently results in premature capacitor failure and other disruptive events in the network.

This document is intended to raise your level of awareness about power electronic loads, promote thorough investigation of a network before connecting power electronic loads, and encourage careful scrutiny of technical documents supporting a specific manufacturer's product.

Due to the exponential growth of power electronics, many utilities are adopting a standard described in IEEE 519, A Guide to Harmonic Control in Electrical Systems, which states:

“This guide has incorporated the evolving understanding of the effect of static power converters and other nonlinear loads on electric power systems. This recommended practise recognizes the responsibility that users have not to degrade the voltage of the utility serving other users by requiring nonlinear current from the utility. It also recognizes the responsibility of the utilities to provide users with close to sine wave of voltage.”

The origins of harmonics are well known. Though the effects are different in each network, they are predictable. Cost effective and reliable solutions exist to “cure” harmonic-related problems; however, problems caused by power electronics depend on the nature of the device and their effect is network dependent. Severe problems cannot be solved by generic solutions.

HARMONICS AND HARMONIC GENERATORS

Utilities generate an almost perfect sinusoidal voltage, as shown in Figure 1.

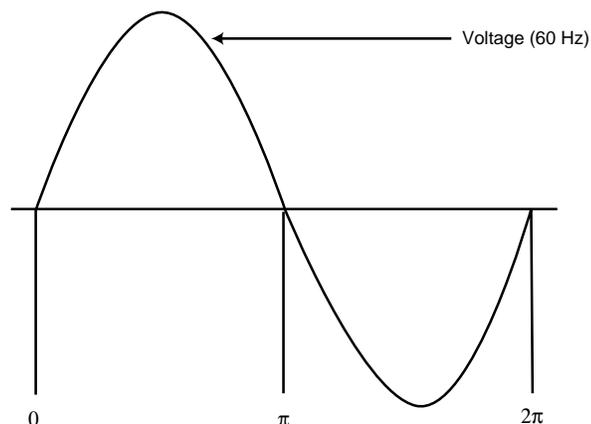


Figure 1 Sinusoidal Voltage Waveform

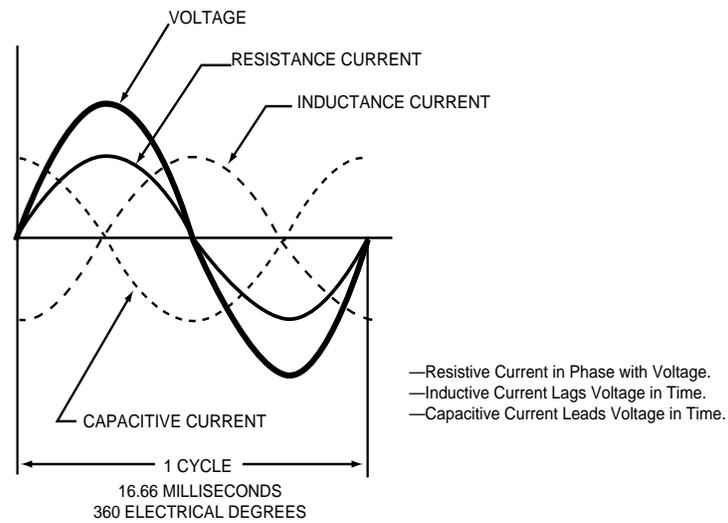


Figure 2 Sinusoidal Current Waveforms

Inductive, capacitive, and/or resistive loads draw current that is precisely proportional to the voltage and is also an almost perfect sinusoid (Figure 2). This is because these loads do not depend on the voltage to determine their impedance. Their response, at a given frequency, is completely linear. In fact, at any single frequency their response to a sinusoidal voltage will be linear.

Power electronic loads do not respond in this way. When presented with a sinusoidal voltage, the current is not proportional to the voltage and is not sinusoidal. These loads are characterized as nonlinear, and include AC and DC variable speed drives, power rectifiers and inverters, arc furnaces and discharge lighting (metal halide, fluorescent, etc.).

The nonsinusoidal current consumed is due to the device impedance changing over a complete voltage cycle.

A common power electronic rectifier, used in drives and other equipment, is a six-pulse design. This rectifier, or converter, is a full wave device that rectifies or converts AC to DC. Six semiconductors are arranged in a three-phase bridge with a specific firing order, as shown in Figure 3.

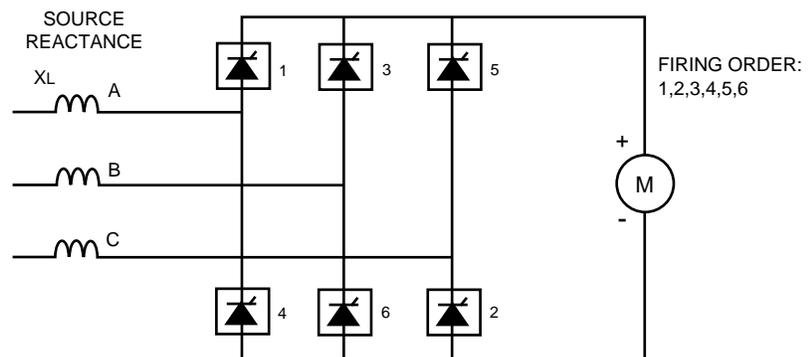


Figure 3 Six Pulse Full Wave Rectifier

The current waveform is not sinusoidal (Figure 4) and can be seen with an oscilloscope or power logic circuit monitor. This time domain representation provides very little useful information in terms of determining network impact.

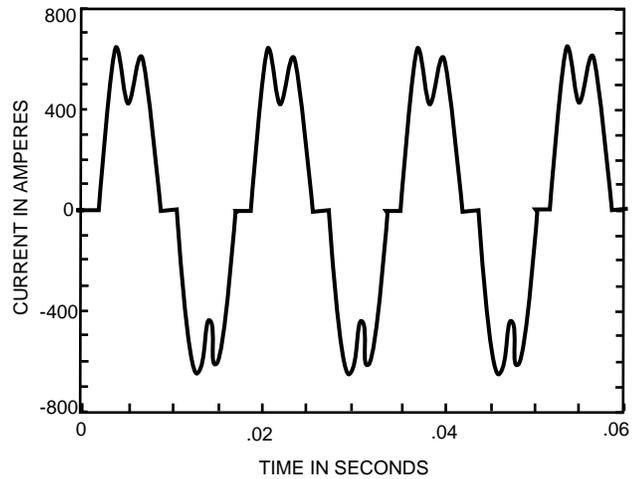


Figure 4 Six-Pulse Full Wave Rectifier Non-Sinusoidal Current Waveform

The most useful information is contained in the frequency spectrum of the non-sinusoidal wave (Figure 5).

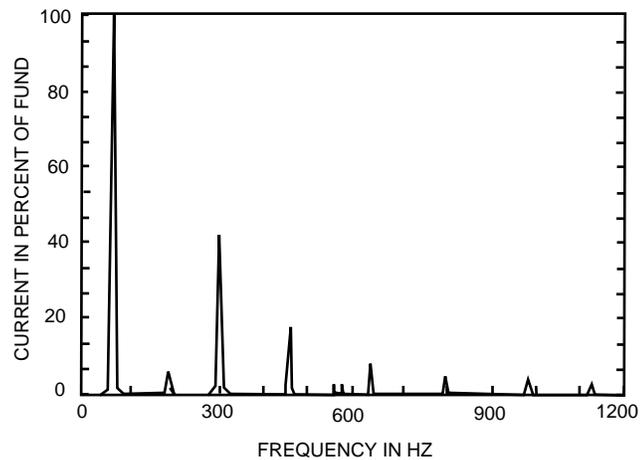


Figure 5 Six-Pulse Full Wave Rectifier Typical Current Spectrum

The waveform shown in Figure 4 can be mathematically represented as the sum of a number of sinusoidal waveforms at different magnitudes and phase angles at integer multiples of the fundamental frequency of 60 Hz.

The following mathematical process is known as the Fourier Transform, developed by Jean Baptiste Fourier (1768-1830):

$$f(t) = A_0 + \sum_{n=1}^{\infty} A_n \cos(n\omega_0\tau + \theta_n)$$

or

$$f(t) = A_0 + A_1 \cos(\omega\tau + \theta_1) + A_2 \cos(2\omega\tau + \theta_2) + A_3 \cos(3\omega\tau + \theta_3) + \dots$$

where A_0 = dc offset
 A_n = magnitude of n^{th} harmonic
 ω = fundamental frequency
 θ_n = phase angle

Note that the fundamental frequency magnitude can be expressed as 100% and the other frequencies (harmonic frequencies) as a percentage of that fundamental.

Harmonic frequencies are whole number multiples of the fundamental. The harmonics produced by the most common nonlinear loads are the 5th, 7th, 11th, and 13th (300, 420, 660, and 780 Hz, respectively).

Frequencies higher than the fundamental are a mathematical representation of a nonsinusoidal waveform, and do not actually exist. Despite the nonexistence of these higher frequencies, electrical networks respond as if they do exist. Therefore, analysis and solutions can be based on the results of a Fourier Transform. A further measurement tool is referred to as Total Harmonic Distortion (THD).

Current Distortion:

$$\% \text{ THD} = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + I_5^2 + \dots}}{I_1} \times 100\% = \frac{\sqrt{\sum_{h=2}^{\infty} I_h}}{I_1} \times 100\%$$

Voltage Distortion:

$$\% \text{ THD} = \frac{\sqrt{V_2^2 + V_3^2 + V_4^2 + V_5^2 + \dots}}{V_1} \times 100\% = \frac{\sqrt{\sum_{h=2}^{\infty} V_h}}{V_1} \times 100\%$$

THD is the geometric addition of the harmonic values, either current or voltage divided by the fundamental value. IEEE 519 discusses limits on voltage and current distortion at the point of coupling to the utility network in terms of acceptable or unacceptable values.

THE EFFECT OF HARMONICS IN NETWORKS

Nonlinear currents flowing through a network impedance to nonlinear devices distort the voltage waveform. The degree to which distortion occurs depends on the level of network impedance. It is the voltage drop across the network impedance at the various frequencies that causes the voltage distortion.

The origin or source of the distortion is the nonlinear devices in the network.

If a sinusoidal voltage is applied to a nonlinear device, the current will not be proportional to the voltage. Normally, doubling the voltage causes a corresponding

change in the current and the current wave shape remains the same. Consider a linear resistor as shown in Figure 6. A sinusoidal and proportional current results from impressing a sinusoidal voltage. With the nonlinear resistor, the same voltage causes a nonsinusoidal current to flow.

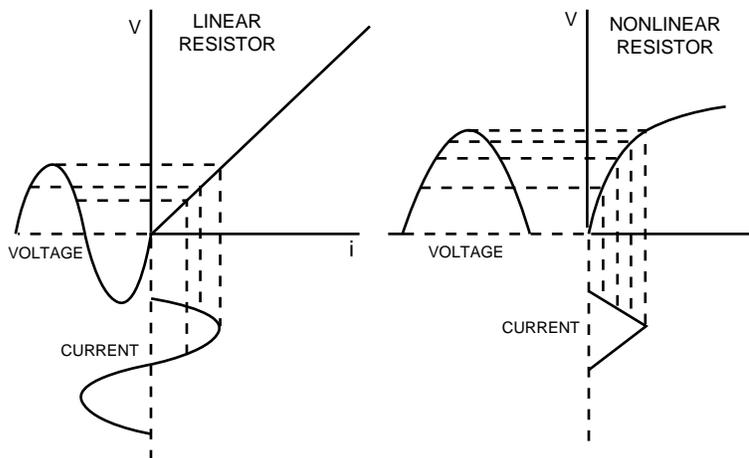


Figure 6 Current Distortion Caused by Nonlinear Resistance

If the frequency of the voltage is changed, the frequency of the current changes accordingly but is still identical to the voltage. The impedance of the resistor also changes but is constant at either frequency.

When the same voltage is applied to the nonlinear resistor, the current becomes distorted. Electrical network distortion, then, is caused by the nonlinear characteristics of the devices connected to that network.

Typically, the impedance of network loads is greater than the source impedance. Most networks are designed in this manner to ensure reasonable voltage regulation at the load. The power source shown in Figure 7 is sinusoidal and of relatively low impedance. Accordingly, the voltage at node A is not distorted. The network has an impedance and is linear. (Networks are typically inductive and thus linear at any normally encountered frequency.) As the nonlinear current required by the load flows through the network impedance, the voltage is distorted at node B due to a voltage drop across the impedance at each frequency present.

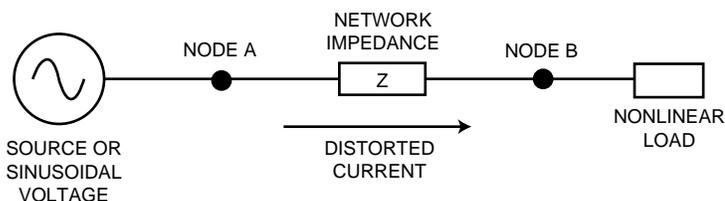


Figure 7 Voltage Distortion is Dependent on System Impedance

The voltage distortion is absolutely dependent on the network impedance. From an analysis point of view, harmonic currents are considered to flow from the nonlinear load(s) to the source impedance and they behave as if this were true.

Frequently, in an attempt to limit available fault current, transformers installed in network substations are designed to have a relatively high impedance. Although

fault current is indeed limited, if nonlinear loads exist, voltage distortion is increased due to nonlinear current flowing through the higher impedance.

Distorted harmonic voltage, at any frequency, caused by the flow of harmonic current through an impedance can be represented by the following equation:

$$V_h = I_h \times Z_h$$

V_h - h th Harmonic Voltage
 I_h - h th Harmonic Current
 Z_h - Network Impedance for h th Harmonic Current

The preceding equation shows that the harmonic voltage is the product of the harmonic current and the impedance at the specific frequency.

The relationships between system impedance, reactance, and frequency work well for low-voltage networks. On high-voltage systems, the relationships are more complex, as shown below.

$$Z_s = \{R_s^2 + X_s^2\}$$
$$X_s = 2\pi f_{\text{Fund}} L_s$$
$$X_{sh} = 2\pi f_{\text{Fund}} h L_s = h X_s$$

Z_s - System Impedance
 X_{sh} - System Reactance at Harmonic h
 X_s - System Reactance
 f_{Fund} - Fundamental Frequency in Hertz
 h - Harmonic Number
 L_s - System Inductance

These equations show that at a higher frequency, the same amount of current creates a larger voltage drop than at a lower frequency.

The tolerance of a network to harmonic distortion depends on the susceptibility of the loads. The least susceptible load is resistive. In this case, the harmonic and fundamental energy is almost fully used and converted to heat. This is not a problem, because it is generally the function of a resistive device. Rotating machines, particularly squirrel cage induction motors, that are in a harmonic path will see abnormal heating, due to iron and copper losses at the higher frequencies. Noise is also increased. In extreme cases, the harmonic flux distribution in the air gap can cause a refusal to start smoothly and can initiate very high slip of the rotating mechanical component behind the rotating magnetic field.

Transformers suffer copper and stray flux losses due to harmonic current. Harmonic voltages may cause severe iron losses. The overall affect is overheating and a resultant operational loss of motor life. There are several standards (IEEE and ANSI) that determine operational loss of motor life.

ANSI/IEEE C57.110, *Recommended Practice for Establishing Transformer Capability When Supplying Non-Sinusoidal Load Current* (1996), indicates that the maximum current distortion seen by a transformer should not exceed 5% at rated current. The root mean square (RMS) overvoltage (the geometric sum of fundamental and harmonic voltages) should not exceed 5% at rated load and 10% at no load.

Conductors carrying harmonic current are subject to abnormal heating due to skin effect and proximity effect. These vary as a function of frequency and spacing, as shown in Figure 8. IEEE 519-1992 provides a cable derating chart for a specific harmonic spectrum.

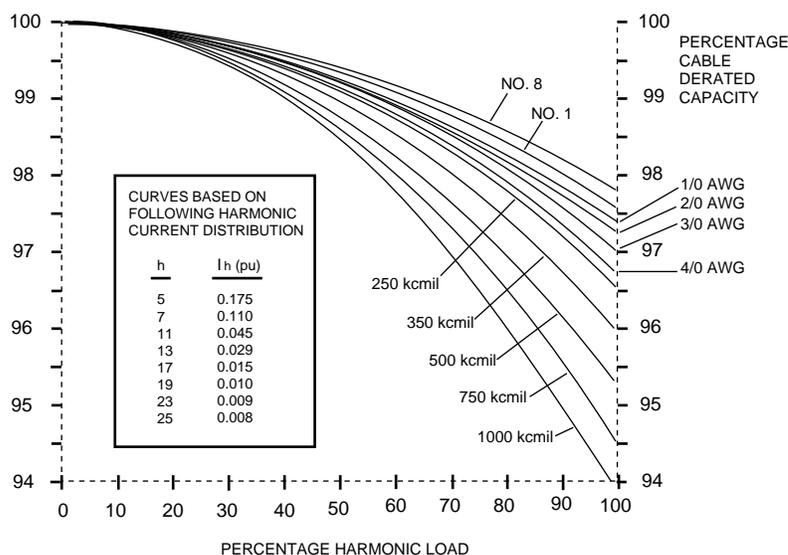


Figure 8 Cable Derating vs. Harmonics with Six-Pulse Harmonic Current Distribution

Power electronic equipment—the devices that generate harmonics—can also suffer from the presence of harmonics. The most common harmonic voltage effect occurs due to distortion of the zero crossing of the voltage wave. Most computers and programmable controllers may not tolerate more than 5% voltage distortion, with the largest single harmonic not exceeding 3% of the fundamental. Induction disc meters, used commonly for revenue purposes, can display positive or negative errors when exposed to severe distortion. The irony is that the network being metered is most often the harmonic source. Telephone and other communication circuits may be subject to harmonic-related magnetic and electric fields. This is frequently the source of communication error and interference.

Standard tables exist to account for the relative levels of interference that may be caused by various harmonic frequencies and their magnitudes. These tables are known as telephone influence factor (TIF) values.

Thermal overload relays, circuit breaker shunt trips, and power fuses are all affected by harmonics. The elements of these protective devices are resistive and operate when a certain current creates a specific temperature over a period of time. The normal fundamental current plus the harmonic current, geometrically added, can often trip the temperature-sensitive element.

Measuring instruments not specifically designated as true RMS devices exhibit significant inaccuracy in the presence of harmonics.

Possibly the most dramatic problems occur when power factor correction capacitors are installed in a network with harmonic generators.

Harmonic currents flow from the nonlinear harmonic sources toward the lowest impedance, usually the utility source. The impedance of the utility source is usually lower than the parallel paths offered by various network loads. Typically the utility source impedance is 1/20 of the parallel load impedances. However, the split of the harmonic currents depends on the various impedance ratios.

Capacitor Impedance Change with Frequency:

$$I_c = \frac{V_c}{Z_c}$$

If $Z_c = 0$ or a small value

Then $I_c = \infty$ or a high value

$$\text{And } Z_c = \frac{1}{j2\pi fC}$$

$$\text{Or } Z_c = \frac{\text{Constant}}{f}$$

Z_c = Impedance of Capacitor

j = Operator

f = Frequency

C = Capacitance in Microfarads

A power factor correction capacitor has a very low impedance, particularly as frequency increases. Consequently, a capacitor becomes an effective trap or filter when exposed to frequencies above the fundamental. This is usually to the detriment of the capacitor (see Figure 9), which may be exposed to harmonic currents. Capacitors are required, by regulatory bodies, to tolerate certain levels of overcurrent on a continuous basis. Below 690 volts, the current capability is defined as 135% of nominal current. The overcurrent may be derived from two sources. Approximately 20% of the 35% may be due to voltage. The balance of 15% may be due to harmonics. However, in the absence of one or the other, neither can exceed the allotted proportion.

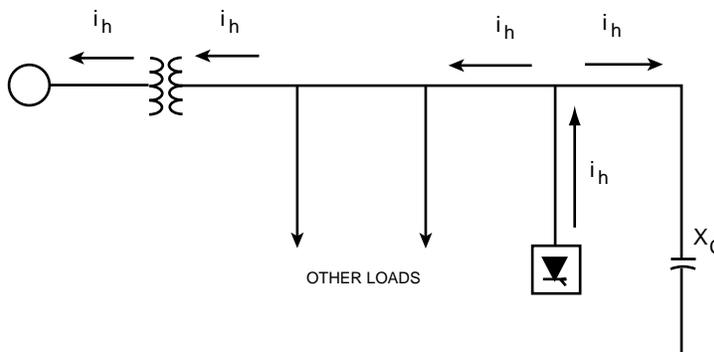


Figure 9 Normal Flow of Harmonic Currents

The heating affect of harmonic currents in capacitors is very damaging and will shorten operating life dramatically.

The impedance of modern capacitors is very low compared to those manufactured previously. This is a function of the design and the materials used. Although lower impedance may, at times, seem to be undesirable, the modern capacitor is very efficient and cost effective, but the network characteristics must be considered when evaluating the application.

Parallel Resonance

Connecting a capacitor into networks with harmonic generators causes several affects. Parallel resonance occurs when the system inductive reactance and capacitive reactances are equal at some frequency. This most often occurs with a capacitor connected at the main switchgear. If the combination of capacitor banks and the system inductance results in a parallel resonance near (not necessarily "at") one of

the harmonic frequencies generated by nonlinear loads, that harmonic current excites the circuit. This causes a highly amplified current to oscillate between the energy storage in the inductance and the energy storage in the capacitance. The resulting high currents cause severe voltage distortion. For example, if telephone circuits are in close proximity to the power circuits, telephone interference results.

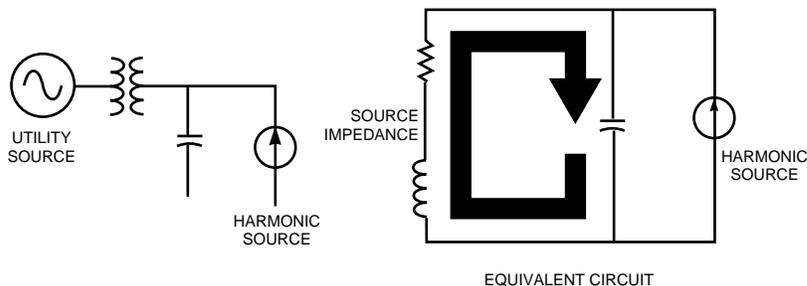


Figure 10 Parallel Resonance of Capacitors with the Utility Source Impedance

Figure 10 shows the parallel combination of the capacitor bank and the source reactance, which appear as a large impedance. Thus, the distorted currents flowing through this high impedance cause severely distorted voltage. The distorted or harmonic voltages result in high harmonic currents in the capacitor and the source reactance. If this resonance is very close to one of the frequencies generated by the harmonic loads, the currents quickly cause a circuit overcurrent device to operate. It is not unusual to find currents that are not high enough to trip breakers or operate fuses but that are high enough to rapidly damage the capacitor. This is called *partial resonance*.

As the network load level increases, the magnification occurring at resonance decreases, due to lower impedance paths for the current to flow. Network circuits are most susceptible to harmonic distortion when lightly loaded. For this reason, fixed capacitor installations should be carefully investigated. If a fixed kVAR is lower than 20% of the substation transformer kVA rating, light load resonance is unlikely. Despite this fact, normal operating resonance must be investigated.

The potential for parallel resonance is easily determined, and is a function of the short circuit kVA available at the point of connecting the capacitor and the kVAR rating of the capacitor. The natural resonant frequency equation shows the results for two kVAR values. The second is close enough to the 11th harmonic (660 Hz) to produce damaging harmonic current values, despite the fact that it cannot be classed as sharp resonance.

$$f_r \text{ (approx.)} = \sqrt{\frac{\text{kVA} \times 100}{\text{kVAR} \times Z_{ss}}} \times f_1$$

$$f_r \text{ (approx.)} = \sqrt{\frac{1500 \times 100}{100 \times 5.9}} \times 60 = 956.68 \text{ Hz}$$

$$f_r \text{ (approx.)} = \sqrt{\frac{1500 \times 100}{200 \times 5.9}} \times 60 = 676.48 \text{ Hz}$$

f_r = Natural Resonant Frequency
 f_1 = Fundamental Frequency
 Z_{ss} = Percent Short-Circuit Impedance

Switched capacitor banks avoid light load resonance. Always investigate the potential for resonance at each stage value and at the total bank rating.

Series Resonance

Series resonance may occur with fixed capacitors at load centers or with capacitors that are switched with motors (Figure 11). In both cases, the capacitor will “see” harmonic currents from any nonlinear loads that may be present. In addition, the relatively high network impedance (as opposed to the source impedance in parallel resonance) causes significant voltage distortion. As in parallel resonance, the capacitor(s) may resonate partially. The network or line impedance is in series with the capacitor looking from the harmonic source. Thus, it can present a low impedance to one of the harmonic currents.

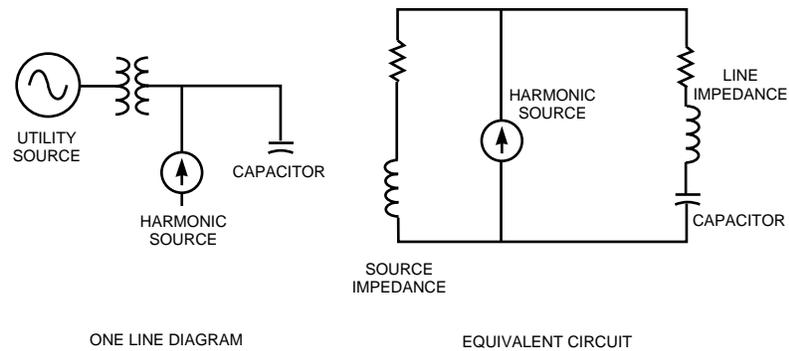


Figure 11 Series Resonance (Capacitor on Feeders)

The potential for series resonance with motor switched capacitors is quite high. The random or sequenced operation of a number of motor/capacitor combinations produces a variable capacitor. Any number of kVAR combinations may produce the value(s) required to produce resonance at a number of different frequencies.

It is often thought that these problems may be circumvented by installing the required capacitors at the line side of the substation transformer supplying the low voltage network that contains nonlinear loads. Remember that the capacitor will still be in the path of nonlinear currents, producing somewhat distorted voltage. Therefore, the possibility of series resonance between the capacitors and the transformer leakage inductance may still be present.

As with parallel resonance, series resonance magnifies harmonics, shortens capacitor life, affects other equipment, and promotes voltage distortion at the point of coupling to the utility network.

Most networks can tolerate high levels of harmonics. The devices in a network range from tolerant (as with a resistive device) to very intolerant (as with capacitors). In all cases, the effects of harmonics are negative. The likelihood of degrading power quality on a utility network is always high. This will be the subject of increased attention as nonlinear loads continue to increase in quantity, and power factor correction is required to mitigate the inevitable increases in utility demand charges.

THE SUPPRESSION OF HARMONICS

Properly designed filters can correct power factor in harmonic rich environments while also performing the primary function of filtering harmonics. In designing filters to avoid network degradation due to high levels of harmonics, some power factor correction takes place as a secondary benefit. In either case, it is imperative to know the harmonic “footprint” at the point of connection.

Power factor correction decisions must be based on technical logic and the characteristics of the corrective equipment being considered. Very rarely can the desired results be achieved with generic devices. The problem is so highly network related

that the effect of a nonlinear load on two different networks, even of the same voltage, is quite different. The solution is also network related and therefore is usually different in each case.

Power Factor Correction in a Harmonic Rich Environment

Consider power factor correction in a harmonic rich environment. Certain values of the 5th, 7th, 11th, and 13th harmonic are present. If a capacitor is installed, the difficulties previously described occur, as shown in Figure 12. Logic dictates that the device must be inductive at the 5th harmonic (300 Hz) and above, ensuring that resonance and harmonic magnification do not occur. In addition, capacitance at 60 Hz must be included to provide power factor correction.

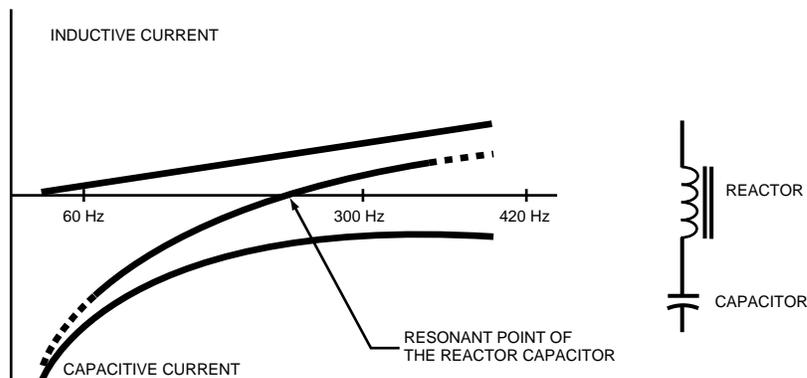


Figure 12 Inductive/Capacitive Current and Resonance

An inductance is linear through the frequencies that are present, and can be seen by its current response as frequency rises. Capacitors are also linear and respond to frequency (see Figure 12).

The combination of these two characteristics (ensuring the proper inductance and capacitance) produces a current response that changes from a capacitive characteristic to an inductive characteristic at a carefully selected frequency. This crossover point must be below the first dominant frequency (excluding the 3rd harmonic) and above 60 Hz. The crossover point is the resonant point of the combined inductive/capacitive device.

A device with this characteristic is simply an iron core inductor in series with a capacitor. It is often called a *detuned* or *reactor capacitor*.

When applying a detuned capacitor, the impedance at the point of connection must be fixed. Since network impedance is constantly changing, this equipment must be connected at the transformer secondary (distribution) switchgear. The presence of the transformer ensures fixed impedance.

In addition, the resultant new network resonant point must be determined. This is always below the resonant point of the detuned capacitor being installed. The detuned capacitor may have a resonant point from 3.8 to approximately 4.5 times the fundamental 60 Hz (228 to 270 Hz). Thus, the network may become resonant at or near the 3rd harmonic (180 Hz). This frequency occurs with single phase nonlinear loads. Many welders and small DC and variable frequency drives are of this design.

Figure 13 provides an example of an inductive/capacitive device tuned at 4.7 or 282 Hz, and shows network resonance at 230 Hz. If the inductive/capacitive device is tuned to 221 Hz, the network is resonant at 180 Hz. If this frequency is present, resonance is excited with the attendant very negative results.

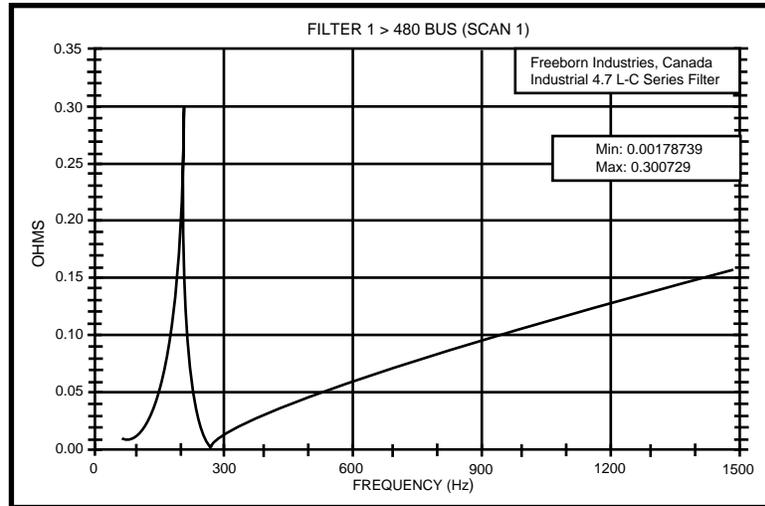


Figure 13 Industrial Network Impedance with 500 kVAR 5th Harmonic Filter Connected. Note Safe Value Resonance at 230 Hz.

Detuned Capacitors

Installing detuned capacitors at the load in a similar fashion to motor switched capacitors or at remote load centers may be desirable; however, you must exercise great care.

- Determine conclusively that the impedance variations at the point of connection do not allow local resonance to be excited by an existing harmonic.
- Several installations within the network means that the detuned capacitors are operating in parallel. If they are being switched with motors, the network resonance point as well as impedance variations are being shifted as the detuned units are being switched. The potential for local resonance is increased.
- Deterioration of the capacitor in the detuned units raises the unit resonance point with respect to frequency. With an inductor and capacitor in series, the capacitor is the most likely to fail. Given the likelihood of higher stresses, as noted previously, the capacitor is more likely to fail in small equipment as compared to a central unit at the main distribution point.
- Large equipment is usually designed to communicate problems of this nature. This is not as easily accomplished in smaller units located at or near specific loads.
- Purchasing small detuned equipment from different manufacturers can present difficulties. The normal tolerance on iron core reactors is $\pm 3\%$. The allowable tolerance on capacitors is $-0/+15\%$.
- If a large drive is supplied by a 1:1 or a step-down transformer, it may be appropriate to install a detuned unit on the load side of the transformer. The impedance is fixed at this point.

Filters

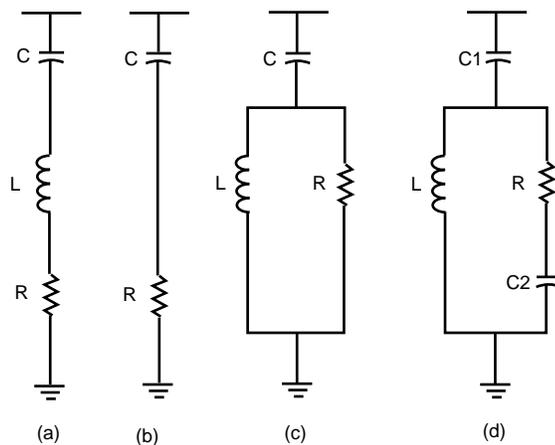
When filtering is required to be the higher priority, all of the issues described for detuned systems apply. The characteristics of the network and the harmonic footprint are even more important in this case. Filters may be designed to lower any frequency but generally are rated from 4.7 to 4.9 times the fundamental (282 to 294 Hz).

It is common for filters to be designed to resonate close to more than one harmonic frequency, filtering those frequencies accordingly.

In all cases, capacitors should be rated for design life at 115% of nominal voltage. They should also tolerate 180% of nominal current continuously over the design life. This will ensure stability of the resonant point.

Filtering equipment should be equipped with very reliable and sensitive temperature detectors located at the potential hot spots of critical components. Temperature detectors may be connected to relays and alarms that audibly or visually indicate a specific temperature has been achieved over a period of time. Higher temperature and/or extended time should trip the unit off line.

The extra cost of this protection is minimal compared to the basic cost of the equipment or the damage than can result with an off-tune filter.



(a) SINGLE-TUNED FILTER
(b) FIRST ORDER HIGH-PASS FILTER
(c) SECOND ORDER HIGH-PASS FILTER
(d) THIRD ORDER HIGH-PASS FILTER

Figure 14 Shunt Filter Configurations

Various filter designs are shown in Figure 14. Although each has its own application, all provide a low impedance to a specific frequency or frequencies.

An existing capacitor bank should never be converted to a filter by adding a reactor because:

- The long-term stability of the capacitor is impossible to confirm.
- It is probably not sufficiently “tough” to tolerate the higher voltage and current stresses imposed in filter duty.
- It is likely that a specially designed reactor is required. In this case, it may cost less to purchase a previously designed piece of equipment.

Series Reactors

Using series reactors can sometimes solve harmonic problems. Without question, harmonics may be “blocked” by the use of a series-connected high impedance, but the level of blocking is usually low and network dependent. For this reason, using series reactors is not recommended as a generic solution, but may be effective for some applications.

Network Characteristics

Using network simulation software, a network can be modeled and harmonic data, linear load data, impedances, and capacitor or filter characteristics added.

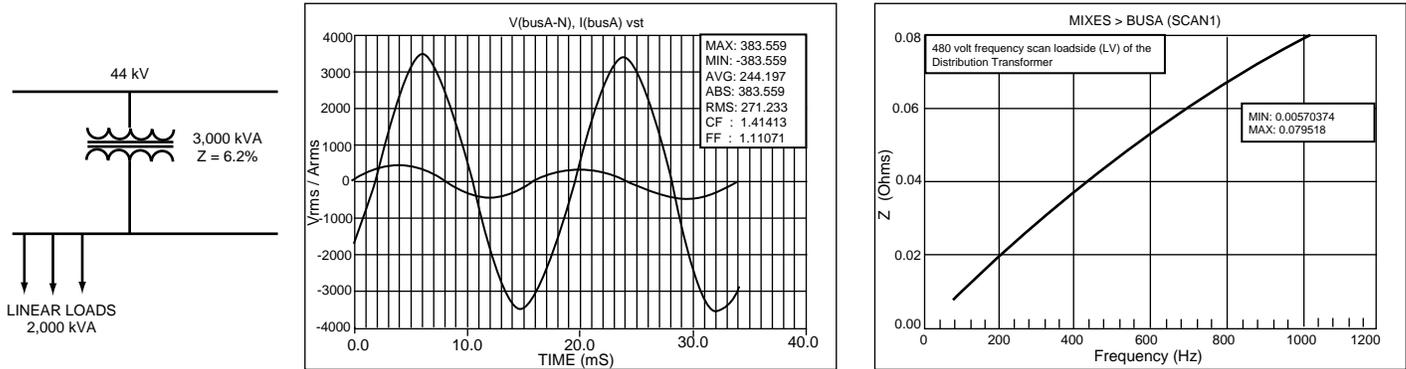


Figure 15 Linear Loads

Figure 15 shows a simple 480 V network with only linear loads. The voltage and current are identified as V (Bus A - N) 1 (Bus A), and measured at the transformer secondary frequency. The impedance (plotted as frequency and ohms) is nearly linear with the frequency.

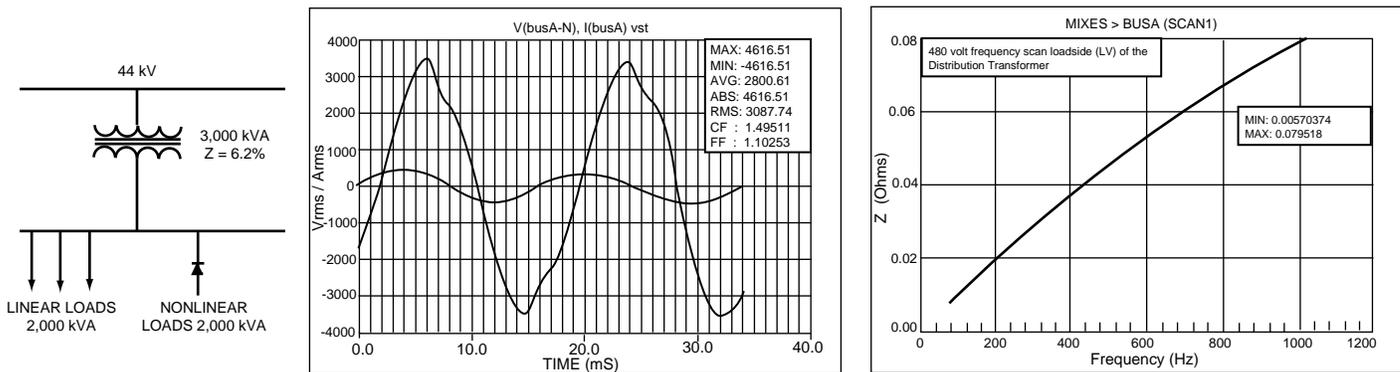


Figure 16 Linear & Nonlinear Loads

Figure 16 shows the same network with a nonlinear load added. The current waveform identified as V (Bus A - N) I (Bus A) is somewhat distorted; the voltage is only slightly distorted. This slight distortion is because this particular model used only the transformer impedance rather than a larger network impedance. (The higher impedance would cause more voltage distortion.)

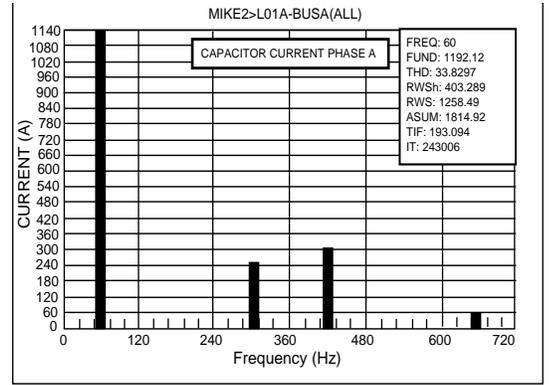
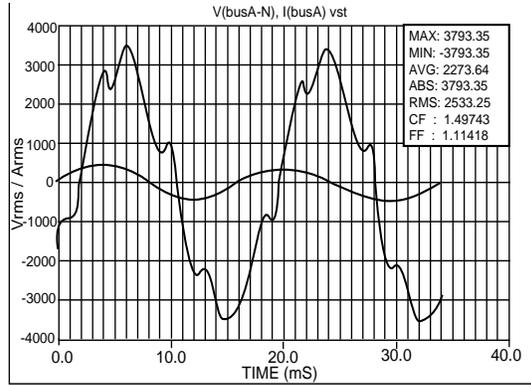
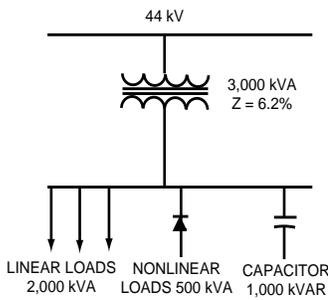


Figure 17 Linear, Nonlinear & Low Voltage Capacitive Loads

Because the network is still inductive, the impedance plot remains unchanged (Figure 17). A capacitor has been added for power factor correction. The current waveform, identified as V (Bus A - N) I (Bus A) is very distorted, as is the voltage wave. The bar graph shows the fundamental current, the 5th harmonic at 270 A or 23% of the fundamental, the 7th at 300 A or 25% and the 11th at 60 A or 5%.

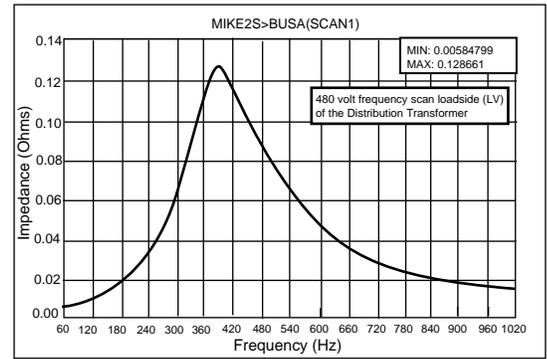
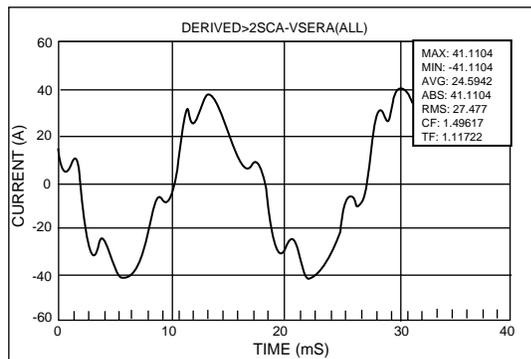
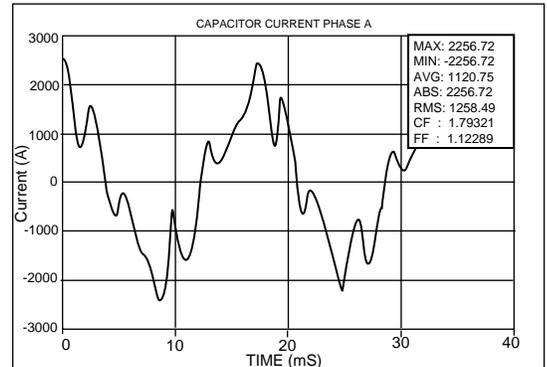
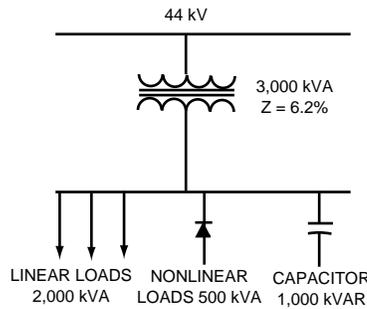


Figure 18 Linear, Nonlinear & Low Voltage Capacitive Loads

In Figure 18, the capacitor current (identified at the top of the plot) is seriously distorted. The operational life expectancy of a capacitor operating with this waveform may not exceed 30 days. The current plot of the transformer primary, identified as 2SCA, is also severe. Impedance, identified as 480 V frequency scan, shows a potential for resonance at 380 Hz (peak of the plot), but the shape of the curve ensures damaging current will be present at any frequency, from 420 Hz to over 1,000 Hz.

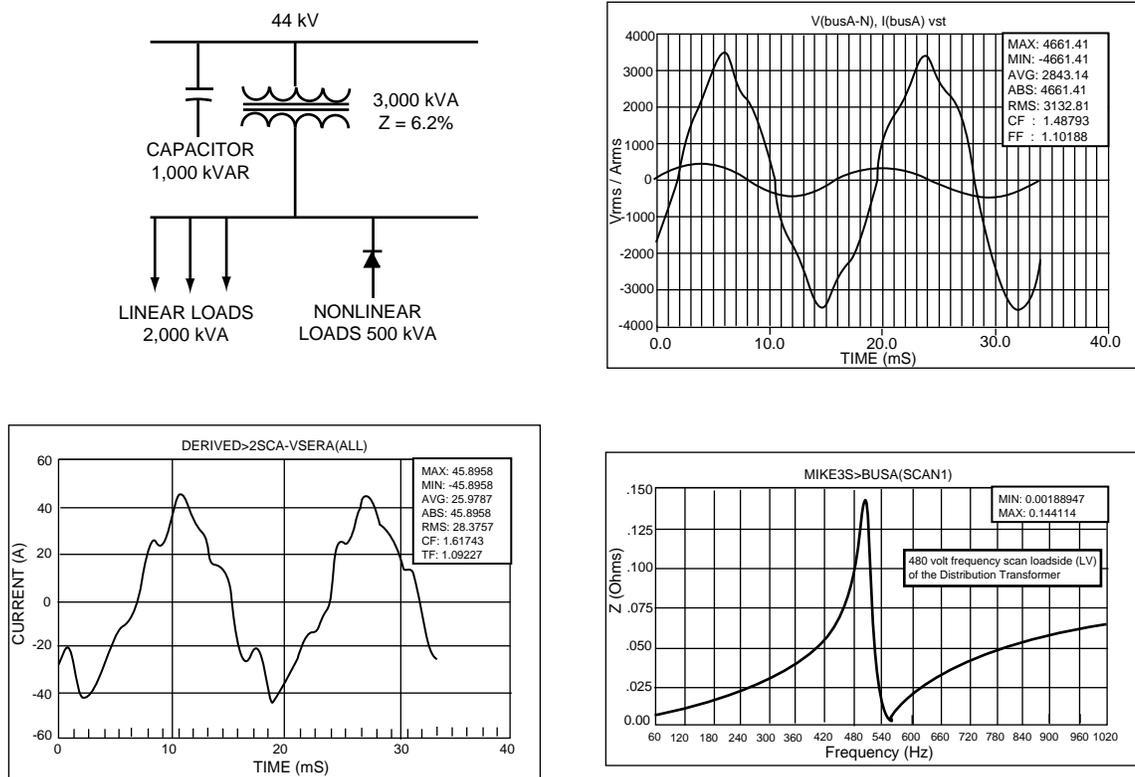


Figure 19 Linear, Nonlinear & High Voltage Capacitive Loads

With the capacitor moved to the primary of the transformer (Figure 19), the 480 V current and voltage waveforms, identified as V (Bus A - N) I (Bus A), are essentially as they were with only the linear and nonlinear loads connected. This is a very desirable improvement. However, the current at the transformer primary (plot identified at the top as 2SCA) is distorted enough to create more than 5% voltage distortion (THD).

The impedance plot (identified as 480 V frequency scan load side) taken at the transformer secondary shows the potential resonance between 500 Hz and 555 Hz with the capacitor and transformer inductance tuned to filter at 545 Hz. Any loss of kVAR in the capacitor would shift this tuning point to the 11th harmonic (660 Hz). There is an abundance of energy to excite resonance at that frequency. kVAR loss may be due to normal degradation of the capacitor or the operation of perhaps a few of its many unit fuses. The utility may also change the characteristics of the network and possibly cause resonance at 420 Hz or 660 Hz.

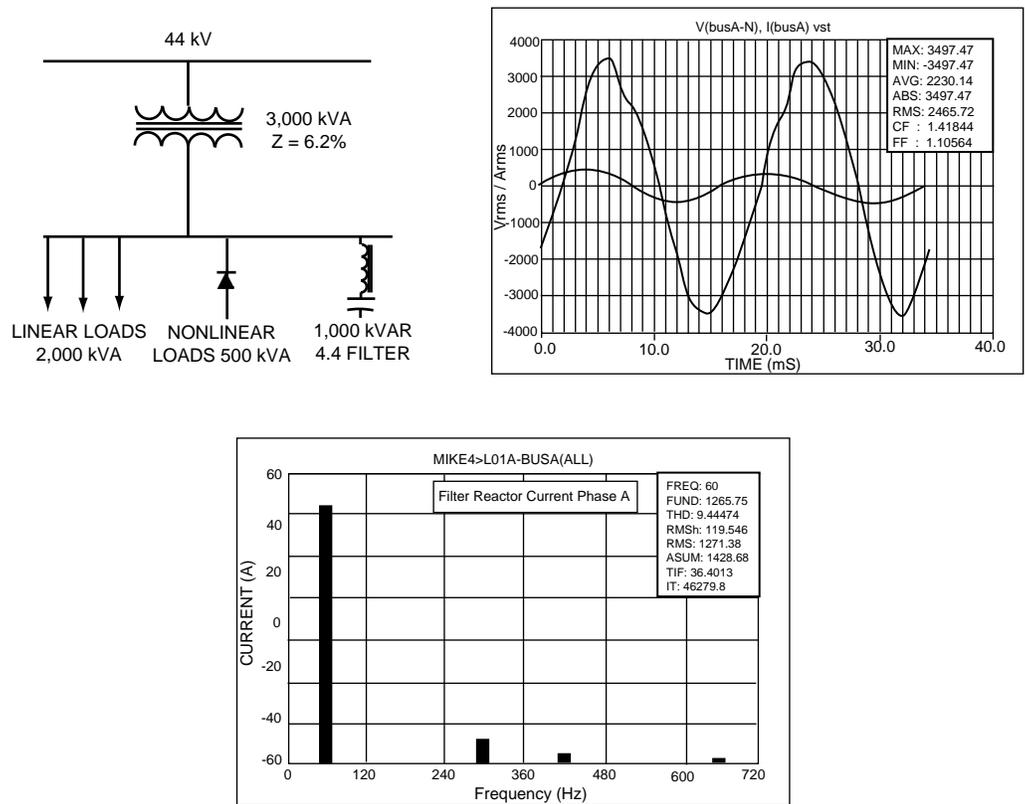


Figure 20 Linear, Nonlinear & Low Voltage Filter Loads

A solution to this problem is a filter tuned to resonate at 4.4 Hz or 264 Hz (Figure 20). This is a detuned capacitor.

The 480 V current and voltage waveforms are better now than with only the linear loads connected. The power factor is also improved with the injection of 1,000 kVAR. The current bar graph, indicated as filter reactor current, shows a reasonable level of filtering. In fact, 51% of the 300 Hz and 75% of the 420 Hz current have been filtered. The 660 Hz has been equally reduced.

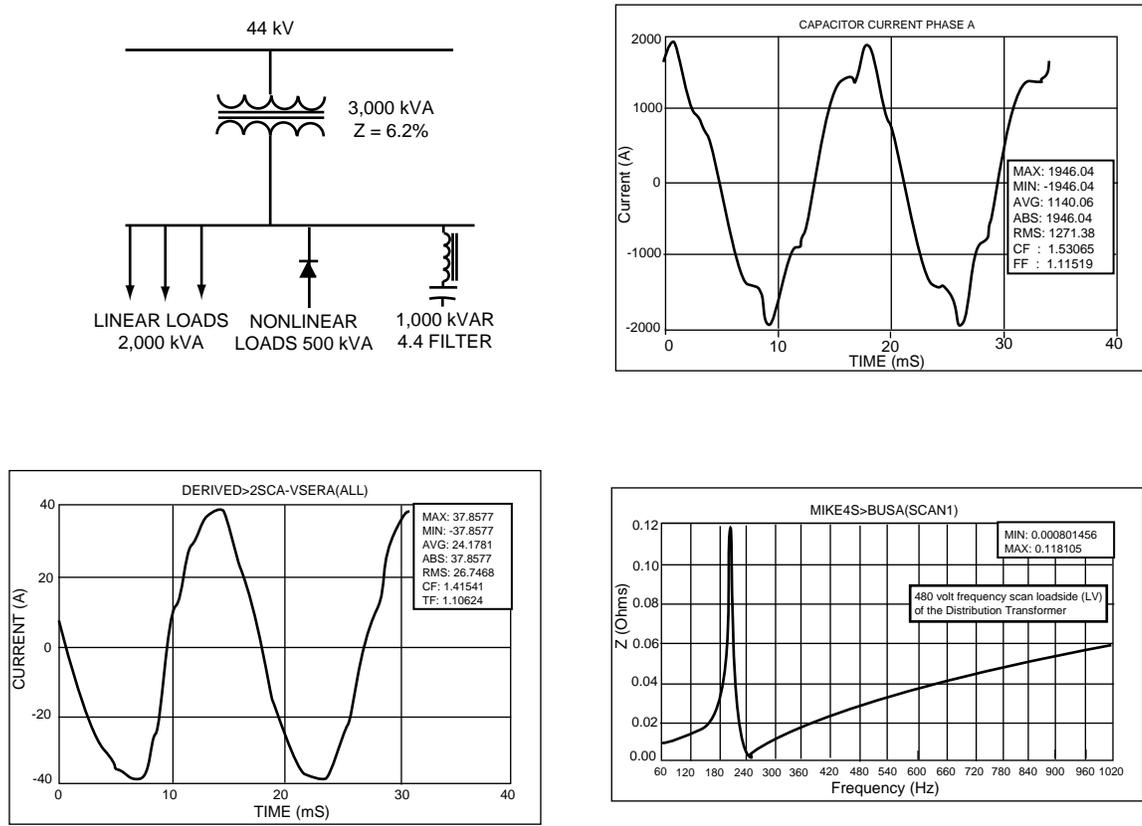


Figure 21 Linear, Nonlinear & Low Voltage Filter Loads

The capacitor current, identified as capacitor current phase A (Figure 21), is heavily distorted because it is “loaded” with 5th, 7th and 11th harmonic current. This current waveform is measured at the capacitor terminals, on the load side of the reactor, which is in series. It clearly illustrates the need for a robust capacitor.

The transformer primary current waveform, identified as 2SCA, is not badly distorted.

And finally, the 480 V network impedance plot shows resonance at 250 Hz and the network tuned at 210 Hz, both safe values. They are well above 180 Hz and well below 300 Hz. These are both frequencies that could exist.

SUMMARY

Because harmonic solutions are network dependent, future changes in the network must be considered. A reduction in nonlinear loads reduces the duty required of a detuned capacitor or a filter. An increase in nonlinear loads overloads the equipment. Suppliers should provide solutions for potential network changes based on current equipment and usage.

Assuming main distribution connection, there are two possibilities. One is to provide for a significant "overload" capability while maintaining reliability (120 to 130% is a reasonable factor). The other possibility is to make future expansion of the equipment easy and cost effective. The same considerations apply if a filter or detuned capacitor is connected to the load side of a transformer dedicated to a single nonlinear load.

Electrical equipment should be serviced only by qualified electrical maintenance personnel. No responsibility is assumed by Square D for any consequences arising out of the use of this material.



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