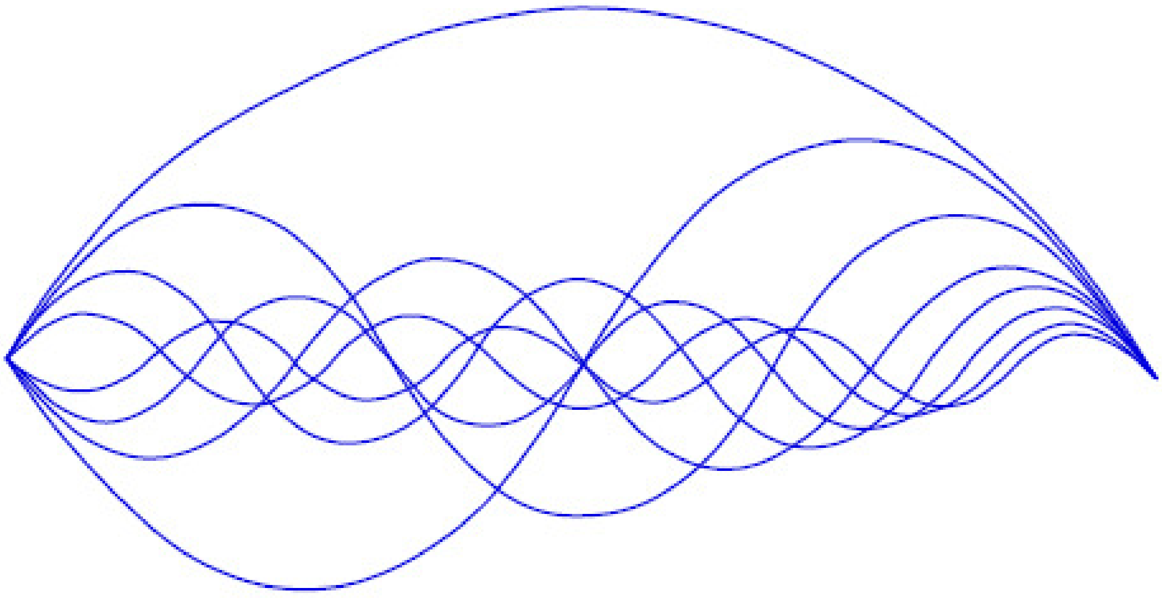
Harmonics



“The Energy Management Series”

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HARMONICS

Energy Management Series

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Table of Contents

Introduction

Harmonics have existed for manty years in the power lines of plants and factories, but only over the last few years have they turned into a major problem to normal operations. This is largely due to the proliferation of harmonic producing equipment and the increased sensitivity of certain types of equipment to harmonics. The effects of harmonics can often be serious - computer systems may fail to operate properly, capacitor banks, such as those used for power factor correction, can become overloaded and fail, and the interference may occur on communication lines.

This publication is intended to help you in dealing with this rapidly growing problem. It discusses how harmonics are generated in an industrial plant, the effects they have on equipment and the methods available to solve current problems and avoid future ones

For further information and assistance on harmonics and power quality, please contact Cos Phi Inc.

Harmonics - An Explanation

Harmonics are distortions to the voltage and current waveforms from their normal sinusoidal shape.

At the power generating stations, a 60 Hertz (Hz) sine wave is generated and distributed to a large number of residential and industrial loads. Certain types of loads distort the 60Hz wave by injecting additional signals of various magnitudes and frequencies. These signals are also sinusoidal in shape but their frequencies are multiples of the original wave for example, 180, 300 and 420Hz. These waves are called harmonics.

The frequency of the power systems waves is given a special term, called the **fundamental**, which in our case is 60Hz. This allows for each harmonic to be expressed as an integer multiple of the fundamental or more commonly as the order of the harmonic. For example, the 3rd, 5th and 7th orders.

An important feature of harmnoics is that the magnitude of the harmonics normally decreases with increasing frequency. Thus, only the first few orders usually need to be considered in examining the effects of harmonics on power system components or equipment.

How Harmonics Differ From Other Forms of Power System Disturbances

Harmonics are often confused with other types of power system disturbances such as voltage transients surges and sags, mainly because they all can affect the proper operation of equipment. Harmonics are nevertheless, unrelated to the other three pheonomena.

Voltage transients, surges and sags are all generally of short duration. Transients are impulses of very short duration, typically in the order of a fraction of a microsecond to a few milliseconds. Voltage sags and surges are periods of under or over voltage lasting from a large portion of a cycle of the power systems waveform to perhaps a few seconds

The presence of harmonics, on the other hand, is generally a steady state problem. The harmonics exist as long as the harmonic generating equipment is in operation. The magnitude and frequency of the injected harmonics can often be predicted and are hence preventable.

Sources of Harmonics in Electrical Systems

There are two ways through which harmonics can be generated.

The first involves the use of solid state devices, such as thyristors and SCR's, that convert or control power by switching the current repetitively in less than a cycle. Power converters, such as rectifiers, inverters, and AC phase control systems belong to this class. Rectifiers are used extensively in variable speed AC and DC drive systems, welders, arc furnaces, battery chargers and in plating and electronic equipment, while AC controllers are present in heating and lighting systems.

Over the past few years, there has been an increase in the use of this type of equipment resulting in a dramatic increase in the number of distorting loads now in operation.

The second way through which harmonics are generated involves the use of equipment with a non-linear voltage to current characteristic. Examples of this include transormers operating close to and beyond their rated voltage, as well as welders, induction heaters, and lighting equipped with ballasts (e.g., fluorescents and high intensity discharge lamps).

The trend has been to design equipment closer to the expected operating values. This has resulted in a larger number of transformers operating in the non-linear state.

Rectifiers

Rectifiers are used to convert an AC signal to DC. This is done by means of sequentially switching thyristors to conduct current through multiple paths to the same DC load. Since the conducting periods for each thyristor are a function of a full cycle, the output voltage waveform is made up of sinusoidal waveforms. Also, the input waveform exhibits notches at the points where the thyristor switching takes place. Due to the inductance of the circuit, the transfer of the current from one thyristor to the next is not instantaneous. There is a period of overlap where the two thyristors share the total DC load current. This further modifies the waveform of the load current and the input AC supply waveforms.

Variable Speed DC and AC Drives

DC drives obtain their DC power from rectifiers. AC drives obtain their variable frequencey AC power from fixed frequency AC (60Hz) by means of a combination of a rectifier and an inverter. These Adjustable Speed Drives (ASD's) are finding increased acceptance. Both these drives create a significant amount of harmonics. Some variable speed drives available on the market are supplied with harmonic filters, but at present there is no regulation regarding the level of harmonics that may be produced. The closer the AC and DC motors operate to their rated conditions, the lower the level of harmonics.

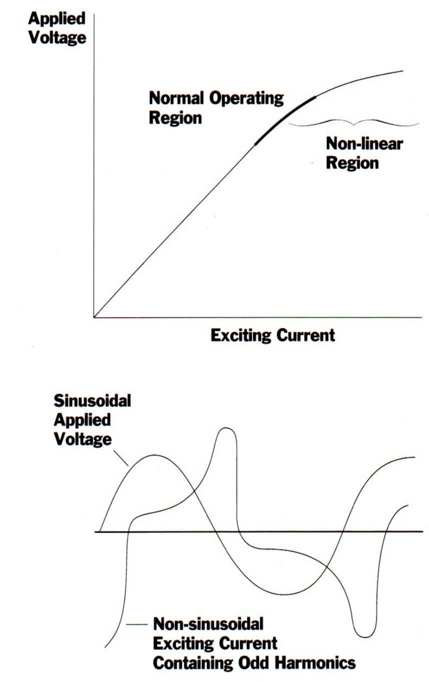
Transformers

Iron core transformers, when operated above their rated voltage, will be driven into the saturated regions of their ferromagnetic core (Figure 1) resulting in an exciting current much higher than normal in magnitude, and appreciably distorted with harmonics.

Arc Equipment

Due to the very non-linear voltage-current characteristics of the arc and the associated iron core transformers, arc furnaces and welding equipment are potential sources o harmonics.

FIGURE 1 Transformer Excitation Curve and Waveforms in Non-linear Region



Induction Heaters

Induction heaters use currents of high frequencies, in the order of a few kilohertz, to heat objects. By passing this current through a coil enclosing a metal object, a similar current can be induced in the object, causing it to heat. The conversion of the 60Hz current wave to this new frequency using solid state converters produces the harmonics.

Compact Fluorescent, HID and Low Pressure Sodium Lamps

These lights produce harmonics because of their non-linear operating characteristic. Examples of high intensity discharge lights are mercury vapour, high pressure sodium, and metal halide lamps.

Motors

Asymmetrical air gaps, slight irregularities in the metal and changes in the load can cause motors in equipment such as pumps, fans and compressors to produce harmonics. A fortunate characteristic of motor generated harmonics is that the magnitude of the harmonics tend to decrease as the load increases towards rated values.

Power Factor Correction Capacitors

It should be noted that power factor capacitors, though not a direct source, can magnify harmonics if not properly applied.

Effect on Electrical Equipment

Harmonics are present to some degree in all plant operations and will not normally create any problems, but nevertheless, depending on the system characteristics and the severity of the harmonics, they can produce any or all of the following effects:

Temperature Rise of Motors and Transformers

In the presence of harmonic currents, motors and transformers will run at a higher temperature. When the frequency of the current increases, as with harmonics, a larger proportion of the current is carried near the outer edge of the conductor. This decreases the effective size and increases the resistance of the conductor. Larger I^2R losses are produced, which cause the increase in operating temperature. This can often result in a breakdown in the insulating materials and a reduction in the life of the motor or transformer. A recent Canadian Electrical Association report indicated that typical reductions in lifetime are 32.5 percent for single phase machines, 18 percent for three phase machines and 5 percent for transformers and universal machines.

Motor Noise and Vibration

Harmonics can produce torque pulsations in electric motors, which in turn can result in mechanical vibrations and noise.

Disruptions in the Operation of Electronic Equipment

Electronic equipment often requires an accurate voltage and current waveform. Harmonics, however, can distort the waveform by reducing its magnitude, shifting the zero crossings, and misshaping the wave. All of these can cause disruptions in the operation of the equipment.

Mal-Operation of Computer-Controlled Production Equipment

Robots, numerically-controlled machines and motor controllers all rely on accurate control signals. The presence of harmonics can reduce the reliability of these signals and cause the device to malfunction.

Torques Due to Harmonics

Meter and relays which use induction discs (e.g., mechanical timing relays, watt-hour meters, etc.) are calibrated for accurate operation on the fundamental frequency only. Harmonics can cause high or low readings on meters and incorrect operating times on protective relays.

Conflict with Harmonic Restraint Relays

When power is first applied to a transformer of an induction motor, there is often a large initial inrush of current which may cause normal overcurrent relays (used to protect transformers from abnormally high currents) to trip. Certain types of protective relays, known as harmonic restraint relays, use the harmonics which are present in this inrush as an indicator not to trip. The presence of other harmonics may prevent these relays from operating properly, leaving the transformer or motor unprotected.

Confilct with Power Line Carrier Signals

Harmonics can often interfere with signals super-imposed on the power line for communications and control purposes. Control signals for energy management systems and utility-controlled water heaters are often used in this manner.

Capacitor Failues

Capacitors generally have only a small design margin on their insulation level. If the peak voltage is excessive, the dielectric material can break down and the capacitor can fail. Large capacitors are often protected from this by the use of protective relays and fuses, which trip before damage can occur. The capacitors used in computers are usually unprotected and have closer tolerances on peak voltages, making them very susceptible to damage.

Power factor correction capacitors have very low tolerances to continuous overvoltage and overcurrent conditions. With systems operating at or below 600 volts, these tolerances are often only 110 percent of rated voltage and 135 percent of rated current, including the effects of harmonics. The increased current and voltage levels due to harmonics can cause damage to the capacitors such as overheating, blown fuses, short circuits, and capacitor can explosions.

For more information on power factor and power factor correction capacitors, refer to the Energy Management Series brochure titled “Power Factor”.

Telephone Interference

Voice and data communication circuits close to power lines pick up harmonics electromagnetically, and as a result distortions are produced. The problem is particularly evident in cases where harmonics travel outside the plant into the utility lines

Other Equipment

Disturbances to the pictures on television can result from harmonic voltages in the supply.

Short Circuit Ratio

The short circuit ratio can be used as a rule of thumb in determining if the harmonics produced by a rectifier will be significant.

$$\text{Short Circuit Ratio (SCR)} = \frac{\text{Transformer Short Circuit Power Rating (MVA)}}{\text{Power Rating of Rectifier (MW)}}$$

An SCR value above 20, combined with a resonant harmonic order greater than 8.5, will usually rule out the possibility of harmonic problems in the circuit.

The transformer short circuit MVA are those volt-amperes which would result if the supply transformer were short circuited. It is equal to the MVA rating of the transformer, divided by its per-unit impedance. These values can usually be found on the transformer name plate.

The impedance used in the short circuit MVA calculations is actually the total of all impedances between the point of the short circuit and transformer. In many cases, the other impedances (transmission line, and the impedances on any loads) are small relative to the impedance of the transformer, and are not significant to the calculation.

Resonance

Resonance is a cause for concern in electrical systems as it can cause serious damage to the system components

The reactance of the inductive components of the power system increases with increasing frequency, while the reactance of capacitors decreases with frequency. At a certain frequency, known as the resonant frequency, the reactance of the capacitors and inductors are equal. At this point, the impedance of the parallel combination is also maximum and can be much higher than the impedance of either of the individual components. If the frequency of one of the harmonics happens to coincide with the resonant frequency, then the circuit will be excited. Large voltages may appear across the circuit components and very high currents may flow within the branches of the resonant circuit (Figure 2 on next page). This can cause damage to capacitor banks, motors and transformers.

Resonant Frequency

Resonant Frequency of Parallel Circuit

$$= 60\text{ Hz}\sqrt{\frac{\text{Transformer Short Circuit MVA}}{\text{Capacitor Bank MVA}}}$$

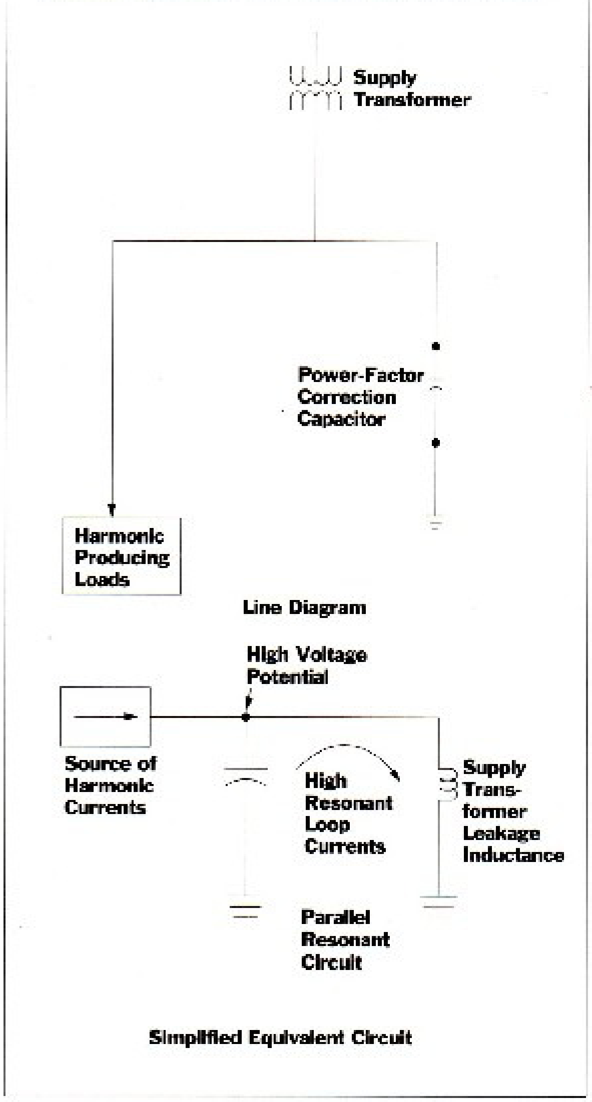
The MVA of the capacitor is its power rating and can be found on the capacitor nameplate.

The transformer short circuit MVA are those volt-amperes which would result if the supply transformer were short circuited. It is equal to the MVA rating of the transformer, divided by its per-unit impedance. These values can be found on the transformer nameplate.

Harmonic Content of Semiconductor Converters

A rectifier can be described by the number of pulses or ripples which are present in the DC output over one cycle of the supply voltage (Figure 3 on next page). This number can be used to determine the frequencies of the characteristic harmonics which are present in the AC wave-form - namely (60Hz x N x number of pulses) +/- 1, where N is an integer. The multiple of 60Hz is known as the order of the harmonics. For example, a single phase full-wave rectifier produces two pulses and will contain all of the odd harmonics. A three phase, six pulse rectifier generates

FIGURE 2 Harmonic Amplification Due to Resonance



harmonics of the 5th, 7th, 11th, 13th, 17th, 19th, 23rd, 25th etc., orders. Two six pulse rectifiers can be combined to produce 12 pulse rectification and will generate harmonics of the 11th, 13th, 23rd, 25th etc., orders.

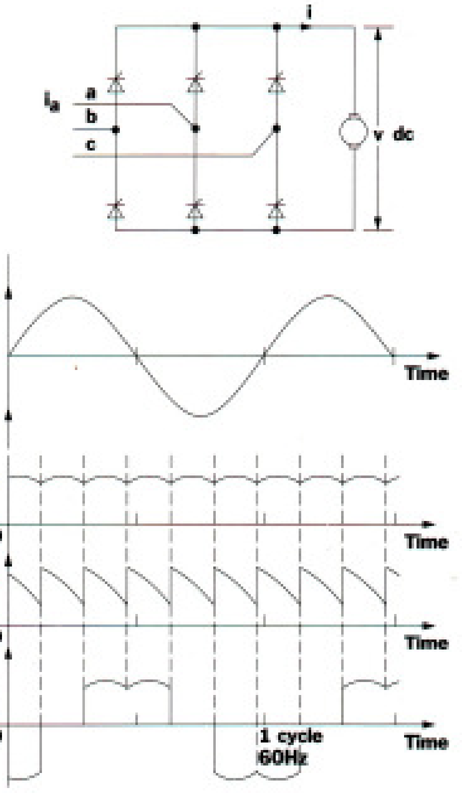
In the simple case of a non-phase controlled rectifier, the magnitude of the harmonics in the current waveform decreases with increasing frequency and can be related to the fundamental as follows:

$$\text{Magnitude of the Harmonic} = \frac{\text{Magnitude of the Fundamental}}{\text{Harmonic Order}}$$

Voltage Harmonics

Harmonic currents flow into the system and create voltage drops across the system's impedances at the corresponding harmonic frequencies. Because the system impedances are generally low except under resonant conditions, the magnitudes of the voltage harmonics are usually lower than those of the current harmonics. Therefore, the overall distortion of the voltage waveform is less severe than that of the current waveform.

FIGURE 3 3 Phase – Phase Controlled 6 Pulse Rectifier Feeding DC Motor



Avoiding Resonance Due to Power Factor Capacitors

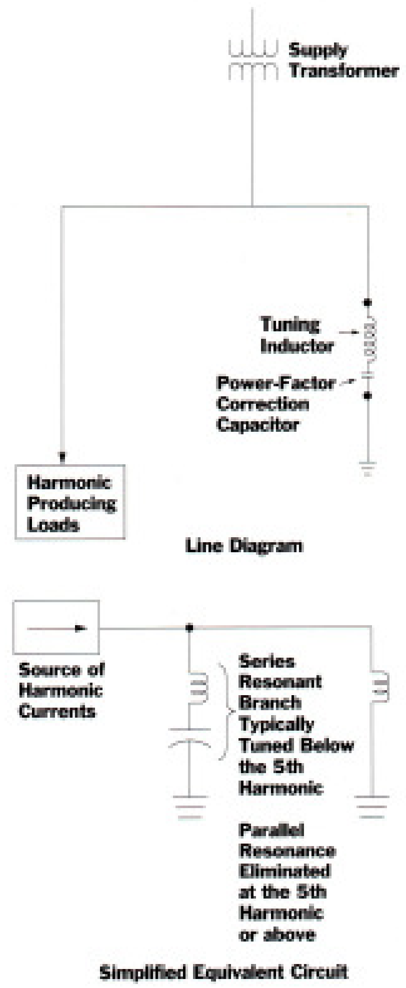
In order to avoid resonance effects when applying power factor correction capacitors, it is a common practice to add a series inductor to the capacitor (Figure 4). By selecting the right size of inductor, a series resonance with the power factor capacitors (as opposed to parallel resonance with the supply transformer) can be made to occur below any of the major harmonics, usually below the 5th, where there are generally little or no harmonics.

As explained earlier, at this point the reactance of the inductor and the capacitor will be equal. At frequencies above this point, the impedance of the inductor will be greater than that of the capacitors. The combination will then appear inductive to the rest of the circuit, elminating the capacitve component required for resonance with the supply system inductance.

Temporary Control of the Resonance Point by Power Factor Correction Bank Size

Sometimes, a more economical but temporary solution is to vary the size of the power factor capacitor bank to shift the resonance point away from a major harmonic. Capacitors can be added or removed from the bank as required to achieve the desired size. In some cases, depending on the major source of the harmonics, triplens (harmonics that are odd multiples of three) and even order harmonics have much lower magnitudes than the characteristic harmonics. The capacitor size may be chosen to establish the resonance at the 9th harmonic. Placing the resonant point above the 13th harmonic would require significant reduction in the capacitance. This might result in insufficient capacitance for its power factor correction function.

FIGURE 4 Controlling Harmonic Amplification By Tuning Inductor with P.F. Capacitors



This method is not recommended as a permanent solution. Changes in the power system (which occur regularly), or changes in the amount of power factor correction required, can cause the resonance problems to return.

In general, the use of a series inductor is the preferred practice.

Confirming The Presence of Harmonics

The existence of harmonics in sufficient quantity to cause problems should be confirmed before any possible corrective action is taken. A fairly simple test consists of viewing the power system waveforms on an oscilloscope.

Figure 5 represents a harmonically-distorted wave, but not in sufficient quantity to cause any real problems. On the other hand, Figure 6 represents a high degree of harmonics and should demand immediate attention.

FIGURE 5 Example of a Reasonably Undistorted Waveform

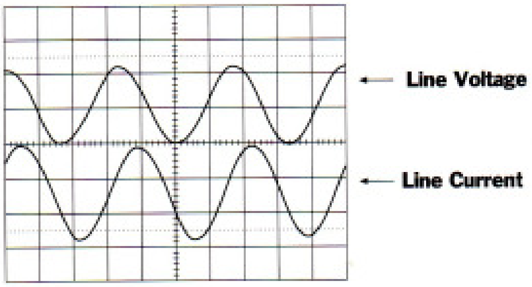
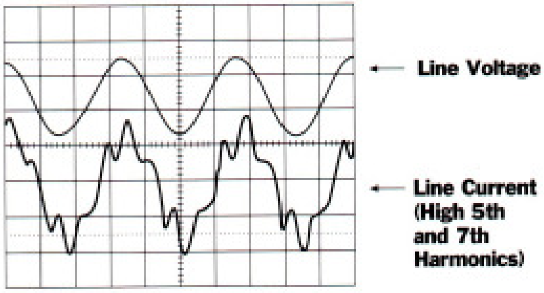


FIGURE 6 Example of a Distorted Waveform

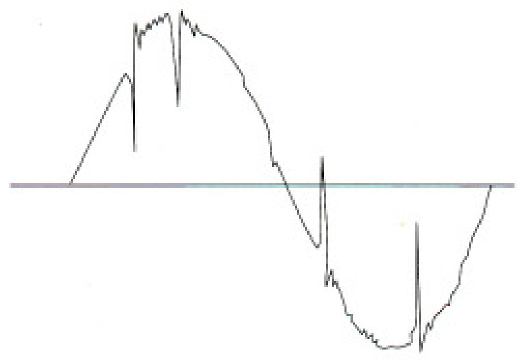


When viewing the voltage wave, a waveform consisting of notches (Figure 7) may appear. This signifies the presence of a solid state converter. The position and size of the notches on the waveform convey a great deal of information about the harmonics present in the system. This analysis is usually left to experts.

Power harmonic analyzers can be used to measure the magnitude of the individual harmonics which are usually given as a percentage of the fundamental.

In order to get a true representation of the situation, these tests should be carried out when the power system is in operation with all harmonic-producing equipment operating.

FIGURE 7 Notches on The Voltage Wave – 1 of 3 Phases



Dealing with Harmonics

There are a variety of ways in which companies can resolve the problems of harmonics within their operations. The following is a list of some of the actions that can be taken, most of which can be done without outside help. In some cases, consultants and suppliers with particular expertise in harmonics may be required, and your local utility can facilitate access to these sources.

Isolating Sensitive Loads

Ideally, loads producing harmonics or notches and sensitive loads should have entirely separate feeds and independent supply transformers (Figure 8). Another alternative is to supply all the harmonic sensitive loads by means of a motor-generator or an uninterruptible power supply (UPS).

Where these methods are not feasible, an isolation transformer in the converter circuit, as shown in Figure 9, will reduce the effects of notches. This transformer will usually be required whenever a converter is connected to the secondary system of a supply transformer feeding sensitive loads.

FIGURE 8 Isolating the Harmonic Producing Loads from the Harmonic Sensitive Loads

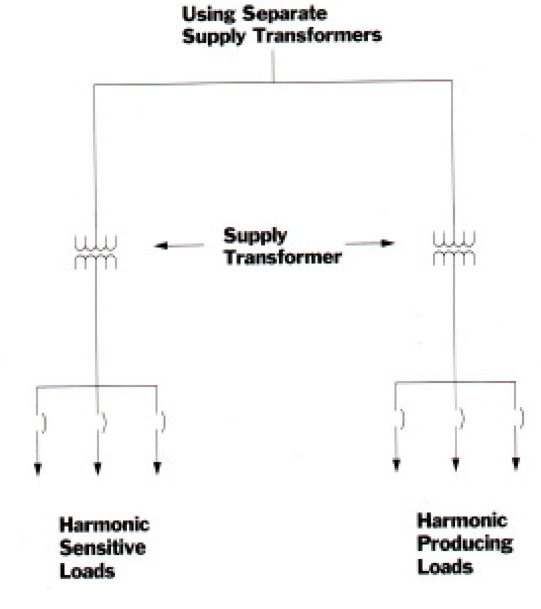
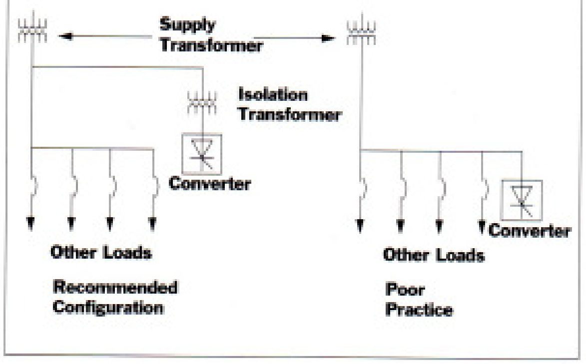


FIGURE 9 Configuration for Reducing the Effect of Notches



Filtering Harmonics

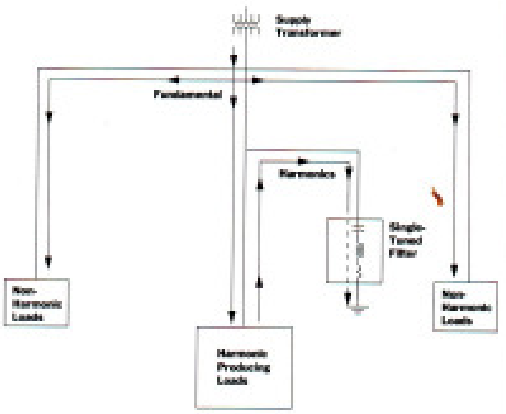
The magnitude of the harmonics can be significantly reduced through the use of two types of special filters: shunt filters and series filters.

Shunt Filters

The shunt filter consists of an inductor and capacitor placed in series. These are then tuned in such a way so as to present an impedance to the particular harmonic which is negligible when compared to that of the power system (Figure 10). These are placed in parallel with the plant's distribution system, one filter per harmonic order. The low impedance of the filter draws the harmonics away from, and reduces, the harmonic content of the main current. Filter circuits should be employed for the 5th harmonic in particular as well as for the 7th, 11th and 13th harmonics (after the 13th harmonic the magnitude of the harmonics become much smaller). At the fundamental frequency, the filter circuit will appear capacitive, and the filter will then contribute to the power factor correction of the plant.

A second type of shunt filter called a high pass filter can be employed either in conjunction with the above type for serious problems, or alone for less serious problems. A high pass filter will shunt a portion of the harmonics above a specified frequency to ground. This method is more economical than having one filter per harmonic, but it is not as effective on the lower order harmonics. High pass filters have resistive circuit elements so their running costs tend to be higher than normal shunt filters. They are more effective for notch reduction than normal shunt filters.

FIGURE 10 Harmonic Filters: Shunt

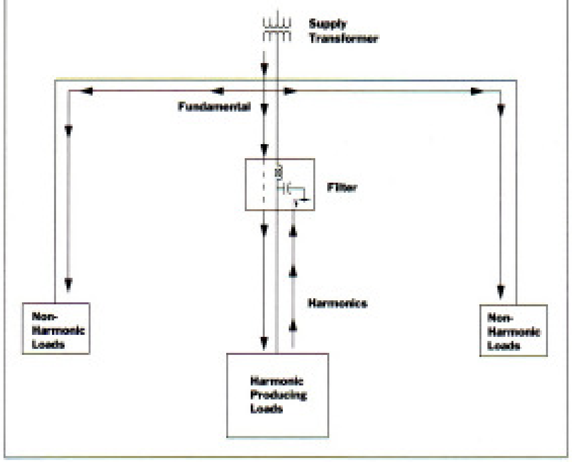


Series Filters

This type of harmonic filter is a low pass filter placed directly in the main line. This type of filter will allow the fundamental to pass virtually unattenuated while channelling the harmonics to the ground (Figure 11). A very major drawback of this method is that the filter must be rated for full line current because it is situated in the main line, making it very expensive. For this reason, it is not used.

Care should be taken in the implementation of harmonic filters. They may act as a sink for harmonics produced elsewhere in the plant or system.

FIGURE 11 Harmonic Filters: Series

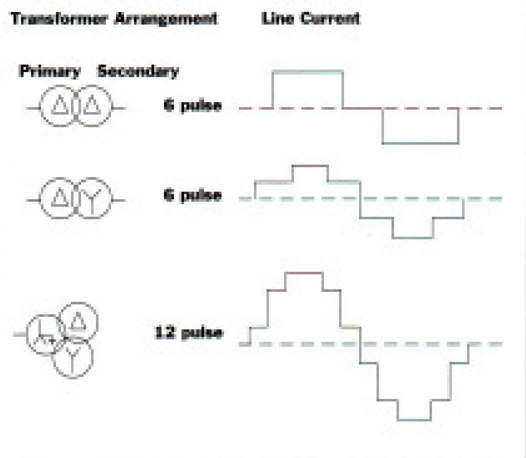


Modifying Rectifiers

For large rectifier installations, the harmonic content of the source can be reduced by increasing the numberr of pulses produced by the rectifier. By using a higher pulse number, some of the harmonics present in the six pulse rectifier, such as the 5th, 7th, 17th and 19th, will theoretically be eliminated. However, owing to some unbalance in the system, there will be some levels present, although usually very low.

Increasing the number of pulses can be accomplished by connecting the DC side of several rectifiers with a phase shift between the input voltages. The phase shift will in effect convert two six-pulse rectifiers into one twelve pulse rectifier. This phase conversion is easily performed through the use of a grounded wye transformer on the primary, and both a delta and a wye transformer on the secondary. As a result, the waveform on the primary becomes more sinusoidal and its harmonic content is reduced (Figure 12). In this figure, the primary current is the current on the secondary (rectifier side) transformed back to the primary.

FIGURE 12 Modification of Rectifiers



Call and Expert

If serious harmonic problems persist, even after implementing some of the solutions described above, more extensive action may be necessary. In most cases, the use of an expert in the field will be required.

Preventing Harmonic Problems

The best time to prevent future harmonic problems is at the time equipment is first ordered. By stating the equipment's specifications in terms of its ability to handle harmonics, future harmonics problems can be minimized. It should be noted that, as the equipment requirements provided to the manufacturer become more stringent, the price of the equipment can be expected to rise.

The Institute of Electrical and Electronic Engineers (IEEE), in Standard 519, has established a set of limits for harmonic distortion. Based on these, the following general requirements might be specified:

Power Conditioning Equipment Using Switching Devices
When ordering power conditioning equipment, the following might be specified to the manufacturer: "The power conditioning equipment shall not produce voltage distortion or notches in excess of the limits suggested in IEEE 519".

Harmonic Susceptible Equipment
For harmonic susceptible equipment, the following might be specified to the manufacturer: "The equipment shall operate successfully when fed from a system meeting the limits suggested in IEEE 519".

Summary

We hope this booklet has been informative and helpful. By understanding harmonics better you will now be able to minimize harmonic problems and safeguard sensitive equipment by installing protective measures.

For more information on Harmonics, Power Factor,
Power Quality and Energy Managment
be sure to visit:

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