Reference materials for the Harmonic 80 quiz

Harmonic Currents

Power quality used to be to the ability of the electric utilities to provide electric power without interruption. Today, power quality encompasses any deviation from a perfect sinusoidal waveform. This includes EMI and RFI noise, transients, surges, sags, brown outs, black outs, and any other distortions to the sinusoidal waveform. One distortion to the sinusoidal waveform which has dangerous consequences is harmonics.

Harmonics can be present in voltage, current or both. It is forecast that before the end of the century, half of all electrical devices will operate with nonlinear current draw. These nonlinear loads are the cause of current harmonics.

The term " harmonic currents" is a popular buzz word in the power quality industry and the layman needs some information to understand the term and realize they can be a serious problem if not treated properly. The treatment and the details of harmonics is better left to the expert with the proper tools and training.

Harmonic currents cause overheating of electrical distribution system wiring, transformer overheating and shortened transformer service life. Electrical fires resulting from distribution system wiring and transformer overheating were rare occurrences until harmonic currents became a problem. The frequency of such fires is now becoming more common. The life safety issues of electrical fires are not part of this discussion, but should be considered.

Imagine the cost to a company such as a stock brokerage firm if a transformer and the distribution wiring failed during a busy trading day. Power is lost to their trading computer equipment and they cannot carry out their normal business of buying and selling financial instruments. An electrical system fire could result and destroy part of the electrical distribution system.

These events could take days to correct to put this firm back in business. The entire distribution system would have to be surveyed for damage. All damaged or weakened distribution system equipment and wiring would have to be replaced. This list of damages could include damaged conduit, transformers, switch gear, electrical panels, wire, etc. This list of damaged equipment probably will include equipment connected to the electrical distribution system at the time of system breakdown. During such a breakdown, other power quality problems will be encountered including shorting of transformers and wiring. Imagine the effect on sensitive computer equipment not isolated from the electrical distribution system. Transient activity can have a catastrophic effect on computer and telecommunications networks.

In effect, the stock brokerage firm in our example has been put out of business by harmonics until repairs can be completed or operations moved to another location. What could be the bottom line cost? Millions of dollars would be a conservative estimate if they were a <u>small</u> firm. Estimate the cost to your own company if you were out of business for days or a week or longer. Who would service your customer? Would it be your competition? Could your company financially survive such a catastrophic event?

Harmonic currents cause false circuit breaker tripping. Peak sensing circuit breakers often will trip even though the amperage value has not been exceeded. Harmonic current Peak values can be many times higher than sinusoidal waveforms. In electronic equipment that relies on the zero crossing of the sinusoidal waveform, such as clock timing devices, heavy harmonic content can cause a zero crossing point offset.

In many cases, power factor correction capacitor failure can be directly attributed to harmonic content. Capacitors appear as extremely low impedance values and are more susceptible to harmonics. High Harmonic currents have been known to overheat correction capacitors, causing premature failure and sometimes resulting in explosion.

Utilities invest millions of dollars annually to ensure the power supplies their customers receive are as close as possible to a sinusoidal waveform. Resistive linear loads such as the incandescent light bulb result in sinusoidal waveforms, but switching loads do not. The power supply in a modern personal computer is a good example of a non-linear load. The switching action of the computer power supply results in distortion of the current waveform. There are many other switching loads and a few are listed in the chart below.

LOADS PRODUCING HARMONIC CURRENTS

Electronic Lighting Ballast	**Adjustable Speed Drives**
Electric Arc Furnaces	**Personal Computers**
Electric Welding Equipment	**Solid State Rectifiers**
Industrial Process Controls	**UPS Systems**
Saturated Transformers	**Solid State Elevator Controls**
Medical Equipment	

The above list is not complete and is being expanded every day. The common characteristic shared by most of the equipment on this list is seen more today than before the microprocessor. Most of this equipment relies on an internal DC power supply for operation.

Large commercial buildings have many different sizes and types of loads. The most common power distribution to office systems and equipment is 208/120 transformers in a Wye configuration. This configuration does not include what are known as high voltage loads such as air handlers or high voltage lighting that are powered by 480 Delta or Wye configuration transformers. Delta and Wye distribution systems are also used in some facilities for specialized equipment. For the purpose of our discussion we will consider the distribution system to be 480 - 208/120 Wye.

The following are definitions that will assist your understanding of this section.

<u>Harmonic</u>: A sinusoidal waveform with a frequency that is an integral multiple of the fundamental 60 Hz frequency.

60 Hz fundamental
120 Hz 2nd harmonic
180 Hz 3rd harmonic
240 Hz 4th harmonic, etc.

<u>Triplen Harmonics:</u> Odd multiple of the 3rd harmonic (3rd, 9th, 15th, 21st, etc.)

<u>Harmonic Distortion</u>: Non-linear distortion of a system characterized by the appearance in the output of harmonic currents (voltages) when the input is sinusoidal.

<u>Voltage Harmonic Distortion (VHD):</u> Voltage harmonic distortion is distortion caused by harmonic currents flowing through the system impedance. The utility power system has relatively low system impedance, and the VHD is very low. VHD on the distribution power system can be significant due to its relatively high system impedance. $E + I^2R$ Ohm's Law

<u>Total Harmonic Distortion (THD):</u> The square root of the sum of the square of all harmonic currents present in the load excluding the 60 Hz fundamental. It is usually expressed as a percent of the fundamental.

<u>Harmonic Spectrum "K" Factor:</u> The sum of the product of each harmonic current squared and that harmonic number squared for harmonics from the fundamental (60 Hz) to the highest harmonic of any measurable consequence. When the "K" factor is multiplied by the stray losses of the transformer, the answer represents the loss in the transformer caused by harmonic currents. When these losses are added to the I^2R losses of the transformer, the total load losses are known.

Current waveforms from non-linear loads appear distorted because the non-linear waveform is the result of adding harmonic components to the fundamental current.

Non-linear loads generate high levels of harmonic currents and when supplying power to these loads, a special transformer design is necessary.

Of these non-linear loads, the major source of harmonic currents is the switch mode power supply found in most desktop computers, terminals, data processors and other office equipment.

The amount of harmonics produced by a given load is represented by the term "K" factor. The larger the "K" factor, the more harmonics are present. The chart below provides a guide of typical "K" factors of different loads. This chart is only a guide and the "K" factor of equipment will vary from one manufacturer to another. The best way to determine "K" factor is by spectrum analysis and should be left to a professional with the proper power quality analysis equipment.

K-Factor By Type of Load

K-1	**Resistance Heating** **Incandescent Lighting** **Electric Motors** **Control Transformers** **Distribution Transformers**	**K-13**	**Telecommunications Equipment** **Branch Circuits in Classrooms** **Health Care Facilities**
K-4	**Welders** **Induction Heaters** **HID Lighting** **Fluorescent Lighting** **Solid State Controls**	**K-20**	**Main Frame Computers** **AC Variable Speed Drives** **Circuits With DP Equipment** **Personal Computers** **Computer Terminals**

Harmonics are produced by the diode-capacitor input section of power supplies. The diode-capacitor section rectifies the AC input power into the DC voltage used by the internal circuits. The personal computer uses DC voltage internally to power the various circuits and boards that make up the computer. The circuit of the power supply only draws current from the AC line during the peaks of the voltage waveform, thereby charging a capacitor to the Peak of the line voltage. The DC equipment requirements are fed from this capacitor and, as a result, the current waveform becomes distorted.

The harmonics in the electric power distribution system combine with the fundamental (60 Hz) to create distortion. The level of distortion is directly related to the frequencies and amplitudes of the harmonic current. All of the harmonic frequency currents combine with the fundamental current to form the total harmonic distortion. (THD) The THD value is expressed as a percentage of the fundamental current and any THD values over 10% are significant enough for concern.

Modern power quality instruments will read harmonics and do the calculation of the above formula. These are preferably used by trained operators . If you suspect you have problems or want to be sure you do not have harmonics present in your electrical distribution system, call upon a professional in the field of power quality.

Wherever there are large numbers of nonlinear loads, there are harmonics in the distribution system. It is not uncommon for THD levels in industrial plants to reach 25%. Normally, THD levels in office settings will be lower than in industrial plants, but office equipment is much more susceptible to variations in power quality.

Odd number harmonics (3rd, 5th, 7th, etc.) are of the greatest concern in the electrical distribution system. Even number harmonics are usually mitigated because the harmonics swing equally in both the positive and negative direction.
The heating effect causes the greatest problem in electrical distribution systems and equipment. Electrical equipment often overheats and fails even when operating well below the design ratings. The increase in temperature is directly related to the increase in RMS current.

Harmonic frequencies are always higher than the 60 Hz fundamental frequency so "skin effect" also becomes a factor. Skin effect is a phenomenon where the higher frequency causes the electrons to flow toward the outer sides of a conductor. This reduces the ability of the conductor to carry current by reducing the cross sectional diameter of the conductor and thereby reduces the ampere capacity rating of the conductor. Skin effect increases as the frequency and the amplitude increase and this is the reason higher harmonic frequencies cause a greater degree of heating in conductors.

Industrial environments can have many three phase, non linear loads drawing high levels of load current. The effect on transformer operation when multiple loads are connected is that each load generates triplen harmonic currents on the neutral conductor. These are sent on to the transformer secondary and reflected into the delta primary and these currents circulate within the delta primary causing overheating, shortened service life, catastrophic failure or worse.

On balanced, three phase systems with no harmonic content, the line currents are 120° out of phase, cancel each other and result in very little neutral current. However, when there is distortion in any one of the phase currents, the harmonic currents increase and the cancellation effect is lessened. The usual result is the neutral current THD is significantly higher than planned. The triplen harmonics (odd multiples of three) are additive in the neutral and can quickly cause dangerous overheating.

In theory, the maximum current that the neutral will carry is 1.73 times the phase current and if not sized correctly, overheating will result. Higher than normal

neutral current will cause voltage drops between neutral and ground which are well above normal. Readings above 4 volts indicate high neutral current.

Parallel resonance between the capacitor bank and the source impedance can cause system resonance resulting in higher than normal currents and voltages. The resulting power factor correction capacitor failure can be directly attributed to harmonics. Inductive reactance varies directly with frequency (XL=2x3.14 fl).

The majority of problems result when the resonant frequency is close to the 5th or 7th harmonic. These happen to be the largest harmonic amplitude numbers that most adjustable speed drives create. When this situation arises, capacitor banks should be re-sized to shift the resonant point to another frequency.

Modern electronics grade distribution panels have lugs for neutrals 2X the phase conductor size in anticipation of neutral currents. K rated transformers are also built to accommodate high neutral currents.

Another useful parameter is the Distortion Factor, or %DF. %DF is the Total Harmonic Distortion referenced to the total RMS signal. The %DF is expressed as a percentage and may not be grater than 100%. International standard IEC-555 has requirements for equipment that must be met.

The Following are steps to take in alleviating the many problems encountered when harmonics are present in an electric distribution system. Step #1 can be started by the layman, after that, a professional should be called in.

1. **Inventory all equipment that may generate harmonic currents.**
2. **List the nonlinear loads which are on each branch circuit.**
3. **Record true RMS current in each phase at the service entrance.**
4. **Record the neutral current of the transformer secondary.**
5. **Compare the measured neutral current to the anticipated current due to phase imbalance. If the phase currents are equal, the vector sum of the neutral currents will add up to zero. If excessive amounts of triplen harmonics are present in the neutral, neutral current may exceed phase current. Consult the NEC® for the maximum capacity for each of the conductors that have been measured.**
6. **Measure each feeder for harmonic content. A high degree at this location is often heard as a buzzing sound. A voltage THD reading is also useful at this location.**

IEEE standard 519-1992 is a guidance document for utilities and electric power users which specifies both the maximum distortion levels and recommends correction levels. The harmonic distortion limit of 5% is proven to be the point where harmonics begin to have a detrimental effect on the electrical distribution system.

Harmonic current measurements define the harmonic generation characteristics of the load, so measurements should be taken there when possible. Voltage measurements define the system response and are usually taken at the individual busses.

Distribution systems compound the problems that harmonic currents present to the system. The nonlinear harmonic load currents also have an Ohm's Law relationship with the source impedance of the system to produce voltage harmonics. Consider a heavily loaded transformer that is affected by one branch circuit feeding a non linear load; the resulting voltage harmonics can then be passed down to all the remaining circuits fed by that transformer.

Voltage Harmonics

Voltage harmonics may cause havoc within the electrical distribution system. Motors are typically considered to be linear loads; however, when the source voltage supply is rich in harmonics, the motor will draw harmonic current. The result is typically a higher than normal operation temperature and shortened service life.

Different frequency harmonic currents can cause additional rotating fields in the motor. Depending on the frequency, the motor will rotate in the opposite direction (counter-torque). The fifth harmonic, which is very prevalent, is a negative sequence harmonic causing the motor to have a backward rotation, shortening the service life.

Noise can be picked up in computer networks, communications equipment and telephone systems when harmonics are at audio or radio frequencies. With the increase in speed of computer networks, the future will bring these systems into the frequencies where they will be more affected by harmonic generated noise. The noise is inductively or capacitively coupled into the communications and data lines.

When induction-disc watt-hour meters are monitoring non linear loads, depending on the content of the harmonics, the disk may run slower or faster, resulting in erroneous readings.

The majority of generators and transformers base their operating characteristics on non disturbed 60 Hz waveforms. When the waveforms are rich in harmonics, shortened service or complete failure is sure to result.

One option in distribution system if harmonics are present is to de-rate the transformer supplying the system. De-rating K factors can be applied specifically to transformers to ensure dangerous heating will not result when supplying load currents which are rich in harmonic content.

The K factor is determined by measuring the True RMS current of each harmonic, multiplied by the harmonic order and squared. The total sum is then multiplied by the eddy current losses. The K factor of a transformer should be thought of as the index of the transformer's ability to handle nonlinear load currents without abnormal heating.

The alternate method for de-rating transformers is for buildings which supply single phase, 120 VAC receptacles. This method is established by The Computer & Business Equipment Manufacturers Associations (CBEMA).

CBEMA De-rating Factor = 1.414 divided by Crest Factor

Crest Factor (CF) = Peak Value divided by RMS Value

De-rating certain types of electrical equipment is the easiest way to limit the effects increased heating has on equipment. A 25% de-rating for transformers and generators is commonly employed in industry.

Filtering is currently the most common method used to limit the effects that harmonics present to the rest of the system. Filters typically consist of tuned series L-C circuits. Filter impedance is negligible with respect to the rest of the distribution system. These filter products are commercially available under different trade names. Most filter products are no more than 50% effective. The best solution is to install transformers, with the appropriate K rating and wiring that is sized to meet the equipment and systems needs.

Harmonic Distortion

Problems and Solutions

Like surfers, most electrical devices are looking for the perfect wave. For alternating current, perfection is defined by a sinusoidal (or sine) wave in which electrical voltage changes smoothly from positive polarity to negative and back again 60 times per second. Unfortunately, modern equipment is having a negative effect on the quality of this perfect wave. A variety of solid state devices, including desktop computers and other microprocessor-based devices, create high levels of harmonic distortion.

Harmonic Problems

Harmonic distortion may or may not create a problem for your facility. You may have harmonics present, but experience no adverse effects. However, as harmonic levels increase, the likelihood of experiencing problems also increases. Typical problems include:

- malfunctioning of microprocessor-based equipment.
- overheating in neutral conductors. transformers, or induction motors.
- deterioration or failure of power factor correction capacitors.
- erratic operation of breakers and relays.
- pronounced magnetic fields near transformers and switchgear.

To make matters worse, harmonics can sometimes be transmitted from one facility back through the utility's equipment to neighboring businesses, especially if they share a common transformer. This means harmonics generated in your facility can stress utility equipment or cause problems in your neighbor's facility and vice versa. Electric utilities have recognized this problem and are adopting standards, like the Institute of Electrical and Electronics Engineers (IEEE) Standard 519 which defines allowable harmonic distortion at customer service entrances. This standard is designed to protect both businesses and utilities.

Solutions

There are a number of ways to deal with harmonics, but not all solutions are appropriate for a given problem. The first step in solving a harmonics problem is to carefully examine your power system and loads to define the nature, source and manifestation of the problem. Your SMMPA Member utility can help identify harmonic distortion in your facility.

Treat Symptoms

In some cases, it's best to simply treat the symptoms. If your only problem is neutral conductor overheating, you can increase neutral conductor size. For transformer overheating, you can install special K-rated transformers designed to tolerate harmonics. You can redistribute or relocate harmonic producing loads around your facility to balance harmonics and produce a more sinusoidal waveform. A "zigzag" transformer uses phase shifting to accomplish much the same thing.

Treat Sources

Another solution involves reducing the level of harmonics produced by equipment. Impedance may be added by installing line reactors at harmonic sources. Tuned filters may be installed to eliminate specific harmonic frequencies. Both have a long track record, are reasonably priced and work effectively. This approach must be carefully implemented to avoid creating other problems, such as harmonic resonance. Six-pulse rectified power supplies like those found in many variable frequency drives, may be replaced with twelve or higher pulse rectifiers. This solution is not likely to be cost effective unless done when the equipment is purchased.

A new class of harmonics mitigation devices injects a mirror-image waveform of the harmonic portions of the distorted waveform. By canceling out the harmonics, the waveform returns to its 60 Hertz base. This type of device--called an active harmonic filter--is based on variable speed drive technology. Active harmonic filters are relatively new and rather costly, but offer several advantages. They are inherently current limiting, have no resonance problems, are "intelligent" and adaptable, and can be configured to either correct the full spectrum of harmonics or to target specific harmonics. Although this technology is new, it has important advantages and should be watched carefully. It is worth stressing that the particular solution for your facility must be the result of careful analysis and isolation of the problem. No harmonics mitigation strategy should be employed without first assessing the situation.

New Equipment

An ideal time to consider harmonics mitigation strategies is during the design of new facilities or at the time of equipment purchases. Harmonics producing equipment can be identified and mitigation devices installed at the equipment. Transformers and neutral conductors can be specified properly. Some variable speed drive manufacturers now offer harmonics correcting components as standard features of their drives and others offer them as factory installed options. Be sure to ask your drive representative about harmonics correction when specifying a new variable speed drive.

Help from Your SMMPA Member utility

Harmonics are not a problem for everyone. Most facilities probably have some level of harmonic distortion, so the mere presence of harmonics does not warrant concern. However, you should be concerned when you see the problems described above. Another time to give harmonics some thought is when purchasing new equipment that is known to produce harmonics. Your SMMPA Member utility has information on harmonics problems and solutions. We can help you diagnose harmonics problems using our array of metering devices and troubleshooting skills.

Harmonic History

For most of the twentieth century, the predominant use of electricity for business and industry was to power motors, lights and heating devices. These uses have little effect on the 60 Hertz (cycles per second) sine waveform of the electricity delivered to them from their utility. They are called linear loads, because the current (amperage) rises and falls in proportion to the voltage wave.

A few industries like steel mills and aluminum smelters used electricity to power arc furnaces, which distorted the waveform, because the current flow was not directly proportional to the voltage. These loads are called non-linear loads.

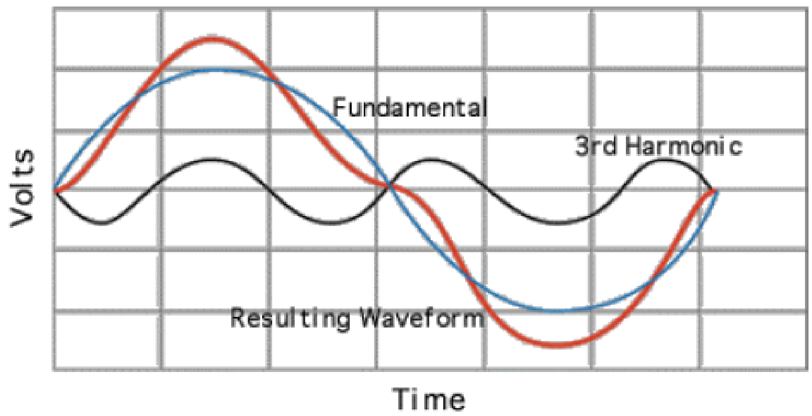
Non-linear loads cause waveforms that are multiples of the normal 60 Hertz sine wave to be superimposed on the base waveform. These multiples are called harmonics. For example, the second harmonic is a 120 Hertz waveform (2 times 60 Hertz), the third is a 180 Hertz waveform, and so on. The combination of the sine wave with all the harmonics creates a new, non-sinusoidal wave of entirely different shape. The change to the wave is called harmonic distortion.

In the last 20 years, there has been an explosion of microprocessor based equipment which are also non-linear loads. Examples include computer systems, variable frequency drives, AC/DC converters, electronic ballasts, X-ray machines, MRI equipment and uninterruptible power supplies. What was once a problem for a very limited number of heavy industries, is now a concern for some smaller business, too.

Harmonics Strike a Sour Note

For most people, the word "harmonics" brings to mind something musical. If you could look at a plucked guitar string in slow motion, you would see it vibrates in several ways. First, it vibrates end to end, anchored at the head of the guitar and the bridge. This is called the fundamental. The string also vibrates as if anchored at the bridge and in the middle of the string. This vibration on top of the fundamental vibration is called the second harmonic. The frequency of the second harmonic is two times the fundamental. The frequency of the third harmonic is three times the fundamental, etc. Harmonics are superimposed on the fundamental to produce the sound we hear.

The translation to electricity is almost direct. Electricity is produced and delivered in its fundamental form as a 60 cycles per second (Hertz) sine wave. Once inside your business, certain types of equipment can superimpose harmonics on the basic sine wave. Harmonics are multiples of the 60 Hertz wave. For example, the second harmonic is at 120 Hertz, the third is at 180 Hertz, etc. Because harmonics are superimposed on the fundamental waveform, the frequency of the electricity no longer follows a smooth sine wave. Most electrical equipment expects to see a smooth frequency and distortions created by harmonics can cause a variety of problems.



Two Modern Power Quality Issues – Harmonics & Grounding

As we connect more electronic devices to our power systems, the "quality" of the power becomes more important. "Quality" can be defined many ways. Stable voltages and undistorted waveforms are two characteristics which are very desirable in power systems. Grounding affects voltage stability, and more importantly, is critical to personal safety. Harmonics are a mathematical model we use to analyze distorted waveforms.

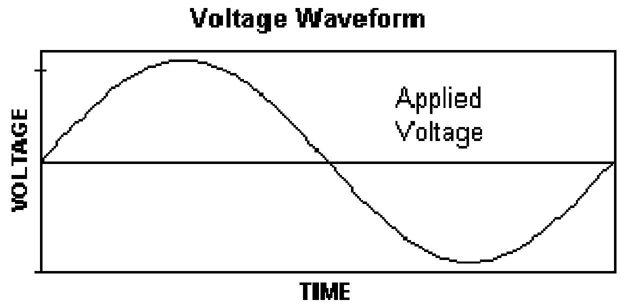
You have probably heard the term "harmonics." Numerous technical articles have been written on this subject; however, these articles do not always address our basic problems in an understandable way:

- What are harmonics?
- How do they affect my building or my product?
- What are the symptoms of harmonics?
- How do I address these systems?
- How do I solve the problem?

Harmonics are a mathematical model of the real world. Harmonics are simply a technique to analyze the current drawn by computers, electronic ballasts, variable frequency drives and other equipment which have modem "transformer-less" power supplies. Let's examine how these power supplies operate.

There is a law in electrical engineering called Ohm's Law. This basic law states that when a voltage is applied across a resistance, current will flow. This is how all electrical equipment operates. In the United States, the voltage we apply across our equipment is a sinewave which operates 60 Hertz (cycles per second).

Figure 1



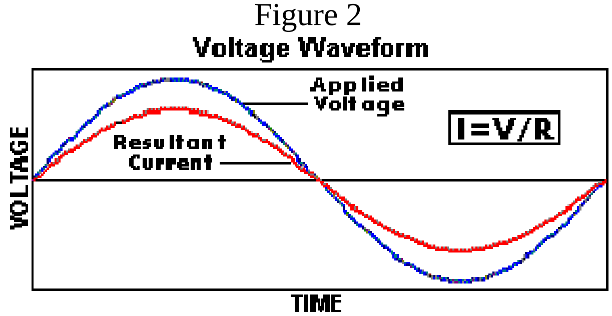
The utilities do a wonderful job of generating this voltage sinewave. It has (relatively) constant amplitude and constant frequency.

Once this voltage is applied to a device, Ohm's Law kicks in. Ohm's Law states that current equals voltage divided by resistance. Expressed mathematically:

I=V/R

Expressed graphically, the current ends up being another sinewave, since the resistance is a constant number. Ohm's Law dictates that the frequency of the current wave is also 60 Hertz. In the real world, this is true; although the two sinewaves may not align perfectly (as a power factor – another topic!) the current wave will indeed be a 60 Hertz sinewave.

Figure 2



Since an applied voltage sinewave will cause a sinusoidal current to be drawn, systems which exhibit this behavior are called linear systems. Incandescent lamps, heaters and, to a great extent, motors are linear systems.

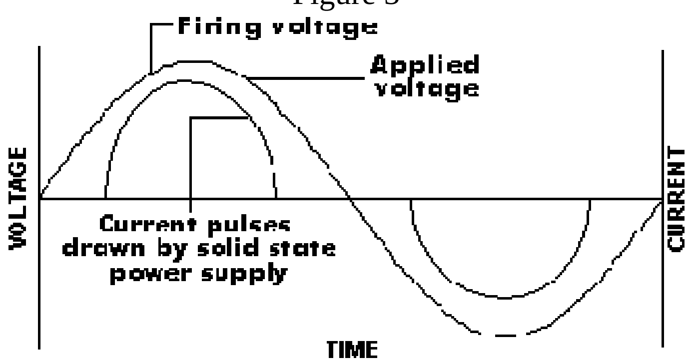
Some of our modem equipment however does not fit this category. Computers, variable frequency drives, electronic ballasts and uninterruptable power supply systems are non-linear systems. In these systems, the resistance is not a constant and in fact, varies during each sinewave. This occurs because the resistance of the device is not a constant. The resistance in fact, changes during each sinewave.

The "front end" or power supply of these systems contain solid state devices such as power transistors, Thyristors or silicon controlled rectifiers (SCRs). These devices draw current in pulses. Let's see how they work:

Non-Linear System – Computers, VFDS, Electronics Ballasts

Examine **Figure 3**. As we apply a voltage to a solid state power supply, the current drawn is (approximately) zero until a critical "firing voltage" is reached on the sinewave. At this firing voltage, the transistor (or other device) gates or allows current to be conducted. This current typically increases over time until the peak of the sinewave and decreases until the critical firing voltage is reached on the "downward side" of the sinewave. The device then shuts off and current goes to zero. The same thing occurs on the negative side of the sinewave with a second negative pulse of current being drawn. The current drawn then is a series of positive and negative pulses, and not the sinewave drawn by linear systems. Some systems have different shaped waveforms such as square waves. These types of systems are often called non-linear systems. The power supplies which draw this type of current are called switched mode power supplies. Once these pulse currents are formed, we have a difficult time analyzing their effect. Power engineers are taught to analyze the effects of sinewaves on power systems. Analyzing the effects of these pulses is much more difficult.

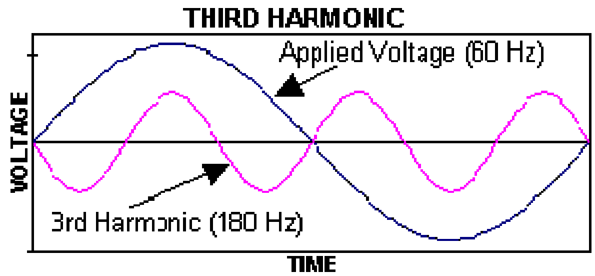
Figure 3



In order to solve this problem we turn to mathematics; specifically, Fourier Analysis. Simply stated, using Fourier analysis we can prove:

Any periodic waveform can be expressed as a series of sinewaves with varying frequencies and amplitudes.
That is, we can create a series of sinewaves of varying frequencies and amplitudes to mathematically model this series of pulses. the frequencies we use are multiples of the fundamental frequency, 60 Hertz. We call these multiple frequencies harmonics. The second harmonic is two times 60 Hertz, or 120 Hertz. The third harmonic is 180 Hertz and so on. In our three phase power systems, the "even" harmonics (second, fourth, sixth, etc.) cancel, so we only need deal with the "odd" harmonics. Refer to **Figure 4** to see what these harmonics look like.

Figure 4



This figure shows the fundamental and the third harmonic. As you can see, there are three cycles of the third harmonic for each single cycle of the fundamental. If we add these two waveforms, we get a non-sinusoidal waveform.

This resultant now starts to form the peaks that are indicative of the pulses drawn by switch mode power supplies. This resultant waveform is very similar to Figure 3. If we add in other harmonics, we can model any distorted periodic waveform, such as square waves generated by UPS of VFD systems.

It's important to remember these harmonics are simply a mathematical model. The pulses or square waves, or other distorted waveforms are what we actually see if we were to put an oscilloscope on the building's wiring systems.

These current pulses, because of Ohm's Law, will also begin to distort the voltage waveforms in the building. This voltage distortion can cause premature failure of electronic devices.

On three phase systems, the three phases of the power system are 120' out of phase. The current on phase B occurs 120 deg (1/3 cycle) after the current on A. Likewise, the current on phase C occurs 120' after the current on phase B. Because of this, our 60 Hertz (fundamental) currents actually cancel on the neutral. If we have balanced 60 Hertz currents on our three phase conductors, our neutral current will be zero. It can be shown mathematically that the neutral current (assuming only 60 Hertz is present) will never exceed the highest loaded phase conductor. Thus, our overcurrent protection on our phase conductors also protects the neutral conductor, even though we do not put an overcurrent protective device in the neutral conductor. We protect the neutral by the mathematics!

When harmonic currents are present, this math breaks down. The third harmonic of each of the three phase conductors is exactly in phase.

When these harmonic currents come together on the neutral, rather than cancel, they actually add and we can have more current on the neutral conductor than on phase conductors. Our neutral conductors are no longer protected by mathematics!

These harmonic currents create heat. This heat over a period of time, will raise the temperature of the neutral conductor. This rise in temperature can overheat the surrounding conductors and cause insulation failure. These currents also will overheat the transformer sources which supply the power system. This is the most obvious symptom of harmonics problems; overheating neutral conductors and transformers. Other symptoms include:

- Nuisance tripping of circuit breakers
- Malfunction of UPS systems and generator systems
- Metering problems
- Computer malfunctions
- Overvoltage problems

Several remedies are available to address these symptoms:

Oversizing Neutral Conductors

In three phase circuits with shared neutrals, it is common to oversize the neutral conductor up to 200% when the load served consists of non-linear loads. For example, most manufacturers of system furniture provide a #10 AWG conductor with 35 amp terminations for a neutral shared with the three #12 AWG phase conductors. In feeders that have a large amount of non-linear load, the feeder neutral conductor and panelboard bus bar should also be oversized.

Using Separate Neutral Conductors

On three phase branch circuits, another philosophy is to not combine neutrals, but to run separate neutral conductors for each phase conductor. This increases the copper use by 33%. While this successfully eliminates the addition of the harmonic currents on the branch circuit neutrals, the panelboard neutral bus and feeder neutral conductor still must be oversized.

Oversizing Transformers and Generators: The oversizing of equipment for increased thermal capacity should also be used for transformers and generators which serve harmonics-producing loads. The larger equipment contains more copper.

K-Rated Transformers

Special transformers have been developed to accommodate the additional heating caused by these harmonic currents. These types of transformers are now commonly specified for new computer rooms and computer lab facilities.

Special Transformers

There are several special types of transformer connections which can cancel harmonics. For example, the traditional delta-wye transformer connection will trap all the triplen harmonics (third, ninth, fifteenth, twenty-first, etc.) in the delta. Additional special winding connections can be used to cancel other harmonics on balanced loads. These systems also use more copper. These special transformers are often specified in computer rooms with well balanced harmonic producing loads such as multiple input mainframes or matched DASD peripherals.

Filtering

While many filters do not work particularly well at this frequency range, special electronic tracking filters can work very well to eliminate harmonics. These filters are presently relatively expensive but should be considered for thorough harmonic elimination.

Special Metering

Standard clamp-on ammeters are only sensitive to 60 Hertz current, so they only tell part of the story. New "true RMS" meters will sense current up to the kilohertz range. These meters should be used to detect harmonic currents. The difference between a reading on an old style clamp-on ammeter and a true RMS ammeter will give you. an indication of the amount of harmonic current present.

The measures described above only solve the symptoms of the problem. To solve the problem we must specify low harmonic equipment. This is most easily done when specifying electronic ballasts. Several manufacturers make electronic ballasts which produce less than 15 % harmonics. These ballasts should be considered for any ballast retrofit or any new project. Until low harmonics computers are available, segregating these harmonic loads on different circuits, different panelboards or the use of transformers should be considered. This segregation of “dirty” and “clean” loads is fundamental to electrical design today. This equates to more branch circuits and more panelboards, thus more copper usage.

Grounding Conductors: Your Safety Lifetime

Grounding conductors are required by the National Electrical code in the United States and by most other major electrical codes in the world. In the British IEE Wiring Regulations they are referred to as earthing conductors. No matter what they are called, these conductors serve the same purpose. Grounding conductors connect all of the non current carrying parts of the electrical system, or any metallic parts in the vicinity of the electrical system together. This part includes conduits, enclosures, supports and other metallic objects. This grounding system has two purposes:

1. **Safety.** The grounding conductor system provides a low impedance path for fault currents to flow. This allows the full current to be detected by overcurrent protective devices (fuses and circuit breakers), safely clearing the fault quickly.

2. **Power quality.** The grounding system allows all equipment to have the same reference voltage. This helps the facility electronic equipments operation and helps prevent the flowing of objectionable currents on communication lines, seals and other connections.

Let us examine the safety issue more closely. Consider the following system: a power system consisting of a voltage source (transformer or generator) connected to a disconnect and a panelboard. An appliance is fed from this panelboard. When the circuit is formed current flows in the circuit allowing the appliance to operate. The grounding conductor connects the frame of the appliance to be panelboard enclosure and to the service enclosure. This enclosure is connected to the grounded conductor (often neutral conductor) which in turn is connected to the grounded terminal of the transformer.

If a fault (or short circuit) occurs, the grounding conductor connection allows current to flow**.** This current will be much greater than the normal load current and will cause the circuit breaker to open quickly. This safely clears the fault and minimizes any safety hazard to personnel.

Suppose the grounding conductor is interrupted. If a fault occurs, no current will flow in the grounding conductor since the circuit is interrupted. This opened grounding conductor could be caused by a grounding prong illegally cut off a plug, a loose connection, a conduit which is not connected properly or many other causes. This fault leaves the frame of the appliance energized. When someone comes by and touches the appliance and also touches the building steel , another piping system, and possible even a wet concrete floor, the circuit will then be completed in current flow through the persons body, injuring or killing them.

Many codes allow the use of metallic conduits to be used as grounding conductors. Many designers today do not believe that using steel conduits is adequate for this use. Conduit has connections every ten feet and often low grade, cast metal couplings and connectors are used. There has been data presented in the text "Grounding" by William Summers (published by the International Association of Electrical Inspectors) which shows that for long branch circuits, the impedance of the steel conduit may limit the fault current so that the overcurrent protective device will not operate correctly. For this reason we believe that copper grounding conductors should be specified in every power circuit.

The secondary benefit of this copper grounding conductor is it will provide an equipotential plane for all equipment connected to it. This often makes the so-called isolated grounding conductors specified by computer and other manufacturers unnecessary.

Harmonic distortion: Problems and solutions

Like surfers, most electrical devices are looking for the perfect wave. For alternating current, perfection is defined by a sinusoidal (or sine) wave in which electrical voltage changes smoothly from positive polarity to negative and back again 60 times per second. Unfortunately, modern equipment is having a negative effect on the quality of this perfect wave. A variety of solid state devices, including desktop computers and other microprocessor-based devices, create high levels of harmonic distortion. Harmonic Problems

Harmonic distortion may or may not create a problem for your facility. You may have harmonics present, but experience no adverse effects. However, as harmonic levels increase, the likelihood of experiencing problems also increases. Typical problems include:

- malfunctioning of microprocessor-based equipment.
- overheating in neutral conductors. transformers, or induction motors.
- deterioration or failure of power factor correction capacitors.
- erratic operation of breakers and relays.
- pronounced magnetic fields near transformers and switchgear.

To make matters worse, harmonics can sometimes be transmitted from one facility back through the utility's equipment to neighboring businesses, especially if they share a common transformer. This means harmonics generated in your facility can stress utility equipment or cause problems in your neighbor's facility and vice versa. Electric utilities have recognized this problem and are adopting standards, like the Institute of Electrical and Electronics Engineers (IEEE) Standard 519 which defines allowable harmonic distortion at customer service entrances. This standard is designed to protect both businesses and utilities.

Solutions

There are a number of ways to deal with harmonics, but not all solutions are appropriate for a given problem. The first step in solving a harmonics problem is to carefully examine your power system and loads to define the nature, source and manifestation of the problem. EWEB's Power Quality Team can help identify harmonic distortion in your facility.

Treat Symptoms

In some cases, it's best to simply treat the symptoms. If your only problem is neutral conductor overheating, you can increase neutral conductor size. For transformer overheating, you can install special K-rated transformers designed to tolerate harmonics. You can redistribute or relocate harmonic producing loads around your facility to balance harmonics and produce a more sinusoidal waveform. A "zigzag" transformer uses phase shifting to accomplish much the same thing.

Treat Sources

Another solution involves reducing the level of harmonics produced by equipment. Impedance may be added by installing line reactors at harmonic sources. Tuned filters may be installed to eliminate specific harmonic frequencies. Both have a long track record, are reasonably priced and work effectively. This approach must be carefully implemented to avoid creating other problems, such as harmonic resonance.

Six-pulse rectified power supplies like those found in many variable frequency drives, may be replaced with twelve or higher pulse rectifiers. This solution is not likely to be cost effective unless done when the equipment is purchased.

A new class of harmonics mitigation devices injects a mirror-image waveform of the harmonic portions of the distorted waveform. By canceling out the harmonics, the waveform returns to its 60 Hertz base. This type of device--called an active harmonic filter--is based on variable speed drive technology. Active harmonic filters are relatively new and rather costly, but offer several advantages. They are inherently current limiting, have no resonance problems, are "intelligent" and adaptable, and can be configured to either correct the full spectrum of harmonics or to target specific harmonics. Although this technology is new, it has important advantages and should be watched carefully.

It is worth stressing that the particular solution for your facility must be the result of careful analysis and isolation of the problem. No harmonics mitigation strategy should be employed without first assessing the situation.

New Equipment
An ideal time to consider harmonics mitigation strategies is during the design of new facilities or at the time of equipment purchases. Harmonics producing equipment can be identified and mitigation devices installed at the equipment. Transformers and neutral conductors can be specified properly. Some variable speed drive manufacturers now offer harmonics correcting components as standard features of their drives and others offer them as factory installed options. Be sure to ask your drive representative about harmonics correction when specifying a new variable speed drive.

Help from EWEB
Harmonics are not a problem for everyone. Most facilities probably have some level of harmonic distortion, so the mere presence of harmonics does not warrant concern. However, you should be concerned when you see the problems described above. Another time to give harmonics some thought is when purchasing new equipment that is known to produce harmonics.

EWEB has information on harmonics problems and solutions. We can help you diagnose harmonics problems using our array of metering devices and troubleshooting skills.

Harmonic History

For most of the twentieth century, the predominant use of electricity for business and industry was to power motors, lights and heating devices. These uses have little effect on the 60 Hertz (cycles per second) sine waveform of the electricity delivered to them from their utility. They are called linear loads, because the current (amperage) rises and falls in proportion to the voltage wave.

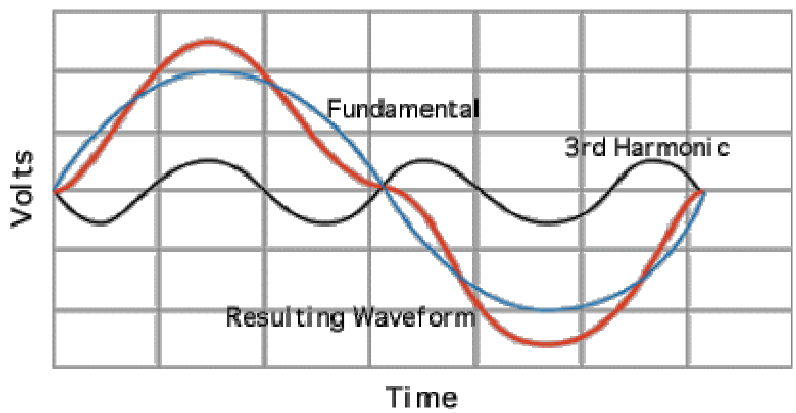
A few industries like steel mills and aluminum smelters used electricity to power arc furnaces, which distorted the waveform, because the current flow was not directly proportional to the voltage. These loads are called non-linear loads.

Non-linear loads cause waveforms that are multiples of the normal 60 Hertz sine wave to be superimposed on the base waveform. These multiples are called harmonics. For example, the second harmonic is a 120 Hertz waveform (2 times 60 Hertz), the third is a 180 Hertz waveform, and so on. The combination of the sine wave with all the harmonics creates a new, non-sinusoidal wave of entirely different shape. The change to the wave is called harmonic distortion.

In the last 20 years, there has been an explosion of microprocessor based equipment which are also non-linear loads. Examples include computer systems, variable frequency drives, AC/DC converters, electronic ballasts, X-ray machines, MRI equipment and uninterruptible power supplies.

What was once a problem for a very limited number of heavy industries, is now a concern for some smaller business, too.

Harmonics Strike a Sour Note



For most people, the word "harmonics" brings to mind something musical. If you could look at a plucked guitar string in slow motion, you would see it vibrates in several ways. First, it vibrates end to end, anchored at the head of the guitar and the bridge. This is called the fundamental. The string also vibrates as if anchored at the bridge and in the middle of the string. This vibration on top of the fundamental vibration is called the second harmonic. The frequency of the second harmonic is two times the fundamental. The frequency of the third harmonic is three times the fundamental, etc. Harmonics are superimposed on the fundamental to produce the sound we hear.

The translation to electricity is almost direct. Electricity is produced and delivered in its fundamental form as a 60 cycles per second (Hertz) sine wave. Once inside your business, certain types of equipment can superimpose harmonics on the basic sine wave. Harmonics are multiples of the 60 Hertz wave. For example, the second harmonic is at 120 Hertz, the third is at 180 Hertz, etc.

Because harmonics are superimposed on the fundamental waveform, the frequency of the electricity no longer follows a smooth sine wave. Most electrical equipment expects to see a smooth frequency and distortions created by harmonics can cause a variety of problems.

Harmonics and Total Harmonic Distortion (THD)

Harmonics in power circuits are frequencies that are integer multiples of a fundamental frequency generated by nonlinear electrical and electronic equipment. The fundamental line frequency—50 or 60 hertz (Hz)—combines with the harmonic sine waves to form repetitive, non-sinusoidal distorted wave shapes.

Total harmonic distortion (THD) is a measure of the amount of distortion produced as current flows from the power line. This line current can flow at the fundamental frequency (60 Hz in the U.S.) or it may be combined with odd harmonic currents (multiples of the fundamental) such as 180 Hz (third harmonic), 300 Hz (fifth harmonic), and 420 Hz (seventh harmonic). The THD value is the effective value of all the harmonic currents added together, compared with the value of the fundamental current. For example, 22 percent THD means that the total harmonic current is equal to 22 percent of the total 60 Hz current.

Harmonics on building power-distribution systems are a concern for a number of reasons. Since the neutral conductor has no circuit breaker protection—as do the main conductors—there is the possibility of fire. Harmonics can also cause circuit breaker tripping (with no apparent overload), overloading of power distribution transformers, and high-frequency dissipation in power factor correction capacitors. In addition, voltage waveforms can be distorted to other loads, and interference can be coupled between power and telephone lines where these lines are co-located or run together. This phenomenon is called telephone interference factor, or TIF.

What are harmonics and what cause harmonics?

Harmonics are currents or voltages with frequencies that are integer multiples of the fundamental power frequency being 50 or 60Hz (50Hz for European power and 60Hz for American power). For example, if the fundamental power frequency is 60 Hz, then the 2nd harmonic is 120 Hz, the 3rd is 180 Hz, etc. In modern test equipment today harmonics can be measured up to the 63rd harmonic. When harmonic frequencies are prevalent, electrical power panels and transformers become mechanically resonant to the magnetic fields generated by higher frequency harmonics. When this happens, the power panel or transformer vibrates and emits a buzzing sound for the different harmonic frequencies. Harmonic frequencies from the 3rd to the 25th are the most common range of frequencies measured in electrical distribution systems.

Additionally, harmonics are caused by and are the by-product of **modern electronic equipment** such as **personal or notebook computers, laser printers, fax machines, telephone systems, stereos, radios, TVs, adjustable speed drives and variable frequency drives, battery chargers, UPS, and any other**

equipment powered by switched-mode power supply (SMPS) equipment. The above-mentioned electronic SMPS equipment is also referred to as non-linear loads. This type of non-linear loads or SMPS equipment generates the very harmonics they're sensitive to and that originate right within your building or facility. SMPS equipment typically forms a large portion of the electrical non-linear load in most electrical distribution systems. There are basically two types of non-linear loads: single-phase and three-phase. Single-phase non-linear loads are prevalent in modern office buildings while three-phase non-linear loads are widespread in factories and industrial plants.

In today's environment, all computer systems use SMPS that convert utility AC voltage to regulated low voltage DC for internal electronics. These non-linear power supplies draw current in high amplitude short pulses. These current pulses create significant distortion in the electrical current and voltage wave shape. This is referred to as a harmonic distortion and is measured in Total Harmonic Distortion (THD). The distortion travels back into the power source and can effect other equipment connected to the same source.

To give an understanding of this, consider a water piping system. Have you ever taken a shower when someone turns on the cold water at the sink? You experience the effect of a pressure drop to the cold water, reducing the flow of cold water. The end result is you get burned! Now imagine that someone at a sink alternately turns on and off the cold and hot water. You would effectively be hit with alternating cold and hot water! Therefore, the performance and function of the shower is reduced by other systems. This illustration is similar to an electrical distribution system with non-linear loads generating harmonics. Any SMPS equipment will create continuous distortion of the power source that stresses the facility's electrical distribution system and power equipment.

Harmonics are generally not an issue if you do not have any electronic SMPS equipment or non-linear loads in your building or facility. However, for the remainder of this discussion, we are assuming that you do.

What problems do harmonics create?

In an electrical distribution system harmonics create:

1. Large load currents in the neutral wires of a 3 phase system. Theoretically the neutral current can be up to the sum of all 3 phases therefore causing overheating of the neutral wires. Since only the phase wires are protected by circuit breakers of fuses, this can result in a potential fire hazard.
2. Overheating of standard electrical supply transformers which shortens the life of a transformer and will eventually destroy it. When a transformer fails, the cost of lost productivity during the emergency repair far exceeds the replacement cost of the transformer itself.
3. High voltage distortion exceeding IEEE Standard 1100-1992 "Recommended Practice for Powering and Grounding Sensitive Electronic Equipment" and manufacturer's equipment specifications.
4. High current distortion and excessive current draw on branch circuits exceeding IEEE Standard 1100-1992 "Recommended Practice for Powering and Grounding Sensitive Electronic Equipment" and manufacturer's equipment specifications.

5. High neutral-to-ground voltage often greater than 2 volts exceeding IEEE Standard 1100-1992 "Recommended Practice for Powering and Grounding Sensitive Electronic Equipment."
6. High voltage and curent distortions exceeding IEEE Std. 519-1992 "Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems."
7. Poor power factor conditions that result in monthly utility penalty fees for major users (factories, manufacturing, and industrial) with a power factor less than 0.9.
8. Resonance that produces over-current surges. In comparison, this is equivalent to continuous audio feedback through a PA system. This results in destroyed capacitors and their fuses and damaged surge suppressors which will cause an electrical system shutdown.
9. False tripping of branch circuit breakers.

How do harmonics affect my site or facility?

Above we identified the problems directly affecting your electrical distribution system. In turn, these problems affect your entire site or facility in a number of different ways:

1. Voltage distortion and voltage drop as mentioned in above items #3 and #6 cause the equipment connected to the branch circuit to draw more current to maintain the power rating (watts) of the unit. The bigger the current draw from the unit, the more it produces excess heat within the unit that was not factored for by its original design. In turn, the excessive heat causes premature component level failures within the unit. Additionally, you will experience computers locking up and other operational malfunctions that are unexplainable. Think about how many times we have experienced the "no problem found" syndrome with our computers! The excessive heat produced can directly contribute to **downtime**. Therefore, downtime is identified as any event that incurs or contributes to lost productivity, lost revenues, lost savings, and more importantly lost time. As we all have heard in the business world, "Time is Money".
2. In special facilities such as call centers or data centers, the excessive heat produced due to the large concentration of monitors and PCs will also cost you money in **energy dollars**. The air computer room (CRAC) or building air conditioning system will run longer or harder, therefore requiring more energy to maintain the desired temperature.
3. Telecommunications cabling is commonly run right next to power cables. If harmonics are above normal tolerances (more than 5% THD) as outlined in IEEE Standard 519-1992, then high frequency harmonics can be induced into phone lines and data cabling. The end result is noisy phone lines and unexplained data lose or data corruption in your LAN or WAN.
4. Soon to be imposed utility regulations limiting harmonics per IEEE Standard 519-1992.

Why are harmonics unknown or untreated in electrical distribution systems?

First, one must understand that the electrical distribution system of most sites or facilities was never designed to deal with an abundance of non-linear loads. It’s a problem that has only recently begun to be recognized in the building industry. Within the last decade, the widespread use of computers and SMPS equipment is turning modern office buildings, factories, and industrial plants into high-tech computer environments. Even older buildings that are renovated are not retrofitted with modern harmonic treatment or cancellation. The end result is a building or facility unable to fully support today's technology and the high-tech problems that it brings along with it. Obviously, given the problems harmonics can cause, it is imperative that today's electrical distribution systems be designed for non-linear electronic loads, not just linear electrical loads. Unfortunately standard building codes and engineering designs do not meet the requirements of today's technology. With the advent of newer SMPS equipment the harmonic problem will continue to get worse along with inadequate facility grounding. Grounding which is another subject is mentioned here because it too is seldom addressed or considered a problem area.

How can we wire electrical distribution systems for harmonics?

These are recommended ways to wire for the harmful effects that harmonics cause. However, these recommendations only keep the electrical distribution systems **safe**. These wiring recommendations do not eliminate or cancel high levels of harmonics.

1. Use double-size neutral wires or separate neutrals for each phase.
2. Specify a separate full-size insulated ground wire rather than relying on the conduit alone as a return ground path.
3. On a branch circuit use an isolated ground wire for sensitive electronic and computer equipment.
4. Segregate sensitive electronic and computer loads on separate branch circuits all the way back to the electrical panel.
5. Run a separate branch circuit for every 10 Amps of load.
6. Install a comprehensive exterior copper ground ring and multiple deep driven ground rods as part of the grounding system to achieve 5 ohms or less resistance to earth ground.
7. Oversize phase wires to minimize voltage drop on branch circuits.
8. Shorten the distance on branch circuits from the power panel to minimize voltage drop.

How can we treat harmonics?

In order to ensure the highest "Power Quality" for your building or facility, it is necessary to treat harmonics. Harmonic treatment can be performed by two methods: filtering or cancellation. A harmonic filter consists of a capacitor bank and an induction coil. The filter is designed or tuned to the predetermined non-linear load and to filter a predetermined harmonic frequency range. Usually this frequency range only accounts for one harmonic frequency. This application is mostly used when specified for a UPS or variable frequency drive motor in a manufacturing plant.

Harmonic cancellation is performed with harmonic canceling transformers also known as phase-shifting transformers. A harmonic canceling transformer is a relatively new power quality product for mitigating harmonic problems in electrical distribution systems. This type of transformer has patented built-in electromagnetics technology designed to remove high neutral current and the most harmful harmonics from the 3^{rd} through 21^{st}. The technique used in these transformers is call "low zero phase sequencing and phase shifting". These transformers can be used to treat existing harmonics in buildings or facilities. This same application can be designed into new construction to prevent future harmonics problems.

Case Study 5 - Harmonic Distortion of Current

Environment

Office building with personal computers, terminals, copiers and other electric office equipment supplied by three-phase wye service.

Problem

Facility engineers at this site experienced repeated problems with the failure of electrical distribution equipment. A distribution transformer overheated and failed, circuit breakers were tripping and electrical connectors were burning out. These problems are all symptomatic of overload conditions.

However, initial measurements of phase currents using a true RMS ammeter showed current readings of 257 to 298 amps. These values did not exceed equipment ratings.

Measurements

The real problem started to become apparent when readings were taken of the current in the common neutral conductor. The neutral was carrying 229 amps, nearly equal to the phase currents, even though the phase loads were well balanced.

Further analysis was performed using a power monitor. *Figure 1* shows the wave form of Phase A current. The non-sinusoidal shape is due to harmonic currents typical of switching mode power supplies which are used in the majority of modern office automation equipment. These are nonlinear loads. The peak current shown here is 475 amps. If the wave form was sinusoidal, its peak current would be only 363 amps. As shown in the plot of *Figure 2* total harmonic distortion is about 32 percent, of which the third harmonic contributes about 31 percent.

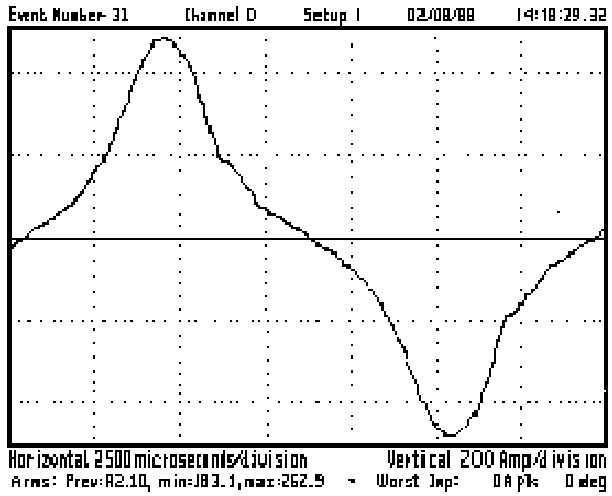


Figure 1. Non-sinusoidal Phase A current wave form caused by nonlinear loads.

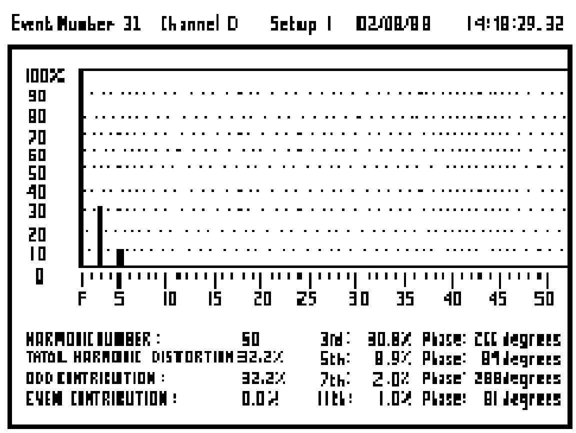


Figure 2. Plot of Phase A current harmonics showing high third harmonic content.

When phase currents are distorted to this extent, the normal three-phase cancellation, which results in near zero neutral current, does not take place. The odd harmonics produced at 180 Hz, 300 Hz and higher frequencies in the phase conductors result in large currents being carried by the neutral at predominantly 180 Hz. This is shown in Figure 3.

The net effect on facility wiring is that the common neutral conductor will frequently be carrying current beyond its rated capacity. In severe cases this can well exceed phase currents. These high frequency currents can be damaging to transformers and other devices designed to operate at 60 Hz.

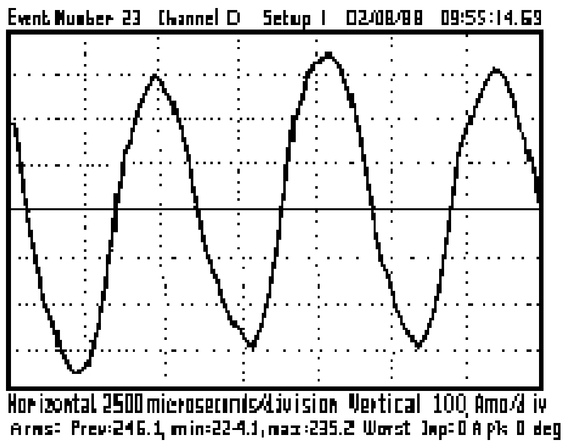


Figure 3. Common neutral current wave form showing predominance of 180 Hz, modulated by 60 Hz fundamental.

Solution

In the short term these problems can be addressed by over-sizing neutral conductors and de-rating transformers to a more conservative value of 60 percent.