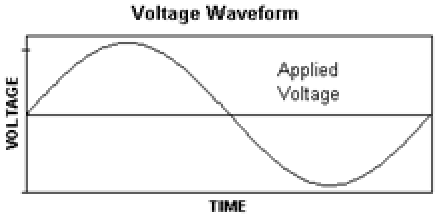
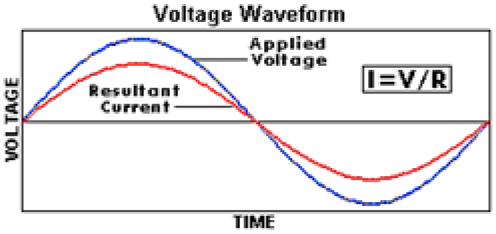
Harmonics and It’s Effects

What is Harmonics?.

- Harmonics are sinusoidal voltages or currents having frequencies that are whole multiples of the frequency at which the supply system is designed to operate (e.g. 50Hz or 60 Hz).
- 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.
- There are two important concepts to bear in mind with regard to power system harmonics.
- The first is the nature of harmonic-current producing loads (non-linear loads) and the second is the way in which harmonic currents flow and how the resulting harmonic voltages develop.
- 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. The voltage we apply across our equipment is a sine wave which operates 60 Hertz (cycles per second).



- To generate this voltage sine wave. 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 equal’s voltage divided by resistance. Expressed mathematically **I=V/R**
- Expressed graphically, the current ends up being another sine wave, 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 sine waves may not align perfectly (as a power factor) the current wave will indeed be a 60 Hertz sine wave.



- Since an applied voltage sine wave will cause a sinusoidal current to be drawn, systems which exhibit this behaviour are called linear systems. Incandescent lamps, heaters and 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 sine wave. This occurs because the resistance of the device is not a constant. The resistance in fact, changes during each sine wave

Linear and non-linear loads (motors, heaters and incandescent lamps):

- A linear element in a power system is a component in which the current is proportional to the voltage.
- In general, this means that the current wave shape will be the same as the voltage (See Figure 1). Typical examples of linear loads include motors, heaters and incandescent lamps.

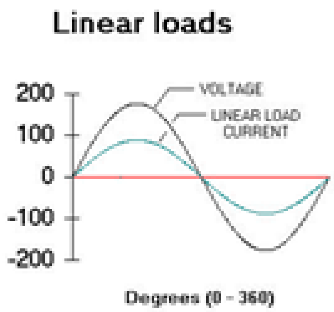


Figure 1. Voltage and current waveforms for linear

Non-Linear System (Computers, VFDS, Electronic Ballasts):

- As in Figure 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 sine wave. 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 sine wave and decreases until the critical firing voltage is reached on the "downward side" of the sine wave. The device then shuts off and current goes to zero. The same thing occurs on the negative side of the sine wave with a second negative pulse of current being drawn. The current drawn then is a series of positive and negative pulses, and not the sine wave 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 sine waves on power systems. Analyzing the effects of these pulses is much more difficult.

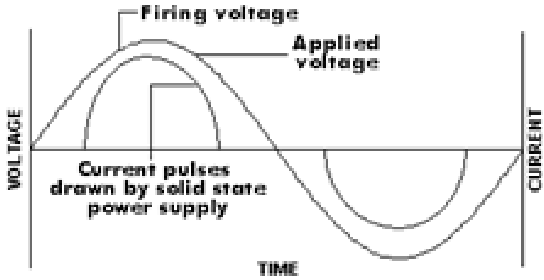


Figure 2. Voltage and current waveforms for linear

- The current drawn by non-linear loads is not sinusoidal but it is periodic, meaning that the current wave looks the same from cycle to cycle. Periodic waveforms can be described mathematically as a series of sinusoidal waveforms that have been summed together.

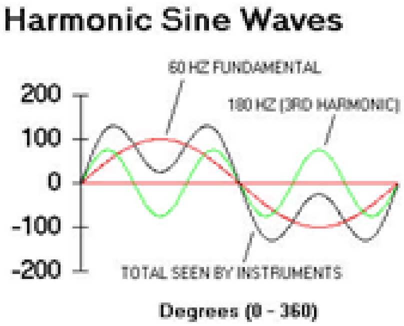


Figure 3. Waveform with symmetrical harmonic components

- The sinusoidal components are integer multiples of the fundamental where the fundamental, in the United States, is 60 Hz. The only way to measure a voltage or current that contains harmonics is to use a true-RMS reading meter. If an averaging meter is used, which is the most common type, the error can be Significant.

- Each term in the series is referred to as a harmonic of the fundamental. The third harmonic would have a frequency of three times 60 Hz or 180 Hz. Symmetrical waves contain only odd harmonics and un-symmetrical waves contain even and odd harmonics.
- A symmetrical wave is one in which the positive portion of the wave is identical to the negative portion of the wave. An un-symmetrical wave contains a DC component (or offset) or the load is such that the positive portion of the wave is different than the negative portion. An example of un-symmetrical wave would be a half wave rectifier.
- Most power system elements are symmetrical. They produce only odd harmonics and have no DC offset.

Harmonic current flow

- When a non-linear load draws current that current passes through all of the impedance that is between the load and the system source (See Figure 4). As a result of the current flow, harmonic voltages are produced by impedance in the system for each harmonic.

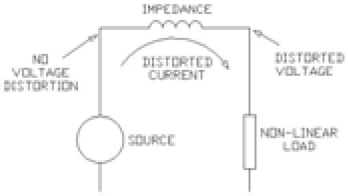


Figure 4 – Distorted-current induced voltage distortion

- These voltages sum and when added to the nominal voltage produce voltage distortion. The magnitude of the voltage distortion depends on the source impedance and the harmonic voltages produced.
- If the source impedance is low then the voltage distortion will be low. If a significant portion of the load becomes non-linear (harmonic currents increase) and/or when a resonant condition prevails (system impedance increases), the voltage can increase dramatically.

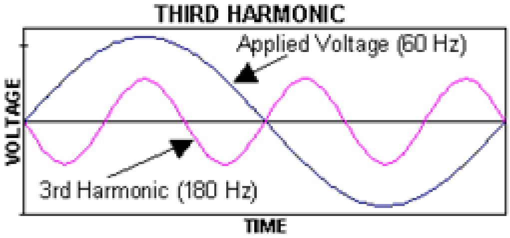
Harmonic currents can produce a number of problems:

1. Equipment heating
2. Equipment malfunction
3. Equipment failure
4. Communications interference
5. Fuse and breaker mis-operation
6. Process problems
7. Conductor heating.

How harmonics are generated

- In an ideal clean power system, **the current and voltage waveforms are pure sinusoids**. In practice, non-sinusoidal currents are available due to result of the current flowing in the load is not linearly related to the applied voltage.
- In a simple circuit containing only linear circuit elements resistance, inductance and capacitance. The current which flows is proportional to the applied voltage (at a particular frequency) so that, if a sinusoidal voltage is applied, a sinusoidal current will flow. Note that where there is a reactive element there will be a phase shift between the voltage and current waveforms the power factor is reduced, but the circuit can still be linear.
- But in The situation where the load is a simple full-wave rectifier and capacitor, such as the input stage of a typical switched mode power supply (SMPS). In this case, current flows only when the supply voltage exceeds that stored on the reservoir capacitor, i.e. close to the peak of the voltage sine wave, as shown by the shape of the load line.
- Any cyclical waveform can be de constructed into a sinusoid at the fundamental frequency plus a number of sinusoids at harmonic frequencies. Thus the distorted current waveform in the figure can be represented by the fundamental plus a percentage of second harmonic plus a percentage of third harmonic and so on, possibly up to the thirtieth harmonic.
- For symmetrical waveforms, i.e. where the positive and negative half cycles are the same shape and magnitude, all the **even numbered harmonics is zero.** Even harmonics are now relatively rare but were common when half wave rectification was widely used.

- The frequencies we use are multiples of the fundamental frequency, 60 Hz. We call these multiple frequencies harmonics. The second harmonic is two times 60 Hertz, or 120 Hz. 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.



- This figure shows the fundamental and the third harmonic. 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. If we add in other harmonics, we can model any distorted periodic waveform, such as square waves generated by UPS of VFD systems. It is 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 over current protection on our phase conductors also protects the neutral conductor, even though we do not put an over current 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:

1. Nuisance tripping of circuit breakers
2. Malfunction of UPS systems and generator systems
3. Metering problems
4. Computer malfunctions
5. Over voltage problems

Types of equipment that generate harmonics:

- Harmonic load currents are generated by all non-linear loads. These include:
- **For Single phase loads, e.g.**

1. Switched mode power supplies (SMPS)
2. Electronic fluorescent lighting ballasts
3. Compact fluorescent lamps (CFL)
4. Small uninterruptible power supplies (UPS) units

- **For Three phase loads, e.g.**

1. Variable speed drives
2. Large UPS units

Single phase loads

(A)Switched mode power supplies (SMPS)

- The majority of modern electronic units use switched mode power supplies (SMPS).
- These differ from older units in that the traditional step-down transformer and rectifier is replaced by direct controlled rectification of the supply to charge a reservoir capacitor from which the direct current for the load is derived by a method appropriate to the output voltage and current required.
- The advantage – to the equipment manufacturer – is that the size, cost and weight is significantly reduced and the power unit can be made in almost any required form factor.
- The disadvantage – to everyone else – is that, rather than drawing continuous current from the supply, the power supply unit draws pulses of current which contain large amounts of third and higher harmonics and significant high frequency components .
- A simple filter is fitted at the supply input to bypass the high frequency components from line and neutral to ground but it has no effect on the harmonic currents that flow back to the supply.

(B)Single phase UPS units exhibit very similar characteristics to SMPS.

- For high power units there has been a recent trend towards so-called power factor corrected inputs.
- The aim is to make the power supply load look like a resistive load so that the input current appears sinusoidal and in phase with the applied voltage. It is achieved by drawing input current as a high frequency triangular waveform that is averaged by the input filter to a sinusoid.
- This extra level of sophistication is not yet readily applicable to the low-cost units that make up most of the load in commercial and industrial installations. It remains to be seen what problems the wide-scale application of this technology may involve!

(C)Fluorescent lighting ballast

- Electronic lighting ballasts have become popular in recent years following claims for improved efficiency. Overall they are only a little more efficient than the best magnetic ballasts and in fact, most of the gain is attributable to the lamp being more efficient when driven at high frequency rather than to the electronic ballast itself.
- Their chief advantage is that the light level can be maintained over an extended lifetime by feedback control of the running current – a practice that reduces the overall lifetime efficiency.
- Their great disadvantage is that they generate harmonics in the supply current. So called power-factor corrected types are available at higher ratings that reduce the harmonic problems, but at a cost penalty. Smaller units are usually uncorrected.

(D)Compact fluorescent lamps (CFL)

- CFL are now being sold as replacements for tungsten filament bulbs. A miniature electronic ballast, housed in the connector casing, controls a folded 8mm diameter fluorescent tube.
- CFLs rated at 11 watt are sold as replacements for a 60 watt filament lamp and have a life expectancy of 8000 hours.
- The harmonic current spectrum is shown in the figure. These lamps are being widely used to replace filament bulbs in domestic properties and especially in hotels where serious harmonic problems are suddenly becoming common.

Three phase loads

(A)Variable Speed Drives / UPS:

- Variable speed controllers, UPS units and DC converters in general are usually based on the three-phase bridge, also known as the six-pulse bridge because there are six pulses per cycle (one per half cycle per phase) on the DC output.
- The six pulse bridge produces harmonics at 6n +/- 1, i.e. at one more and one less than each multiple of six. In theory, the magnitude of each harmonic is the reciprocal of the harmonic number, so there would be 20% fifth harmonic and 9% eleventh harmonic, etc.
- The magnitude of the harmonics is significantly reduced by the use of a twelve-pulse bridge. This is effectively two six-pulse bridges, fed from a star and a delta transformer winding, providing a 30 degrees phase shift between them.

- The 6n harmonics are theoretically removed, but in practice, the amount of reduction depends on the matching of the converters and is typically by a factor between 20 and 50. The 12n harmonics remain unchanged. Not only is the total harmonic current reduced, but also those that remain are of a higher order making the design of the filter much easier.
- Often the equipment manufacturer will have taken some steps to reduce the magnitudes of the harmonic currents, perhaps by the addition of a filter or series inductors. In the past this has led some manufacturers to claim that their equipment is ‘G5/3’ compliant. Since G5/3 is a planning standard applicable to a complete installation, it cannot be said to have been met without knowledge of every piece of equipment on the site.
- A further increase in the number of pulses to 24, achieved by using two parallel twelve-pulse units with a phase shift of 15 degrees, reduces the total harmonic current to about 4.5%. The extra sophistication increases cost, of course, so this type of controller would be used only when absolutely necessary to comply with the electricity suppliers’ limits.

Problems caused by harmonics

- Harmonic currents cause problems both on the supply system and within the installation.
- The effects and the solutions are very different and need to be addressed separately; the measures that are appropriate to controlling the effects of harmonics within the installation may not necessarily reduce the distortion caused on the supply and vice versa.
- **Harmonic problems within the installation**
- **Problems caused by harmonic currents:**

1. overloading of neutrals
2. overheating of transformers
3. nuisance tripping of circuit breakers
4. over-stressing of power factor correction capacitors
5. skin effect

- **Problems caused by harmonic voltages:**

1. voltage distortion
2. induction motors
3. zero-crossing noise
4. Problems caused when harmonic currents reach the supply

Problems caused by harmonic currents

(1) Neutral conductor over-heating

- In a three-phase system the voltage waveform from each phase to the neutral so that, when each phase is equally loaded, the°star point is displaced by 120 combined current in the neutral is zero.
- When the loads are not balanced only the net out of balance current flows in the neutral. In the past, installers (with the approval of the standards authorities) have taken advantage of this fact by installing half-sized neutral conductors. However, although the fundamental currents cancel out, the harmonic currents do not – in fact those that are an odd multiple of three times the fundamental, the ‘triple-N’ harmonics, add in the neutral.
- The third°phase currents, are introduced at 120 harmonic of each phase is identical, being three times the frequency and one-third of a (fundamental) cycle offset.
- The effective third harmonic neutral current is shown at the bottom. In this case, 70% third harmonic current in each phase results in 210% current in the neutral.
- Case studies in commercial buildings generally show neutral currents between 150% and 210% of the phase currents, often in a half-sized conductor!
- There is some confusion as to how designers should deal with this issue.
- The simple solution, where single-cored cables are used, is to install a double sized neutral, either as two separate conductors or as one single large conductor.

- The situation where multi-cored cables are used is not so simple. The ratings of multi-core cables (for example as given in IEC 60364–5-523 Table 52 and BS 7671 Appendix 4) assume that the load is balanced and the neutral conductor carries no current, in other words, only three of the four or five cores carry current and generate heat. Since the cable current carrying capacity is determined solely by the amount of heat that it can dissipate at the maximum permitted temperature, it follows that cables carrying triple-N currents must be de-rated.
- In the example illustrated above, the cable is carrying five units of current – three in the phases and two in the neutral – while it was rated for three units. It should be de-rated to about 60% of the normal rating.
- IEC 60364-5-523 Annex C (Informative) suggests a range of de-rating factors according to the triple-N harmonic current present. Figure 13 shows de-rating factor against triple-N harmonic content for the de-rating described in IEC 60364-5-523 Annex C and for the thermal method used above.

(2) Effects on transformers

- Transformers are affected in two ways by harmonics.
- **Firstly, the eddy current losses**, normally about 10% of the loss at full load, increase with the square of the harmonic number.
- In practice, for a fully loaded transformer supplying a load comprising IT equipment the total transformer losses would be twice as high as for an equivalent linear load.
- This results in a much higher operating temperature and a shorter life. In fact, under these circumstances the lifetime would reduce from around 40 years to more like 40 days! Fortunately, few transformers are fully loaded, but the effect must be taken into account when selecting plant.
- **The second effect concerns the triple-N harmonics**. When reflected back to a delta winding they are all in phase, so the triple-N harmonic currents circulate in the winding.
- The triple-N harmonics are effectively absorbed in the winding and do not propagate onto the supply, so delta wound transformers are useful as isolating transformers. Note that all other, non triple-N, harmonics pass through. The circulating current has to be taken into account when rating the transformer.

(3) Nuisance tripping of circuit breakers

- Residual current circuit breakers (RCCB) operate by summing the current in the phase and neutral conductors and, if the result is not within the rated limit, disconnecting the power from the load. Nuisance tripping can occur in the presence of harmonics for two reasons.
- Firstly, the RCCB, being an electromechanical device, may not sum the higher frequency components correctly and therefore trips erroneously.
- Secondly, the kind of equipment that generates harmonics also generates switching noise that must be filtered at the equipment power connection. The filters normally used for this purpose have a capacitor from line and neutral to ground, and so leak a small current to earth.
- This current is limited by standards to less than 3.5mA, and is usually much lower, but when equipment is connected to one circuit the leakage current can be sufficient to trip the RCCB. The situation is easily overcome by providing more circuits, each supplying fewer loads.
- **Nuisance tripping of miniature circuit breakers (MCB)** is usually caused because the current flowing in the circuit is higher than that expected from calculation or simple measurement due to the presence of harmonic currents.
- Most portable measuring instruments do not measure true RMS values and can underestimate non-sinusoidal currents by 40%.

(4) Over-stressing of power factor correction capacitors

- Power-factor correction capacitors are provided in order to draw a current with a leading phase angle to offset lagging current drawn by an inductive load such as induction motors.
- The effective equivalent circuit for a PFC capacitor with a non-linear load. The impedance of the PFC capacitor reduces as frequency rises, while the source impedance is generally inductive and increases with frequency. The capacitor is therefore likely to carry quite high harmonic currents and, unless it has been specifically designed to handle them, damage can result.
- A potentially more serious problem is that the capacitor and the stray inductance of the supply system can resonate at or near one of the harmonic frequencies (which, of course, occur at 100 Hz intervals). When this happens very large voltages and currents can be generated, often leading to the catastrophic failure of the capacitor system.

- Resonance can be avoided by adding an inductance in series with the capacitor such that the combination is just inductive at the lowest significant harmonic. This solution also limits the harmonic current that can flow in the capacitor. The physical size of the inductor can be a problem, especially when low order harmonics are present.

(5) Skin effect

- Alternating current tends to flow on the outer surface of a conductor. This is known as skin effect and is more pronounced at high frequencies.
- Skin effect is normally ignored because it has very little effect at power supply frequencies but above about 350 Hz, i.e. the seventh harmonic and above, skin effect will become significant, causing additional loss and heating. Where harmonic currents are present, designers should take skin effect into account and de-rate cables accordingly.
- Multiple cable cores or laminated busbars can be used to help overcome this problem. Note also that the mounting systems of busbars must be designed to avoid mechanical resonance at harmonic frequencies.

Problems caused by harmonic voltages

(1) voltage distortion

- Because the supply has source impedance, harmonic load currents give rise to harmonic voltage distortion on the voltage waveform (this is the origin of ‘flat topping’).
- There are two elements to the impedance: that of the internal cabling from the point of common coupling (PCC), and that inherent in the supply at the PCC, e.g. the local supply transformer.
- The distorted load current drawn by the non-linear load causes a distorted voltage drop in the cable impedance. The resultant distorted voltage waveform is applied to all other loads connected to the same circuit, causing harmonic currents to flow in them – even if they are linear loads.
- **Solution:** The solution is to separate circuits supplying harmonic generating loads from those supplying loads which are sensitive to harmonics, as shown in Figure 16. Here separate circuits feed the linear and non-linear loads from the point of common coupling, so that the voltage distortion caused by the non-linear load does not affect the linear load.
- When considering the magnitude of harmonic voltage distortion it should be remembered that when the load is transferred to a UPS or standby generator during a power failure the source impedance and the resulting voltage distortion will be much higher.
- Where local transformers are installed, they should be selected to have sufficiently low output impedance and to have sufficient capacity to withstand the additional heating, in other words, by selecting an appropriately over sized transformer.
- Note that it is not appropriate to select a transformer design in which the increase in capacity is achieved simply by forced cooling – such a unit will run at higher internal temperatures and have a reduced service life. Forced cooling should be reserved for emergency use only and never relied upon for normal running.

(2) Induction Motors

- Harmonic voltage distortion causes increased eddy current losses in motors in the same way as in transformers. However, additional losses arise due to the generation of harmonic fields in the stator, each of which is trying to rotate the motor at a different speed either forwards or backwards. High frequency currents induced in the rotor further increase losses.
- Where harmonic voltage distortion is present motors should be de-rated to take account of the additional losses.

(3) Zero-crossing noise

- Many electronic controllers detect the point at which the supply voltage crosses zero volts to determine when loads should be turned on. This is done because switching inductive loads at zero voltage does not generate transients, so reducing electromagnetic interference (EMI) and stress on the semiconductor switching devices.
- When harmonics or transients are present on the supply the rate of change of voltage at the crossing becomes faster and more difficult to identify, leading to erratic operation. There may in fact be several zero-crossings per half cycle.

(4)Harmonic problems affecting the supply

- When a harmonic current is drawn from the supply it gives rise to a harmonic voltage drop proportional to the source impedance at the point of common coupling (PCC) and the current.

- Since the supply network is generally inductive, the source impedance is higher at higher frequencies. Of course, the voltage at the PCC is already distorted by the harmonic currents drawn by other consumers and by the distortion inherent in transformers, and each consumer makes an additional contribution.

Remedies to Reduce Harmonic Problems:

(1) Over sizing 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 panel board bus bar should also be oversized.

(2) 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 panel board 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.

(3) Passive filters

- Passive filters are used to provide a low impedance path for harmonic currents so that they flow in the filter and not the supply.
- The filter may be designed for a single harmonic or for a broad band depending on requirements.
- Simple series band stop filters are sometimes proposed, either in the phase or in the neutral. A series filter is intended to block harmonic currents rather than provide a controlled path for them so there is a large harmonic voltage drop across it.
- This harmonic voltage appears across the supply on the load side. Since the supply voltage is heavily distorted it is no longer within the standards for which equipment was designed and warranted. Some equipment is relatively insensitive to this distortion, but some is very sensitive. Series filters can be useful in certain circumstances, but should be carefully applied; they cannot be recommended as a general purpose solution.

(4) Isolation transformers

- As mentioned previously, triple-N currents circulate in the delta windings of transformers. Although this is a problem for transformer manufacturers and specifiers – the extra load has to be taken into account it is beneficial to systems designers because it isolates triple-N harmonics from the supply.
- The same effect can be obtained by using a ‘zig-zag’ wound transformer. Zig-zag transformers are star configuration auto transformers with a particular phase relationship between the windings that are connected in shunt with the supply.

(5) Active Filters

- The solutions mentioned so far have been suited only to particular harmonics, the isolating transformer being useful only for triple-N harmonics and passive filters only for their designed harmonic frequency. In some installations the harmonic content is less predictable.
- In many IT installations for example, the equipment mix and location is constantly changing so that the harmonic culture is also constantly changing. A convenient solution is the active filter or active conditioner.
- The active filter is a shunt device. A current transformer measures the harmonic content of the load current, and controls a current generator to produce an exact replica that is fed back onto the supply on the next cycle. Since the harmonic current is sourced from the active conditioner, only fundamental current is drawn from the supply. In practice, harmonic current magnitudes are reduced by 90%, and, because the source impedance at harmonic frequencies is reduced, voltage distortion is reduced.

(6) 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.

(7) 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.

(8) Filtering

- While many filtersdo 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.

(9) 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 panel boards 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 panel boards, thus more copper usage.