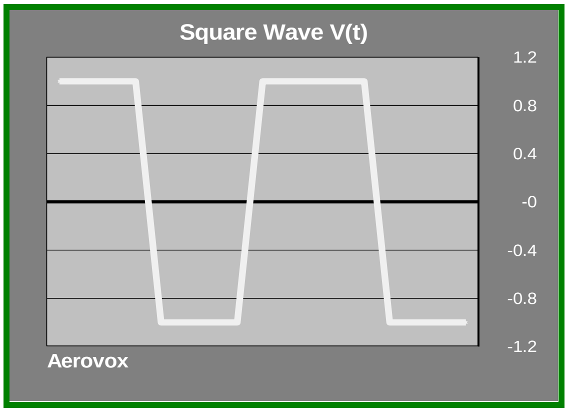
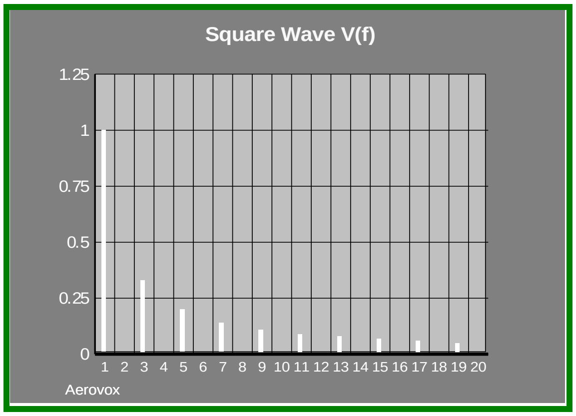
What are Harmonics?

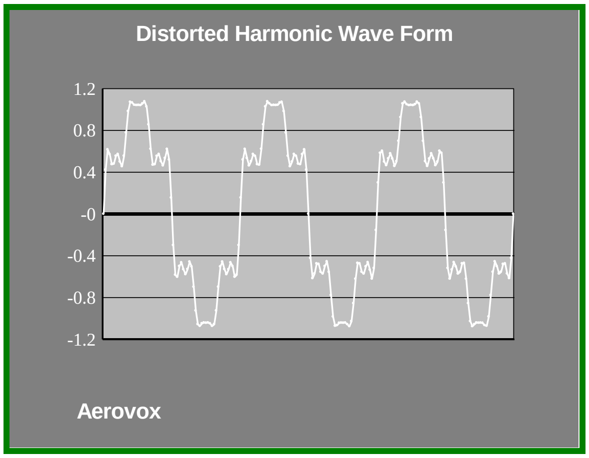
The term "harmonics" is used today to describe many power system problems. The following details some key concepts in understanding harmonic phenomena.

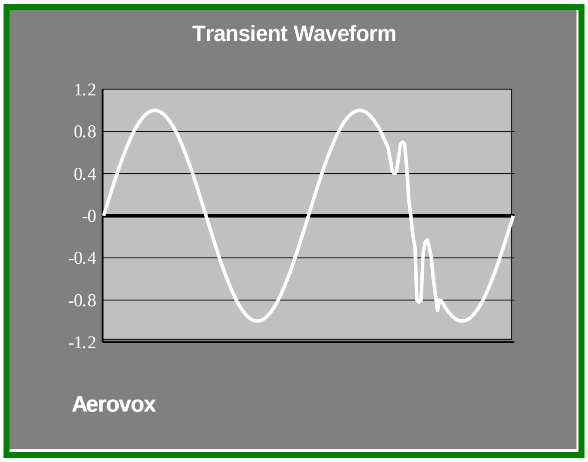
Any periodic wave can be described as a sum of sine waves with varying magnitude and frequency. This is known as a Fourier Series. Each term in the series is referred to as a harmonic of the fundamental frequency. In power systems, the fundamental frequency is 60 Hz. and the harmonics are integer multiples of 60 Hz. (180, 300, 420, etc.) Further, these waves are symmetrical about the vertical axis. One wave form that appears repeatedly in the analysis of harmonics is the square wave. Many harmonic producing loads generate voltage or current wave forms that can be closely matched with a square wave. These devices range from rectifiers to arc furnaces. The figures below illustrates a square wave in both the time and frequency domain.





It should be noted that the term "harmonics" and "transients" are often used interchangeably; however, these two terms describe two very distinct phenomena. Harmonics are steady state occurrences while transients are, as the name implies, random. The following figure illustrates the difference between the two waveforms.





Total Harmonic Distortion (THD) is the quantity that is used to give a general definition of the "quality" of the current and voltage. The greater the value of THD, the more distorted the sine wave. THD is defined as follows:

$$THD = \frac{(V_2^2 + V_3^2 + \ldots + V_n^2)^{1/2}}{V_1}$$

Where, *V_2, V_3, ...V_n = Individual RMS harmonic Voltage Components and V_1 = Fundamental frequency (60 Hz) RMS Voltage*.

Origins of Harmonics on the Power System

Harmonic distortion results from nonlinear loads in the power system. These non-linear loads can be grouped into three major categories.

1. Ferromagnetic Devices
2. Electronic Power Converters
3. Arcing Devices

The most common of these on industrial power systems is electronic power conversion equipment. Some examples of this type of equipment are listed below:

Computer Equipment
Copy Machines
Electronic Ballast's
Facsimile Machines
Adjustable Speed AC Drives
Un interruptible Power Supplies
DC Drives
DC Rectifiers

From the IEEE Standard 519, the typical current harmonic spectrum for a three phase 6-pulse converter is shown in the following table.

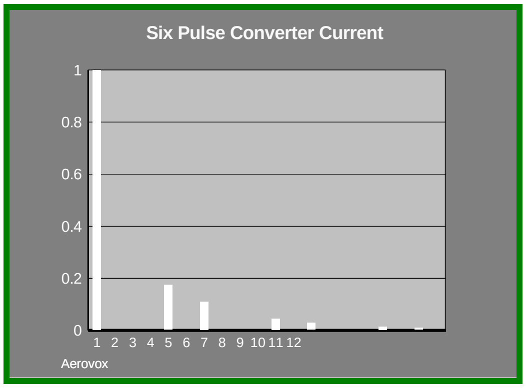


Figure 1

Harmonic	*Magnitude*
5	17.5%
7	11.1%
11	04.5%
13	02.9%
17	01.5%
19	01.0%

Table 1

Notice that there are no triplen harmonics present in a three phase connection. The typical current harmonic spectrum for single-phase inverters interfacing a dc source to an ac power system is illustrated below. Triplen harmonics are present for these loads.

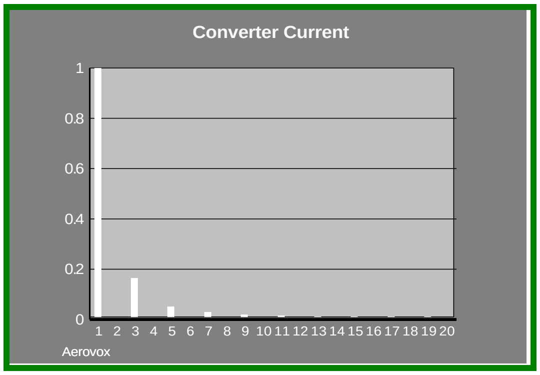


Figure 2

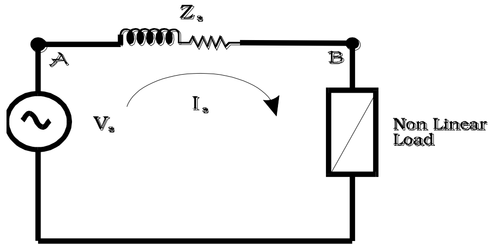
Harmonic	*Magnitude*
3	16.4%
5	05.2%
7	02.9%
9	02.0%
11	01.5%

Table 2

Relationship Between Voltage and Current Distortion

Sinusoidal voltage applied to a non linear load yields a distorted current. Likewise, a non sinusoidal voltage applied across a linear load will yield a distorted current. This illustrates a fundamental principle of non linear circuits; either one or both current and voltage may be distorted, however both cannot be sinusoidal.

Power systems are designed to have good voltage regulation at the load. This equates to the source impedance having low impedance compared to the load impedance. Therefore, voltage distortion in most systems is slight (even though it may be above acceptable limits). The following figure illustrates this principle. The power system source V_s is assumed to be an ideal voltage source (Impedance ≈ 0). Therefore there is no voltage distortion at "A". The source supplies power through the distribution network represented by the impedance, Z_s.



EPower Factor

Relationship Between Voltage and Current Distortion (continued)

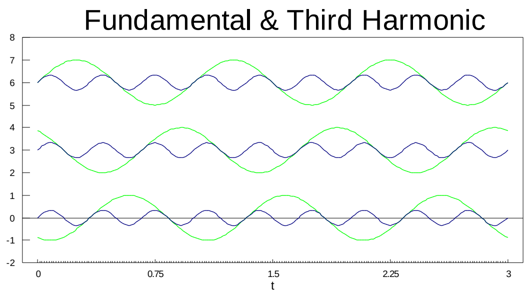
The resulting distorted current through this impedance causes the voltage to be distorted at "B". The amount of voltage distortion is dependent upon the value of Z_s and current magnitude.

The effects of harmonic producing loads are greatly dependent upon the power system characteristics. The presence of harmonic producing loads alone is not a definite indication that there will be an adverse effect to the power system or other connected loads.

Effects of Current Distortion

Although harmonic currents may not directly affect other power system loads connected to the system if the voltage distortion is low, they may have a severe effect on power delivery elements connecting these loads to the power system. This is especially true for distribution feeders providing power to single phase harmonic producing loads. The following figure illustrates such a system.

The majority of single phase loads are connected line to neutral. Under conditions where the loads are linear, a balanced three phase load consisting of 60 HZ current, would be delivered by the transformer secondary resulting in insignificant neutral currents. However when these loads are non linear, such as computers or any office equipment which uses a switch mode power supply, the current contains significant amounts of third order harmonic distortion (180 Hz.). These triplen or zero sequence currents add in the neutral. The figure below illustrates this principle. Under balanced conditions, 60 Hz. three phase currents 120° apart equate to zero. However, 180 Hz currents 120° apart are added together.



Transformers used in these applications are subjected to severe operating conditions which could result in premature failure. Hysteresis, eddy current, and stray losses in the iron core increase dramatically with harmonic currents present. Additional heating occurs due to the triplen harmonic current becoming trapped within the delta winding. Further the neutral conductor used in these circuits is normally sized equal to phase conductors in order to meet code requirements which would accommodate worst case conditions for linear loads where one phase is fully loaded and the other two unloaded. Also, no overload protection is provided on the neutral conductor since this protection would normally be provided by the protection on the phase conductors. The net result is that the neutral conductor can be significantly overloaded and unprotected leading to catastrophic failure. Other effects of zero sequence harmonics include the following:

- High neutral to ground voltage
- High peak phase current
- High average phase current
- High THD of voltage and current
- Low Power Factor
- Telephone Interference
- Increased apparatus vibration
- Electronic device malfunction

Capacitor Installation and Harmonics

As discussed, harmonics are multiples of the fundamental frequency distortions found in electrical power, subjected to continuous disturbances. In a 60 Hz electrical system, 300 Hz is the 5th harmonic, 420 Hz is the 7th harmonic, and so on. These harmonics are created by the increased use of non-linear devices such as UPS systems, solid state variable speed motor drives, rectifiers, welders, arc furnaces, fluorescent ballasts, and personal computers. The source of these harmonics may be internal or external. Individual harmonic frequencies will vary in amplitude and phase angle, depending on the harmonic source. Variable speed drives are usually referred to by the number of rectifiers in the system. The most common are six (rectifiers) and twelve (rectifiers) pulse drives.

Harmonic Resonance occurs when the capacitor reactance and the system reactance are equal. If this occurs, large harmonic currents will circulate between transformer and capacitor. These currents will result in greater voltage distortion. This provides a higher voltage across the capacitor and potentially harmful currents through all capacitor equipment. Harmonic resonance may occur at any frequency but the 5th, 7th, 11 th and 13th are the frequencies with which we are most concerned. If total bus load exceeds 15,20% of harmonic generation load, the potential for a resonance condition is high.

Some indicators of resonance are overheating, frequent circuit breaker tripping, unexplained fuse operation, capacitor failure, electronic equipment malfunction, flicking lights and telephone interference.

Conquering Harmonic Resonance can be accomplished by:

(1) Adding or subtracting capacitance from the system to move the parallel resonance frequency to one that is not deleterious;

(2) Adding tuned harmonic suppression reactors in series with the capacitor to prevent resonance

(3) Altering the size of non-linear devices. It is important that the tuned frequency, for the 5th harmonic, be at approximately the 4.7th harmonic to account for tolerance in manufacturing and to remove the largest offending portion of the 5th harmonic. Parallel resonance will occur around the 4th harmonic, at a much lower amplitude and in an area that does no harm to the system or capacitor. Tuning lower than 282 Hz is not efficient in removing large portions of the offending harmonic.

Considerations of how power factor correction capacitors affect a system are of utmost importance. In systems with more than 5-20% of harmonic loads, a harmonic survey should be performed to indicate potential problem areas. Readings taken over changing load conditions at potential capacitor locations are most useful in determining the types of systems best employed to accomplish the ultimate harmonic suppression, power factor improvement, KVA reduction and other goals.

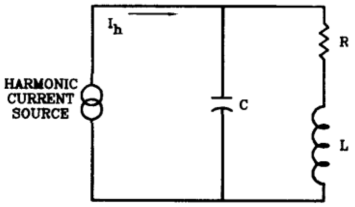
Applying Power Factor Correction in a Harmonic Environment

The use of capacitors has long been accepted as the most practical solution to low power factor problems in power systems. Modem capacitors are a reliable, maintenance free, inexpensive source of VAR's needed in inductive circuits to synchronize the voltage and current waveforms. In the past, the application of capacitors was straightforward; all that was required was a knowledge of KW (or KVA), existing power factor and target power factor. In recent years, however, this practice has been complicated by the proliferation of nonlinear loads.

The Source of the Problem One of the most widely used solid state motor controls is the six-pulse drive. These devices represent non-linear impedance to the power source, drawing a quasi-square wave alternating current rich in harmonics. For six-pulse drives, the characteristic harmonics are: 5, 7, 11, 13, 17, 19.... the higher order harmonics are not usually troublesome because their magnitude is progressively smaller.

Harmonic Resonance

When a capacitor bank is added to a power system, it is effectively connected in parallel with the system's impedance which is primarily inductive. As far as the harmonic source is concerned, it sees a capacitor in parallel with an inductor. This figure shows the model circuit for this system on a per phase basis. Resistor 'R' represents the inevitable system losses.



Understanding Harmonics

Harmonics are multiples of the fundamental frequency distortions found in electrical power, subjected to continuous disturbances. In a 60 Hz electrical system, 300 Hz is the 5th harmonic, 420 Hz is the 7th harmonic, and so on. These harmonics are created by the increased use of non-linear devices such as UPS systems, solid state variable speed motor drives, rectifiers, welders, arc furnaces, fluorescent ballasts, and personal computers. The source of these harmonics may be internal or external. Individual harmonic frequencies will vary in amplitude and phase angle, depending on the harmonic source. Variable speed drives are usually referred to by the number of rectifiers in the system. The most common are six (rectifiers) and twelve (rectifiers) pulse drives.

Harmonic Resonance occurs when the capacitor reactance and the system reactance are equal. If this occurs, large harmonic currents will circulate between transformer and capacitor. These currents will result in greater voltage distortion. This provides a higher voltage across the capacitor and potentially harmful currents through all capacitor equipment. Harmonic resonance may occur at any frequency but the 5th, 7th, 11th and 13th are the frequencies with which we are most concerned. If total bus load exceeds 15,20% of harmonic generation load, the potential for a resonance condition is high. Some indicators of resonance are overheating, frequent circuit breaker tripping, unexplained fuse operation, capacitor failure, electronic equipment malfunction, flicking lights and telephone interference.

Conquering Harmonic Resonance can be accomplished by:

(1) adding or subtracting capacitance from the system to move the parallel resonance frequency to one that is not deleterious;

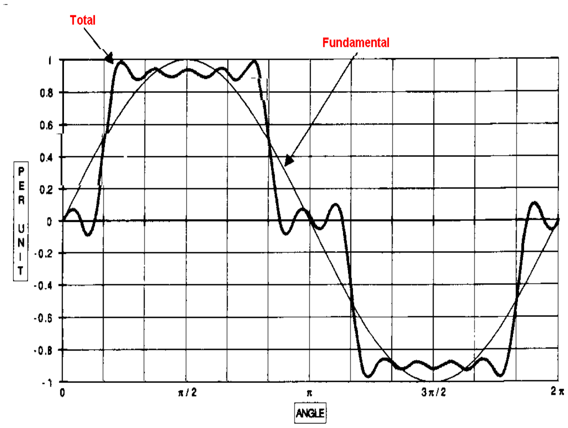
(2) Adding tuned harmonic suppression reactors in series with the capacitor to prevent resonance; (3) altering the size of non-linear devices. It is important that the tuned frequency, for the 5th harmonic, be at approximately the 4.7th harmonic to account for tolerance in manufacturing and to remove the largest offending portion of the 5th harmonic. Parallel resonance will occur around the 4th harmonic, at a much lower amplitude and in an area that does no harm to the system or capacitor. Tuning lower than 282 Hz is not efficient in removing large portions of the offending harmonic.

Considerations of how power factor correction capacitors affect a system are of utmost importance. In systems with more than 5-20% of harmonic loads, a harmonic survey should be performed to indicate potential problem areas. Readings taken over changing load conditions at potential capacitor locations are most useful in determining the types of systems best employed to accomplish the ultimate harmonic suppression, power factor improvement, KVA reduction and other goals.

Applying Power Factor Correction in a Harmonic Environment

The use of capacitors has long been accepted as the most practical solution to low power factor problems in power systems. Modem capacitors are a reliable, maintenance free, inexpensive source of VAR's needed in inductive circuits to synchronize the voltage and current waveforms.

In the past, the application of capacitors was straightforward; all that was required was a knowledge of KW (or KVA), existing power factor and target power factor. In recent years, however, this practice has been complicated by the proliferation of nonlinear loads.



The Source of the Problem One of the most widely used solid state motor controls is the six-pulse drive. These devices represent a non-linear impedance to the power source, drawing a quasi-square wave alternating current rich in harmonics. For six-pulse drives, the characteristic harmonics are: 5, 7, 11, 13, 17, 19.... the higher order harmonics are not usually troublesome because their magnitude is progressively smaller.

When a capacitor bank is added to a power system, it is effectively connected in parallel with the system's impedance which is primarily inductive. As far as the harmonic source is concerned, it sees a capacitor in parallel with an inductor. The figure below shows the model circuit for this system on a per phase basis. Resistor 'R' represents the inevitable system losses. The harmonic source is represented as a constant current source, since it behaves as such.

Since the capacitive (Xc) and inductive (V reactance are frequency dependent (as frequency increases, XC decreases and XL increases), there is a frequency at which these two parameters will be equal; this frequency is called the system's natural resonant frequency.

At this frequency, the system's impedance appears to the harmonic source to be very large, therefore, a harmonic current at the resonant frequency flowing through this impedance will result in a very large harmonic voltage as derived by Ohm's Law ($V_h = I_h Z_h$)

A large harmonic voltage will in turn result in a much larger harmonic current exchange between the capacitor bank and the system impedance This secondary harmonic current may be many orders of magnitude large than the generated harmonic current, resulting in nuisance operation of circuit breakers or fuses that happen to be in the path of this current. The degree of magnification is determined by the system resistance.

Since the generated harmonic current is considered to be constant for a given frequency, then the harmonic voltage will be proportional to the impedance. Consequently, the frequency response of the impedance is a good indication of the system's susceptibility to harmonic resonance.

Where: h = harmonic order KVA_{sc} : available short circuit at point of capacitor bank installation

KVAR =capacitor bank size

$$h = \sqrt{\frac{KVA_{sc}}{KVAR}}$$

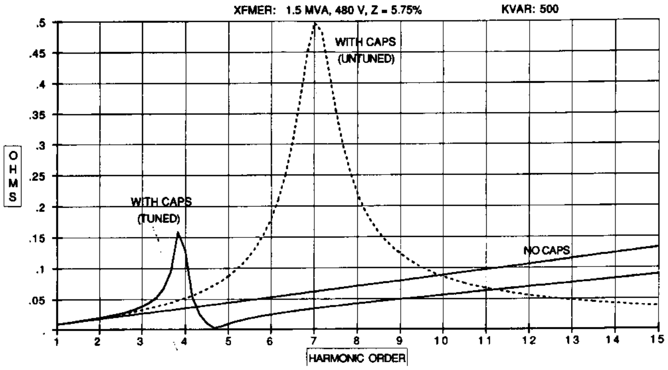
This calculation, even though it does not take into account upstream system impedance, is reasonably accurate for most applications since the bulk of the impedance is contributed by the transformer itself.

Detuning the Circuit

The most effective solution to this problem consists of series tuning the capacitor bank to the lowest offending harmonic, usually the 5th. This is done by introducing an inductor in series with the capacitor.

The impedance versus frequency plot, as seen by the harmonic source, is shown in figure 6; the original impedance response (un-tuned) is shown for comparison.

The minimum impedance occurs at the series resonant point, the 4.7th harmonic, while the peak represents a parallel resonance due to the capacitor and the two inductors. Harmonic currents generated at or near the series resonant frequency (such as the 5th) will flow to the trap harmlessly, provided the capacitor and reactor are sized properly to withstand the additional stresses. These currents are simply following the path of least impedance. The system will not resonate above this frequency since it is inductive.



This approach will accomplish two objectives. %in the line side of the capacitor filter bank, system power factor is corrected and harmonic voltage distortion is reduced, Harmonic voltage (V_h) is the result of a harmonic current Oh) flowing through the system impedance (Z_h), i.e. Ohm's Law ($V_h = I_h Z_h$)- By reducing the system impedance (Zh) we can reduce the harmonic voltage (V_h) even though the harmonic current (I_h) remains the same.

When the main objective is to reduce harmonic distortion, the engineer will consider the use of more filter stages, each tuned to the next higher harmonic (7th, 1 1th, . . .). In some cases, where harmonic currents are excessive, the use of capacitors rated at the next higher voltage may be required.

EPower Factor can perform such a study if required and will design the appropriate Power Factor correction for a given harmonic environment.

END