HARMONICS - Understanding the Facts

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Abstract

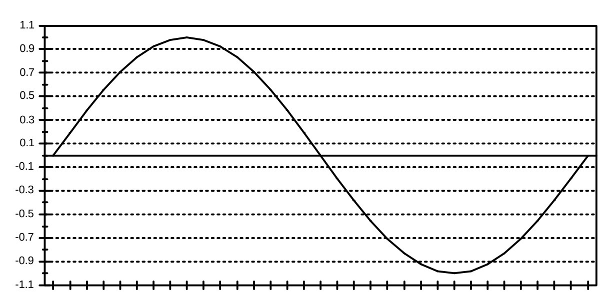
Understanding what is important to know about harmonics can be challenging for those without extensive electrical engineering backgrounds. In this two part series of articles, the first article will help to clarify what those important facts are, and the second will help tell when to raise the flag.

What is a Harmonic

The typical definition for a harmonic is “a sinusoidal component of a periodic wave or quantity having a frequency that is an integral multiple of the fundamental frequency.” [1]. Some references refer to “clean” or “pure” power as those without any harmonics. But such clean waveforms typically only exist in a laboratory. Harmonics have been around for a long time and will continue to do so. In fact, musicians have been aware of such since the invention of the first string or woodwind instrument. Harmonics (called “overtones” in music) are responsible for what makes a trumpet sound like a trumpet, and a clarinet like a clarinet.

Electrical generators try to produce electric power where the voltage waveform has only one frequency associated with it, the fundamental frequency. In the North America, this frequency is 60 Hz, or cycles per second. In European countries and other parts of the world, this frequency is usually 50 Hz. Aircraft often uses 400 Hz as the fundamental frequency. At 60 Hz, this means that sixty times a second, the voltage waveform increases to a maximum positive value, then decreases to zero, further decreasing to a maximum negative value, and then back to zero. The rate at which these changes occurs is the trigometric function called a sine wave, as shown in figure 1. This function occurs in many natural phenomena, such as the speed of a pendulum as it swings back and forth, or the way a string on a voilin vibrates when plucked.

Figure 1. Sine Wave



The frequency of the harmonics are different, depending on the fundamental frequency. For example, the 2nd harmonic on a 60 Hz system is 2*60 or 120 Hz. At 50Hz, the second harmonic is 2* 50 or 100Hz. 300Hz is the 5th harmonic in a 60 Hz system, or the 6th harmonic in a 50 Hz system. Figure 2 shows how a signal with two harmonics would appear on an oscilloscope-type display, which some power quality analyzers provide.

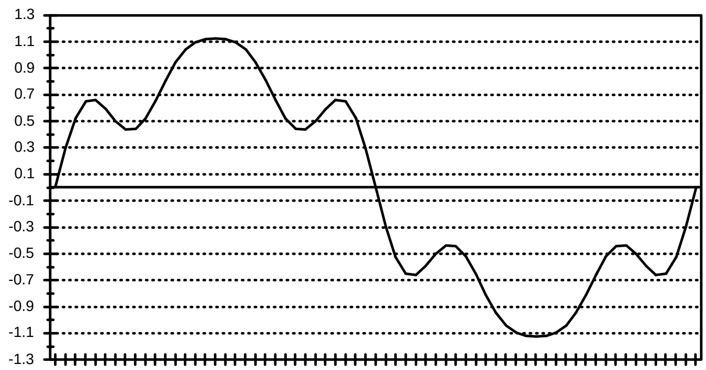


Figure 2. Fundamental with two harmonics

In order to be able to analyze complex signals that have many different frequencies present, a number of mathematical methods were developed. One of the more popular is called the Fourier Transform. However, duplicating the mathematical steps required in a microprocessor or computer-based instrument is quite difficult. So more compatible processes, called the FFT for Fast Fourier Transform, or DFT for Discrete Fourier Transform, are used. These methods only work properly if the signal is composed of only the fundamental and harmonic frequencies in a certain frequency range (called the Nyquist frequency, which is one-half of the sampling frequency). The frequency values must not change during the measurement period. Failure of these rules to be maintained can result in mis-information.

For example, if a voltage waveform is comprised of 60 Hz and 200 Hz signals, the FFT cannot directly see the 200 Hz. It only knows 60, 120, 180, 240,..., which are often called “bins”. The result would be that the energy of the 200 Hz signal would appear partially in the 180Hz bin, and partially in the 240 Hz bin. An FFT-based processer could show a voltage value of 115V at 60 Hz, 18 V at the 3rd harmonic, and 12 V at the 4th harmonic, when it really should have been 30 V at 200 Hz.

These in-between frequencies are called “interharmonics”. There is also a special category of interharmonics, which are frequency values less than the fundamental frequency value, called sub-harmonics. For example, the process of melting metal in an electric arc furnace can result large currents that are comprised of the fundamental , interharmonic, and subharmonic frequencies being drawn from the electric power grid. These levels can be quite high during the melt-down phase, and usually effect the voltage waveform.

Why Worry About Them

The presence of harmonics does not mean that the factory or office cannot run properly. Like other power quality phenomena, it depends on the “stiffness” of the power distribution system and the susceptability of the equipment. As shown below, there are a number of different types of equipment that can have misoperations or failures due to high harmonic voltage and/or current levels. In addition, one factory may be the source of high harmonics but able to run properly. This harmonic pollution is often carried back onto the electric utility distribution system, and may effect facilities on the same system which are more susceptible.

Some typical types of equipment susceptible to harmonic pollution include:

- Excessive neutral current, resulting in overheated neutrals. The odd triplen harmonics in three phase wye circuits are actually additive in the neutral. This is because the harmonic number multiplied by the 120 degree phase shift between phases is a integer multiple of 360 degrees. This puts the harmonics from each of the three phase legs “in-phase” with each other in the neutral, as shown in Figure 3.

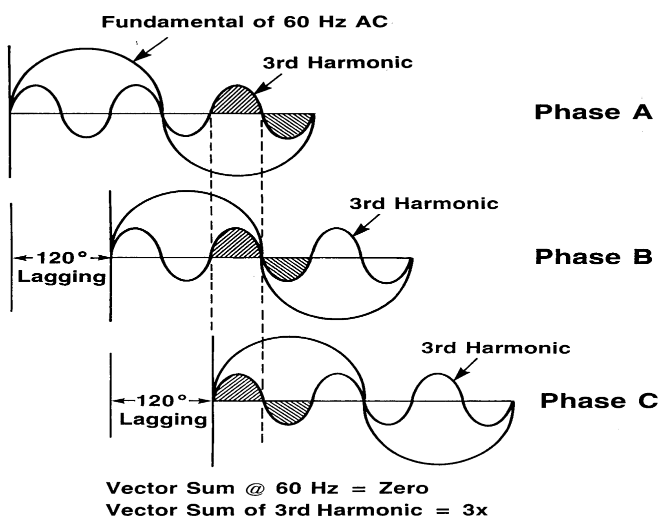


Figure 3. Additive Third Harmonics.

- Incorrect reading meters, including induction discW-hr meters and averaging type current meters.

- Reduced true PF, where PF= Watts/VA.

- Overheated transformers, especially delta windings where triplen harmonics generated on the load side of a delta-wye transformer will circulate in the primary side. Some type of losses go up as the square of harmonic value (such as skin effect and eddy current losses).   This is also true for solenoid coils and lighting ballasts.

- Zero, negative sequence voltages on motors and generators. In a balanced system, voltage harmonics can either be positive (fundamental, 4th, 7th,...), negative (2nd, 5th, 8th...) or zero (3rd, 6th, 9th,...) sequencing values. This means that the voltage at that particular frequency tries to rotate the motor forward, backward, or neither (just heats up the motor), respectively. There is also heating from increased losses as in a transformer.

HARMONIC	FUND	2ND	3RD	4TH	5TH	6TH	7TH	ETC
SEQUENCE	+	-	0	+	-	0	+	.....

Table 3. Harmonic Sequencing Values in Balanced Systems.

- Nuisance operation of protective devices, including false tripping of relays and failure of a UPS to transfer properly, especially if controls incorporate zero-crossing sensing circuits.

- Bearing failure from shaft currents through uninsulated bearings of electric motors.

- Blown-fuses on PF correction caps, due to high voltage and currents from resonance with line impedance.

- Mis-operation or failure of electronic equipment

- If there are voltage subharmonics in the range of 1-30Hz, the effect on lighting is called flicker. This is especially true at 8.8Hz, where the human eye is most sensitive, and just 0.5% variation in the voltage is noticeable with some types of lighting.
[2]

Where They Come From

How this electricity is used by the different type of loads can have an effect on “purity” of the voltage waveform. Some loads cause the voltage and current waveforms to lose this pure sine wave appearance and become distorted. This distortion may consist of predominately harmonics, depending on the type of load and system impedances. Since this article is about harmonics, we will concentrate on those types of sources.

“The main sources of harmonic current are at present the phase angle controlled rectifiers and inverters.” [3] These are often called static power converters. These devices take AC power and convert it to another form, sometimes back to AC power at the same or different frequency, based on the firing scheme. The firing scheme refers to the controlling mechanism that determines how and when current is conducted. One major variation is the phase angle at which which conduction begins and ends.

A typical such converter is the switching-type power supplies found in most personal computers and peripheral equipment, such as printers. While they offer many benefits in size, weight and cost, the large increase of this type of equipment over the past fifteen years is largely responsible for the increased attention to harmonics.

Figure 4 shows how a switching-type power supply works. The AC voltage is converted into a DC voltage, which is further converted into other voltages that the equipment needs to run. The rectifier consists of semi-conductor devices (such as diodes) that only conduct current in one direction. In order to do so, the voltage on the one end must be greater than the other end. These devices feed current into a capacitor, where the voltage value on the cap at any time depends on how much energy is being taken out by the rest of the power supply.

Figure 4. Typical Switching Power Supply.

When the input voltage value is higher than voltage on the capacitor, the diode will conduct current through it. This results in a current waveform as shown in Figure 5, and harmonic spectrum in Figure 6. Obviously, this is not a pure sinoidal waveform with only a 60 Hz frequency component.

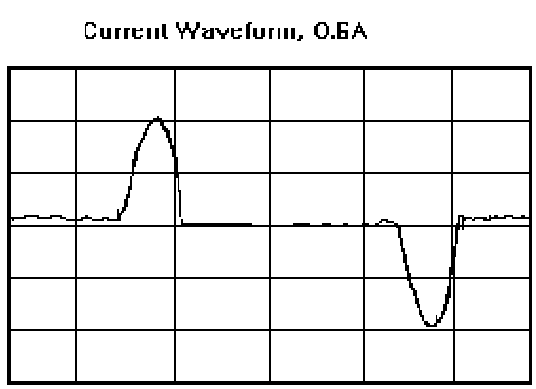


Figure 5. Current Waveform

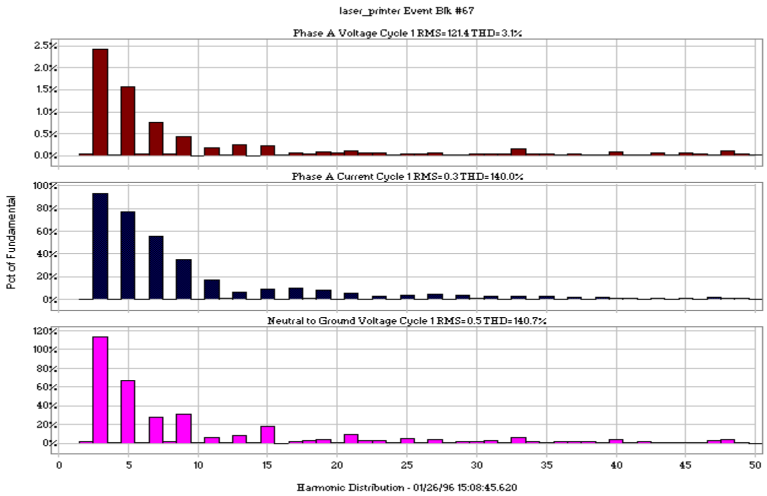


Figure 6. Harmonic Spectrum of Current Waveform Shown in Figure 5.

If the rectifier had only been a half wave rectifier, the waveform would only have every other current pulse, and the harmonic spectrum would be different, as shown in Figure 7.

Figure 7. Harmonic Spectrum of Half-Wave Rectifier.

Fluorescent lights can be the source of harmonics, as the ballasts are non-linear inductors. The third harmonic is the predominate harmonic in this case. (See Table 3) As previously mentioned, the third harmonic current from each phase in a four-wire wye or star system will be additive in the neutral, instead of cancelling out Some of the newer electronic ballasts have very significant harmonic problems, as they operate somewhat like a switching power supply, but can result in current harmonic distortion levels over 30%.

Harmonic # (Current)	Percent of Fundamental
2	4%
3	20%
4	1%
5	10%
6	1%

7	5%
9	6%

Table 3. Sample of Harmonic Values for Fluorescent lighting [4].

Low power, AC voltage regulators for light dimmers and small induction motors adjust the phase angle or point on the wave where conduction occurs. Medium power converters are used for motor control in manufacturing and railroad applications, and include such equipment as ASDs (adjustable speed drives) and VFDs (variable frequency drives). Metal reduction operations, like electric arc furnaces, and high voltage DC transmission employ large power converters, in the 2-20MVA rating.

This type of 3-phase equipment may also cause other types of power quality problems. When the semiconductor device is suppose to turn-off, it does not do so abruptly. This happens under “naturally” commutated conditions, where the voltage that was larger on the anode side compared to the cathode is now the opposite. This occurs each cycle as the voltage waveform goes through the sine waveform. It also happens under “forced” commutation conditions, where the semi-conductor device has a “gate”-type control mechanism built in to it. This commutation period is a time when two semi-conductor devices are both conducting current at the same time, effectively shorting one phase to the other and resulting in large current transients.

When transformers are first energized, the current drawn is different from the steady state condition. This is caused by the inrush of the magnetizing current. The harmonics during this period varies over time. Some harmonics have zero value for part of the time, and then increase for a while before returning to zero. An unbalanced transformer (where either the output current, winding impedance, or input voltage on each leg are not equal) will cause harmonics, as will overvoltage saturation of a transformer.

Where to look for them

Wherever the aforementioned equipment is used, one can suspect that harmonics are present. The amount of voltage harmonics will often depend on the amount of harmonic currents being drawn by the load, and the source impedance, which includes all of the wiring and transformers back to the source of the electricity. Ohm’s Law says that Voltage equals Current multipled by Impedance. This is true for harmonic values as well. If the source harmonic impedance is very low (often referred to as a “stiff” system) then the harmonic currents will result in lower harmonic voltages than if the source impedance were high (such as found with some types of isolation transformers).

Like any power quality investigation, the search can begin at the equipment effected by the problem or at the point-of-common-coupling (PCC), where the utility service meets the building distribution system. If only one piece of equipment is effected (or suspected), it is often easier to start the monitoring process there. If the source is suspected to be from the utility service side (such is the case when there is a neighboring factory that is known to generate high harmonics), then monitoring usually begins at the PCC.

The phase voltages and currents, as well as the neutral-to-ground voltage and neutral current should be monitored, where possible. This will aid in pinpointing problems, or detecting marginal systems. Monitoring the neutral will often show a high 3rd harmonic value, indicating the presence of non-linear loads in the facility.

How do you find them

Hand-held harmonic meters can be useful tools for making spot checks for known harmonic problems. However, harmonic values will often change during the day, as different loads are turned on and off within the facility or in other facilities on the same electric utility distribution system. This requires the use of a harmonic monitor or power quality monitor with harmonic capabilities (such as shown in Figure 8), which can record the harmonic values over a period of time.

Figure 8. Power Quality Monitor with Harmonic Analysis

Typically, monitoring will last for one business cycle. A business cycle is how long it takes for the normal operation of the plant to repeat itself. For example, if a plant runs three identical shifts, seven days a week, then a business cycle would be eight hours. More typically, a business cycle is one week, as different operations take place on a Monday, when the plant equipment is restarted after being off over the weekend, then on a Wednesday, or a Saturday, when only a skelton crew may be working.

Certain types of loads also generate typical harmonic spectrum signatures, that can point the investigator towards the source. This is related to the number of pulses, or paths of conduction. The general equation is $h = (n * p) +/- 1$, where h is the harmonic number, n is any integer (1,2,3,..) and p is the number of pulses in the circuit, and the magnitude decreases as the ration of 1/h (1/3, 1/5, 1/7, 1/9,...). Table 4 shows examples of such.

Type of device	Number of pulses	Harmonics present
half wave rectifier	1	2,3,4,5,6,7....
full wave rectifier	2	3,5,7,9,...
three phase, full wave	6	5,7, 11,13, 17,19,...
(2) three phase, full wave	12	11,13, 23,25, 35,37,...

Table 4. Typical Harmonics Found for Different Converters.

When are they a problem

Most electrical loads (except half-wave rectifiers) produce symmetrical current waveforms, which means that the positive half of the waveform looks like a mirror image of the negative half. This results in only odd harmonic values being present. Even harmonics will disrupt this half-wave symmetry. The presence of these even harmonics should cause the investigator to suspect there is a half-wave rectifier on the ciruit. This also result from a full wave rectifier when one side of the rectifier has blown or damaged components. Early detection of this condition in a UPS system can prevent a complete failure when the load is switched onto back-up power.

To determine what is normal or acceptable levels, a number of standards have been developed by various organizations. ANSI/IEEE C57.110 Recommended Practice for Establishing Transformer Compatibility When Supplying Nonsinusoidal Load Currents is a useful document for determining how much a transformer should be derated from its nameplate rating when operating in the presence of harmonics. There are two parameters typically used, called K-factor and TDF (transformer derating factor). Some power quality harmonic monitors will automatically calculate these values.

IEEE 519-1992 Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems provides guidelines from determining what are acceptable limits. The harmonic limits for current depend on the ratio of Short Circuit Current (SCC) at PCC (or how stiff it is) to average Load Current of maximum demand over 1 year, as illustrated in Table 5. Note how the limit decreases at the higher harmonic values, and increases with larger ratios.

RATIO Iscc / I load	Harmonic Range	Limit as % of Fundamental
Less than 20	Odd numbers less than 11	4.0 %

Between 20 and 50	Odd numbers less than 11	7.0 %
Greater than 1000	Odd numbers greater than 35	1.4%

Table 5. Current Harmonic Limits as per IEEE 519-1992.

For voltage harmonics, the voltage level of the system is used to determine the limits, as shown in Table 6. At the higher voltages, more customers will be effective, hence, the lower limits.

Bus Voltage	Voltage Harmonic Limit as % of Fundamental
69Kv and below	Individual harmonic = 3.0%
69Kv and below	THD= 5.0%
161kv and above	Individual harmonic = 1.0%
161kv and above	THD = 1.0%

Table 6. Voltage Harmonic Limits as per IEEE 519-1992.

The European Community has also developed susceptability and emission limits for harmonics. Formerly known as the 555-2 standard for appliances of less than 16 A, a more encompassing set of standards under IEC 1000-4-7 are now in effect.

How do you get rid of them

Care should be undertaken to make sure that the corrective action taken to minimze the harmonic problems don't actually make the system worse. This can be the result of resonance between harmonic filters, PF correcting capacitors and the system impedance.

Isolating harmonic pollution devices on separate circuits with or without the use of harmonic filters are typical ways of mitigating the effects of such. Loads can be relocated to try to balance the system better. Neutral conductors should be properly sized according to the latest NEC-1996 requirements covering such. Where as the neutral may have been undersized in the past, it may now be necessary to run a second neutral wire that is the same size as the phase conductors. This is particularly important with some modular office partition-type walls, which can exhibit high impedance values. The operating limits of transformers and motors should be derated, in accordance with industry standards from IEEE, ANSI and NEMA on such. Use of higher pulse converters, such as 24-pulse rectifiers, can eliminate lower harmonic values, but at the expense of creating higher harmonic values.

Summary

Harmonics are here to stay. Some estimates show the percentage of the electrical load that is non-linear doubling in the next decade. But the amount of harmonic voltage and current levels that a system can tolerate is dependent on the equipment and the source. Ongoing preventative maintenance programs that include harmonic monitoring can detect problems in the making, eliminating costly failures. Knowing what your system harmonic levels presently are, what the effect of new equipment being added will due to these levels, and how much of an increase in harmonic levels that your system can tolerate are valuable pieces of information that are readily attainable from modern power quality/harmonic analyer monitoring equipment.

References

[1] IEEE 519 Recommended Practices and Requirements for Harmonic Control in Electric Power Systems

[2] NFPA 70B Recommended Practice for Electrical Equipment Maintenance - Chapter 24, National Fire Protection Association, Quincy MA, 1994.

[3]J. Arrillega et.al. Power System Harmonics, John Wiley and Sons, 1985.

[4]Heydt, GT, Electric Power Quality, Stars in the Circle Publication, Indianapolis, 1991, pg 240.

ANSI/IEEE C57.110 Recommended Practice for Establishing Transformer Compatibility When Supplying Nonsinusoidal Load Currents

IEEE 519-1992 Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems

National Electrical Code - NEC-1996, National Fire Protection Association

About the Author

Richard P. Bingham is currently the Chief Technologist for Dranetz Technologies, Inc., having previously been the Vice-President of Engineering and Strategic Planning. He has been with the company since 1977, following completion of his BSEE at the University of Dayton. Richard also has an MSEE in Computer Architecture and Programming from Rutgers University. He is a member of IEEE Power Engineering Society and Tau Beta Pi, the Engineering Honor Society. Richard is currently working with the NFPA 70B committee on Power Quality and several IEEE committees related to IEEE 1159, and has written a number ofl papers in the electric utility and power quality instrumentation fields.