There’s Gold in Those Waveforms

Richard P. Bingham, Dranetz-BMI

OVERVIEW

In the present business climate, companies are under constant pressure to increase profitability by increasing productivity, maximizing assets utilization, and doing more with less (less people, less materials, less time). Much of this has been made possible by the increase in use and reliance on information technology (IT) equipment, such as personal computers (PCs), networks, and electronic communication equipment. Increase in consumption of electrical energy is being countered by the increased use of more efficient power supplies, which are found in IT equipment, programmable logic controllers (PLCs) and adjustable speed drives (ASDs). As the IEEE Std 1100-1992, known as the Emerald Book, points out, this equipment "can be both a contributor to and a victim of powering and grounding incompatibilities in the power system".

Having more problems that must be solved in a shorter time period with less people has forced many companies to outsource some or all of their electrical equipment preventative and emergency maintenance work to electrical contractors. A significant percentage of this work involves dealing with problems caused by power quality disturbances or phenomena interacting with the building's electrical infrastructure and loads. With a basic understand of the most common type of power quality phenomena, electrical contracting firms can provide a very valuable service to your customers, who are then better able to meet their financial objectives.

BASIC UNDERSTANDING OF ELECTRICAL LAWS

In today's electrical power systems, voltages and currents are generally not "pure" sine waves consisting of only a fundamental frequency component (60Hz in North America, 50Hz in Europe), as illustrated in Figure 1. Harmonics are frequencies that are integer multiplies of the fundamental frequency (120Hz, 180Hz, 240Hz, etc). Many of the power supplies in equipment manufactured today, such as lighting ballasts, adjustable speed drives, PCs, laser printers, and programmable logic controllers, draw current during only part of the sine wave, resulting in harmonic currents (Figure 2), which leads to voltage harmonic distortion.

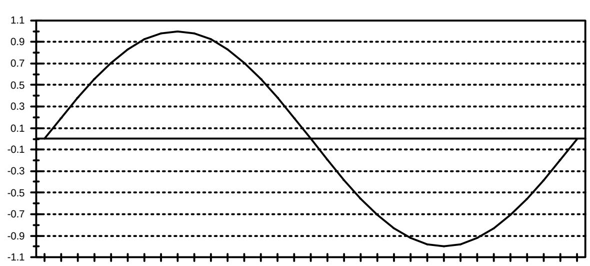

Figure 1. Sine Wave

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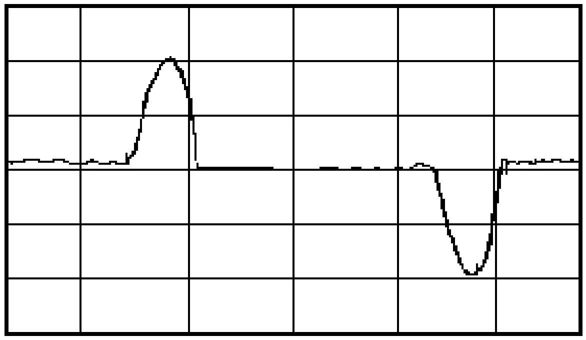

Figure 2. Distorted Wave

There are two basic laws that you need to use in order to track down the source of most power quality related problems. The first is Ohm's Law, which states that the voltage produced is equal to the current multiplied by the impedance (V=I * Z). Likewise, the current drawn is equal to the voltage divided by the impedance (I = V / Z). Impedance can be as simple as a resistor, or as complex as a inductive, non-linear load which has a different impedance magnitude and phase shift at different harmonic frequencies. Ohm's Law applies not just to the fundamental frequency components, but to all frequencies. Harmonic currents times harmonic impedances result in harmonic voltages.

Kirchoff's Law states that the sum of the voltage drops around a closed loop circuit should equal zero. In a single phase circuit with only one load, as shown in Figure 3, the current (I_L) supplied by the source (V_S), flows through the source impedance (Z_S) and the load impedance (Z_L). The source impedance represents the sum of all of the wiring and transformer impedances back towards the voltage source. The current I_L multiplied by the Z_S produces a voltage drop V_Z. What is supplied must equal what is consumed, therefore, $V_S = V_Z + V_L$.

If the current required by the load goes up, such as during the start-up of a motor, or as the loading on a rock crusher changes, or an electrical short occurs, then the current I_L will increase. According to Ohm's Law, the voltage drop across the source impedance V_Z will increase accordingly. If the voltage source V_S is still producing the same voltage level (it isn't overloaded), then the sum of the voltages around the circuit will show that there is less voltage left for the load ($V_L - V_S = V_Z$). The reverse is true if the current should decrease, resulting in an increase in voltage at the load. This is the basic cause of a whole variety of power quality phenomena, including sags, swells, voltage fluctuation (light flicker), and transients.

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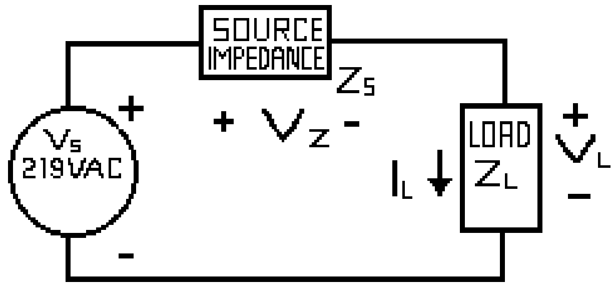

Figure 3. Single Phase Equivalent Circuit

DEFINITION of BASIC PQ PHENOMENA

Power quality phenomena (disturbances) are usually defined in terms of the effect on the supply voltage. They can be broken down into three basic categories: rms voltage variations, voltage transients, and voltage waveform distortion. Most of the power quality standards only consider the effects on the voltage, though many times it is the current that is the source of the problem. In the United States, IEEE Std 1159-1995 Recommended Practice for Monitoring Electric Power Quality is probably the most comprehensive document available. There is also a chapter in the NFPA 70B Electrical Equipment Maintenance standard that is very helpful.

RMS VARIATIONS

The first category is RMS voltage variations, often referred to as sags, swells or interruptions. Before delving into those, it is useful to define what RMS is. RMS is a mathematical procedure for calculating effective amplitude of a varying or alternating waveform (AC) signal as compared to a direct current (DC) signal. RMS stands for root mean squared, which means to square the data sample, average them, and then take the square root of it. The RMS is that value "which would produce the same power loss as if a continuous voltage were applied to a pure resistance". Unabridged Dictionary of Electronics, edited by Rudolf. F. Graf, Howard W. Sams & Co, Inc., Indianapolis, 1972. pg 504.] With distorted waveforms, be sure to use a true RMS meter, or the readings that you get may not be representative of what is happening.

A sag is usually defined as a decrease in the normal voltage supply level, typically to 90% or less of the nominal RMS level, but greater than 10% of the nominal (see Figure 4). A swell (which used to be called a surge) is an increase in the voltage level, usually to 110% or more of the nominal RMS voltage. An interruption (which used to be called outages) are when the supply voltage goes below 10% of nominal. Depending on what types of loads are present, where in the system you are monitoring, and the severity of the disturbance, the same event can be measured as a different level or even a different type of disturbance. And sometimes, the disturbance can produce all three types, as shown in Figure 5.

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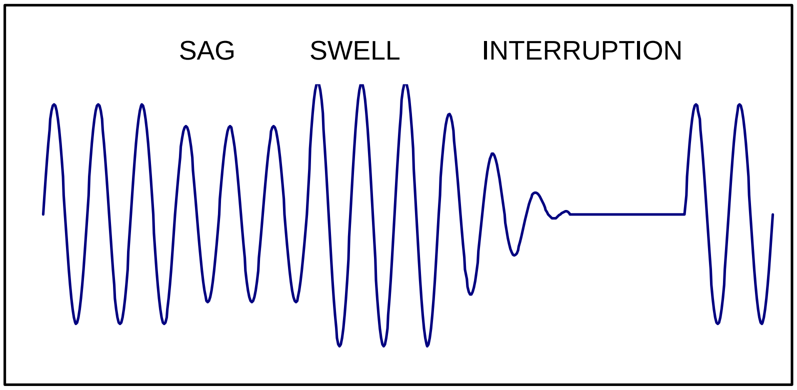

Figure 4. RMS Variations

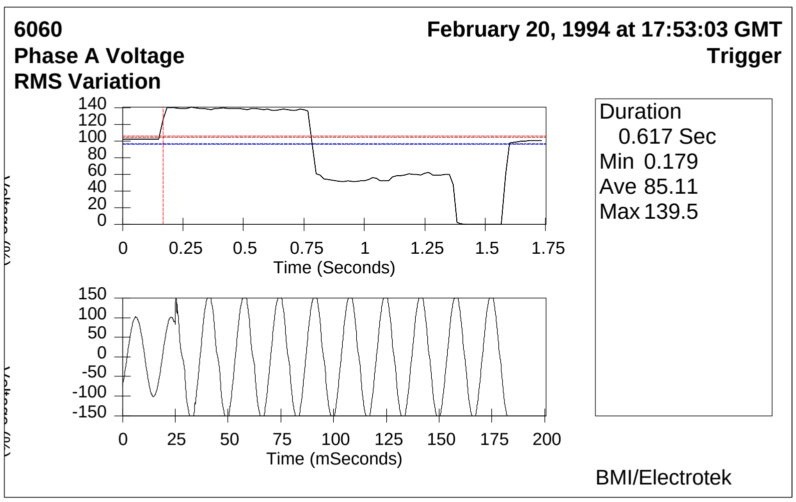

Figure 5. Swell, Sag and Interruption in Same Event

Recent surveys have shown that sags are the most likely type of power quality disturbance, and the source is more likely to be found within the facility than from the electric utility. Faults on the electrical grid, such as a downed wire or an arcing wire in a tree, create large currents that result in voltage drops in the distribution and/or transmission wires until the fault protection (breakers or fuses) open to clear the fault. Hence, many sags originating on the electrical utility distribution system are readily identifiable, lasting 4-10 cyles long with the voltage dropping down and recovering in a step fashion, and no real dramatic change in current at the monitoring point within a facility.

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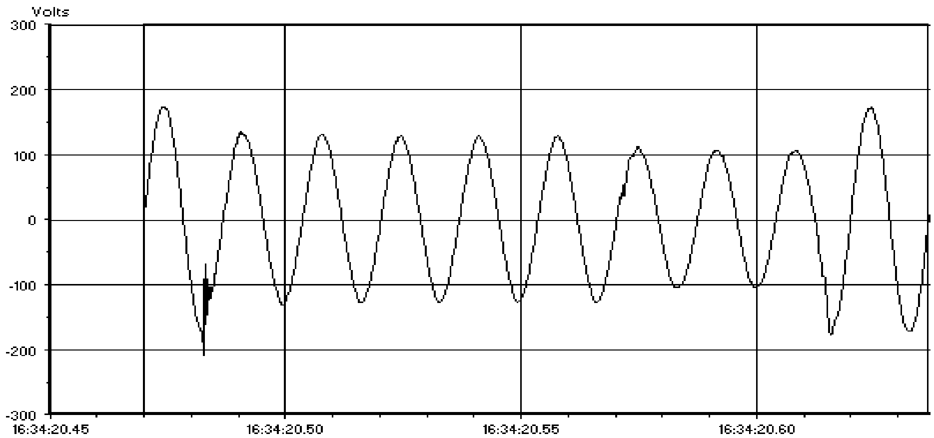

Figure 6. Sag on Utility Distribution System cleared by breaker operation

In contrast, sags originating within a facility are often caused by load changes, electrical system faults, or improper wiring. The "signature" of the sag is often characteristic of the type of load. For example, a motor start usually has a large inrush current (6-10 times nominal), followed by an gradual decay to the nominal value. The resulting sag is the opposite of that, as shown in Figure 7. The voltage decreases abruptly, then slowly recovers towards nominal as the current decreases. This goes back to the previous section, where we described that an increase in current causes a larger voltage drop across the source impedance (all of the wiring and transformers back towards the source), resulting in less voltage for the load.

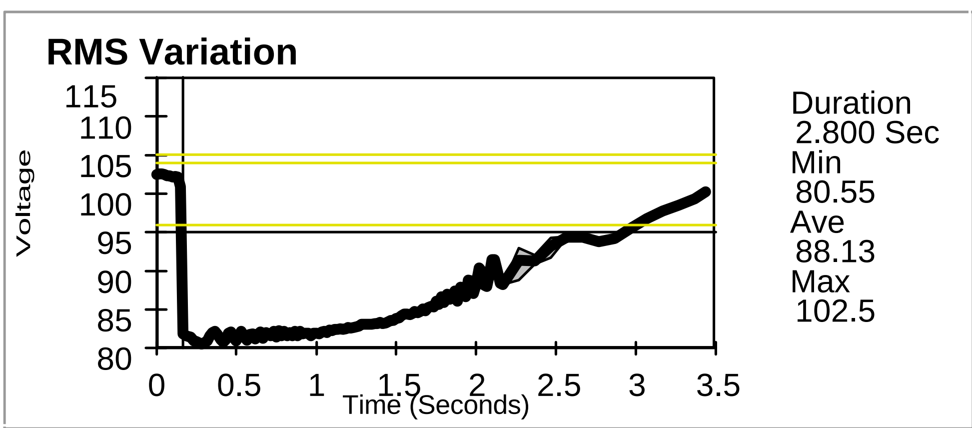

Figure 7. Sag Resulting from Motor Start

Interruptions are usually the result of being downstream from the fault protection in either a distribution substation, transformer on a pole, or the breakers within a facility. When the breaker or fuse opens to stop the overcurrent condition, everyone downstream without a UPS will see an interruption (whereas everyone else saw their sag go away.). Interruptions can also be caused by loose connections of wires or bus bars.

Swells are frequently the result of an sudden decrease in load current. Many distribution systems use automatic tap changing transformers to try to keep the nominal voltage within acceptable limits. As the load increases and the voltage starts to decrease, the tap changer goes to a higher voltage tap to compensate. When the load current drops off suddenly, such as shutting off an electric heat treatment process, there is no longer that voltage drop in the source impedance. The voltage swells up until the automatic tap changer recognizes such and takes action to go to a lower tap. To provide the tap changer from constantly swapping back and forth with short load changes, there is a time constant used to see if it is really necessary to change taps, typically around 30 seconds.

Whereas sags and swells are usually defined as lasting less than 3 minutes, longer duration rms variations are referred to as sustained under voltage or over voltage conditions. These can be the result of overloading of the supply, such as what is often referred to as a "brown-out". Such conditions are much less frequent, and usually can be correct by making sure the proper size transformer tap settings are used.

Sags and interruptions are most often experienced in a facility as a disruption to their operations, which could result in the plastic solidifying in an extrusion machine, the fiber snapping in a textile mill, or the computer servers and PBX systems going down in a financial center. How severe of a sag or interruption that it will take to cause such is based on many factors, including the individual equipment's susceptibility, wiring, interaction with other equipment and so on. And it may not be the $30k computer system that shuts the plant, but instead, the $2 emergency shut-off photocell that improperly trips. Swells can also cause process interruptions in systems designed to detect overvoltage conditions, but can also result in physical damage to sensitive components.

TRANSIENTS

Voltage transients, formerly referred to as impulses, are usually categorized as either impulsive or oscillatory. Lightning striking a distribution line is normally an impulsive transient, where there is a large deviation of the waveform for a short duration (measured in microseconds) in one direction, followed possibly be a couple much smaller transients in both directions. Notches in the waveform due to the instantaneous short circuit of two SCRs during the commutation period are often referred to as unipolar (one direction) impulsive transients. An oscillatory transient is one where there is a ringing signal or oscillation following the initial transient. The switching of power factor correction capacitors is considered the most prevalent type of transient. The large inrush of current into the uncharged capacitor works according to Ohm's Law and Kirchoff's Laws to produce a sharp reduction in voltage. But since the distribution lines have a large inductive component in their impedance, the sudden addition of significant capacitance results in a temporary resonance condition, hence the decaying oscillation shown in Figure 8. Sometimes the oscillations can be larger and more damaging than the initial transient.

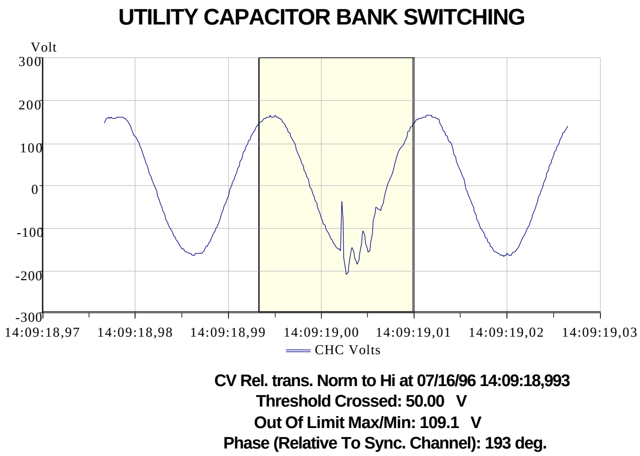

Figure 8. Oscillatory Transient from PF Cap Switching In

Damage from transients can be sneaky. Though there have been catastrophic failures, such as a direct lightning strike to a building's wiring, they are more often failures resulting from the repetitive chipping away of the silicon material inside semiconductors or the dielectric material of capacitors, erroneous data transfers or corrupted data stored in memory.

WAVEFORM DISTORTION

The third category for classifying PQ phenomena is waveform distortion, which encompasses harmonics, interharmonics, voltage fluctuations, notching, and DC offsets. As previously stated, harmonic frequencies are integer multiples [2, 3, 4, 5,...] of the fundamental frequency. For example, the 2nd harmonic on a 60 Hz system is 2 * 60 or 120 Hz. At 50 Hz, 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. Frequencies that are not integer multiples of the fundamental frequency are called “interharmonics”. There is also a special category of interharmonics, which are frequency values less than the fundamental frequency, called sub-harmonics. The presence of sub-harmonics is often observed by the lights flickering.

“The main sources of harmonic current are at present the phase angle controlled rectifiers and inverters.” J. Arrillega et.al. Power System Harmonics, John Wiley and Sons, 1985.] These are often called static power converters. These devices take AC power and convert it to DC, then sometimes back to AC power at the same or different frequency based on the firing scheme. They are found in most ASDs, PCs, PLCs, and other equipment with rectified-input, switching power supplies.

Richard P. Bingham is the manager of technology and products for Dranetz-BMI.

Certain types of loads also generate typical harmonic spectrum signatures, that can point you 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. Table 1 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 1. Typical Harmonics Found for Different Converters.

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. Fluorescent lights are a common source of harmonics, as the ballasts are non-linear inductors. The process of melting metal in an electric arc furnace or welding can result in large currents that are comprised of the fundamental, interharmonic, and subharmonic frequencies being drawn from the electric power grid.

There are a number of different types of equipment that may experience misoperations or failures due to high harmonic voltage and/or current levels:

- Excessive neutral current, resulting in overheated neutrals, especially from the triplen harmonics, (3rd, 6th, 9th, 12th, 15th,...) which are actually additive in the neutral of three phase wye circuits. This is because the harmonic number multiplied by the 120 degree phase shift between the three phases is a integer multiple of 360 degrees, or one complete cycle. This puts the harmonics from each of the three phase conductors “in-phase” with each other in the neutral.

- Incorrect reading meters, including induction disc-type W-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.

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- Positive, negative, and zero sequence voltages on motors and generators. These are voltages at a particular frequency that try to rotate the motor forward, backward, or neither (just heats up the motor), respectively. The voltage of a particular frequency in a balanced system harmonics can have either a positive (fundamental, 4th, 7th,...), negative (2nd, 5th, 8th...) or zero (3rd, 6th, 9th,...) sequencing value.

- Nuisance operation of protective devices, including false tripping of relays and failure of a UPS to transfer properly, especially if the 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.

- Light flicker results when there are voltage subharmonics in the range of 1-30Hz. The human eye is most sensitive at 8.8Hz, where just a 0.5% variation in the RMS voltage is noticeable with some types of lighting.

SUMMARY

As an electrical contractor, having these basic concepts in your back pocket along with a power quality monitor that is capable of capturing what you are interested in and helping you find the answers in a timely manner lets you offer a very valuable service to your customers. Whereas the facility electrician may only be exposed to a small subset of the potential phenomena, the many places and situations that you encounter will make your knowledge even more valuable to your customers. And when you don't know the answer, there are specialists in the area that can help steer you right. Check the Internet, industry magazines, and trade shows for information about which tools and specialists will really do the job for you. And remember, if you observe data that wants to disprove Ohm's and Kirchoff's Laws, think twice about what is really going on before you challenge the laws of physics.

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