Power Quality Starts At the Load

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Abstract

The definition of “power quality” is becoming another one of those terms whose definition gets stretched so far by the marketing departments of measuring/monitoring instrumentation and mitigation equipment that the real meaning is getting lost. What it is really important is that the characteristics of the power required by the load equipment is compatible with the characteristics of the power being supplied. There have been valuable surveys done in the past five years on the quality of supply, along with standards to require delivery of such at the point of common coupling. However, it is often what happens within the facility before it reaches the load (or as a result of the load itself) that results in an incompatibility.

This paper covers the recent work being done on the power supply performance and load susceptibility. This will serve as a background for how to best utilize power quality monitoring tools to determine the source and susceptibility of the most common type of loads that are more sensitive to the quality of the supply. The use of a few simple rules that will help resolve the majority of the power quality problems, from sags (dips) to transients to harmonics, will be reviewed from the load’s perspective.

1. What Does Power Quality Mean - an Overview

The definition of “power quality” is being shaped in the ad campaigns of the producers of measuring/monitoring instrumentation and mitigation equipment that just about anything that digitizes a waveform claims to be a power quality tool. The characteristics of the power required by the load equipment being compatible with the characteristics of the power supplied is what it is really important. This usually requires a power quality monitor with adequate performance to obtain the knowledge of the susceptibility of the equipment and provide information about the power being supplied.

There have been very valuable surveys done in the past five years on the quality of supply in Europe, North America, and other parts of the world. This provides the baseline data to develop standards on the quality of the supply delivered to the point of common coupling, such as EN50160 [1] and NRS:048 in South Africa [2] , and the IEC 1000-3-X [3] and IEEE 519-1992 [4] standards with limit for emissions and susceptibility.

There are older references, such as the CBEMA curve (which has recently been revised and renamed as the ITIC curve), that try to generalize susceptibility of the load equipment. The Power Electronics Application Center (PEAC) of EPRI, PowerCET, Duke Power, and other organizations have conducted considerable tests on equipment to determine the susceptibility of the equipment. This is done by subjecting the equipment to a variety of different characteristics combinations, such as magnitude, duration, phase shift, and point-on-wave. Work within the IEEE has produced a soon-to-be-released document on how to determine susceptibility probability of a specific process as compared to the power being supplied. This is can be done very effectively by plotting the magnitude-duration probability versus the equipment susceptibility graph.

Electrical generators tend to produce pure sine waves at a regulated voltage levels over the specified loading. Lightning, trees, and animals (including humans) can contribute to changing the voltage characteristics as it passes through the transmission and distribution systems to the facility. However, it is often what happens within the facility before it reaches the load (or as a result of the current draw of the load itself) that results in an incompatibility. Most published surveys show that 65-85% of the power quality problems are the result of something happening within the facility, on the customer side of the point of common coupling. It may be the wiring or the loads themselves that make the supplied voltage incompatible with equipment within the facility. The result is that the process is interrupted, productivity is halted, and dollars are lost. For some processes, such as in the financial community, these losses are measured in millions of dollars per minute.

2. Gathering the Data

The uses for power quality monitors can be grouped into three general categories:

1. Diagnostic/Evaluative
2. Characterization and Statistical Indices
3. Predictive

- **Diagnostic**

The diagnostic usage is also known as the troubleshooting mode. Portable power quality monitors are often employed in this mode. Something has failed and the process is interrupted, so what caused it? This is often a difficult, forensic-like task, as the series of events that lead up to the failure may be random and occur infrequently (such as lightning), or may be the result of a random coincidence of a series of conditions. This diagnostic process is often an iterative process, as the initial solution may only mitigate part of the problem. In some cases, the solution may actually make the situation worse. Such can be the case with harmonic filters and switched power factor correction capacitors resonating in high harmonic environments. In the past, it often required a fairly knowledgeable person to interpret the data, determine the cause, and derive a potential solution.

- **Statistical**

The characterization and statistical indices for power quality provide a basis for the user to determine what is “normal”. Permanently installed power quality monitors are usually used to collect this data, as it must be collected over an adequate time period to be statistically valid. The effects of the environment and load patterns may differ significantly over the course of a year.

Data collected during these surveys may be processed into information for the purposes of:

- determine if the quality of service at a particular location over a particular time duration is abnormal.
- to design an overall power supply system that can ride through 99.99% of possible events;
- for the purpose of writing a compliance contract with the electric power provider for a specified level of custom power.

This type of usage often requires the collection and post-processing of large quantities of data, and the associated data management and statistical algorithm complexities. The EPRI DPQ project collected over 40 gigabytes of data in the two year survey of three points on 100 distribution feeders throughout the United States.[5]

- **Predictive**

Predictive tools are just beginning to enter the market place. These will take the next step in the data-to-information-to-answers-to-wisdom path. It is often called the "expert-in-a-box" concept. Based on statistical norms with recent and historical data gathered from permanent monitors and survey information, the system could detect and report any degradation in the infrastructure, loads, or electric supply that will lead to a failure in an estimated future time, whether that time is in minutes or months. The result of this is "prevented" costs for the user. Maintenance can be done at scheduled times before the failure and without lost productivity. It also minimizes unnecessary scheduled maintenance, when the information indicates there is nothing to be gained by taking the system out-of-service to look for something that doesn't exist.

3. Defining "Normal"

A number of survey programs have been undertaken throughout the world to provide a baseline for what is consider "normal" quality of supply in that particular part of the world. Most of the surveys have been commissioned by electric utility companies. These include the Enel, IQF, and East Midlands surveys in Europe, the EPRI DPQ project in the United States, and the CEA study in Canada.

In this era of de-regulation (or re-regulation), the surveys provided the basis for determining the effects (if any) on the quality of supply as the result of effects of deregulation, such as any reduction in O&M expenses by the utility. The data may also be used when contracts are being written between industrial or commercial users and the electric utility for custom power. When the number of events or disturbances of a specified type exceed the contract limitation, then the electric utility may be required to pay a financial penalty. Such contracts are in place between the "Big Three" auto manufacturers in the United States, and the two local electric utilities, Detroit Edison and Consumers Power.

The three surveys done in North America were conducted on the distribution system (EPRI DPQ), at the point-of-common-coupling (CEA), and at the point-of-utilization (NPL). The latter was one of the few non-utility surveys, funded and conducted by National Power Laboratories, which was part of a UPS manufacturer, Best Power. The data from these three surveys must first be "normalized" to provide for similar classification of the data. For example, what voltage level constitutes the trigger points for sags (or dips) and swells was not the same on all surveys. Industry-accepted definitions can be found in IEEE 1159-1995 [6] and EN50160.

Papers by D.Dorr at PEAC show the results after reclassifying the data. [7][8] Such data clearly shows that there are more disturbances originating within the facility than supplied from the distribution system.

4. Turning Data into Information and into Answers

The information obtained from the surveys can be turned into answers by statistically processing the data. One such process is by plotting the magnitude versus duration versus frequency of occurrence of a particular PQ phenomena on a 3-D contour plot.
An example of the sag data from the NPL survey is shown in Figure 1. The survey was conducted at the point-of-utilization within the facility at 130 sites, typically the 120V single phase outlet. Limits for determining whether an event or disturbance occurred were based on the CBEMA limits. The mag-dur 3-D contour plot shows two distinct peaks. The first peak at a 6-10 cycle sag duration is most likely caused predominately by faults on the the distribution system and the subsequent operation of the fault protection breakers in the distribution voltage substations. The larger peak in the 1-30 second region, is most likely the result of electric motor starts within the facility.

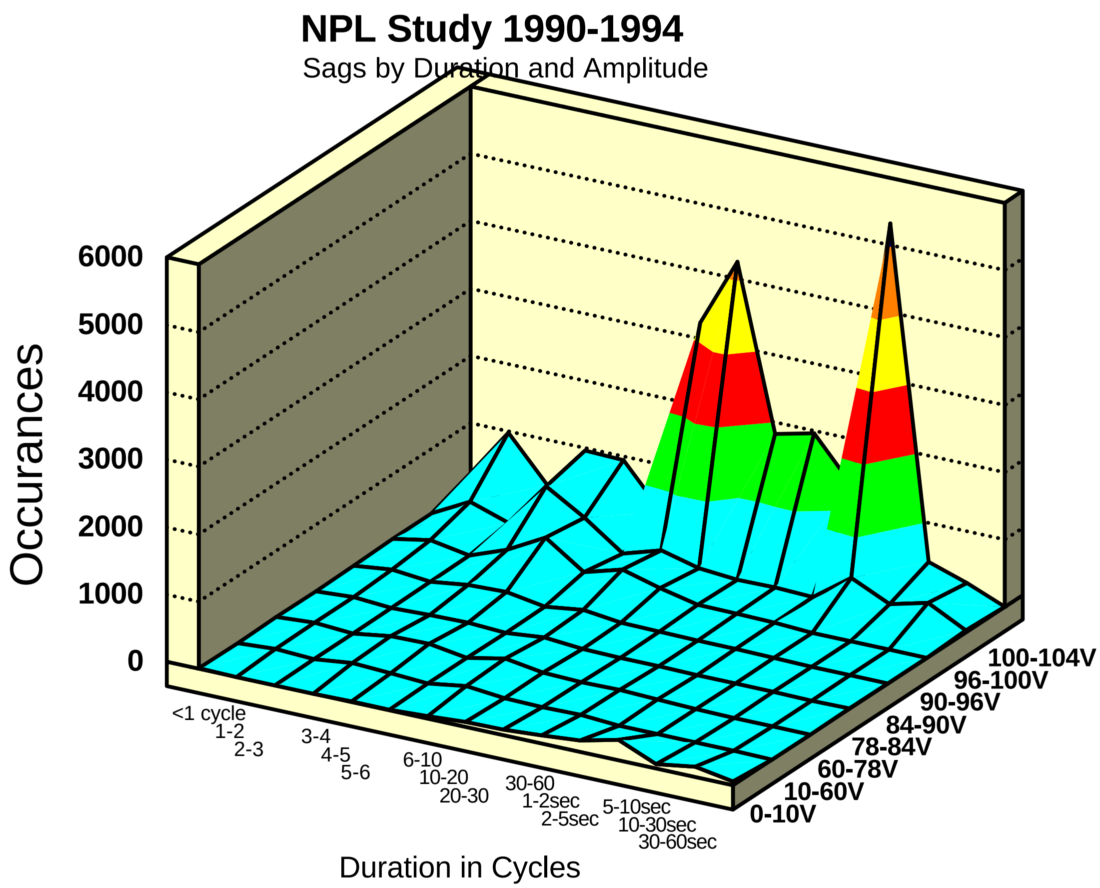

Figure 1. Number of Occurances of Magnitude versus Duration of Sags from NPL Survey [5]

The IEEE Std 1100-1992, referred to as the Emerald Book, states that “electronic equipment can be both a contributor to and a victim of powering and grounding incompatibilities in the power system". [9] Since most power quality related problems originate within the facility itself, a set of simple PQ rules allow the user of monitoring equipment to turn the data gathered from within their facility into answers to questions such as, “what was the cause of the power quality disturbance“ or “was the cause of the process interruption related to the quality of the electric power”.

5. PQ Rules

Most of the so-called power quality rules are based on two laws – Kirchoff’s and Ohm’s Laws. Kirchoff’s Law can be summarized as the sum of the voltages around a closed loop circuit should equal zero. Ohm’s Law equates voltage to current multiplied by the impedance. These laws can be applied to basically all of the power quality phenomena, from sags (dips) to transients to harmonics.

One of the first steps in interpreting the data is to determine if the sag was caused by a load or source side disturbance or event, also referred to as downstream or upstream, respectively, from the monitoring point. The type of load and source, as well as distance from the disturbance and the wiring configuration, will all have an effect on the characteristics of the sag.

Generally, the current will increase significantly when the voltage decreases if the load is the cause of the sag. The increased current multiplied by the source impedance results in a larger voltage drop across the source impedance. The available voltage at the load is the originally supplied voltage level minus the increased voltage drop. For example, the start of a medium hp electric motor or large transformer can cause an in-rush current of 6-10 times the steady state current levels, with an accompanying voltage sag, as shown in Figure 2.

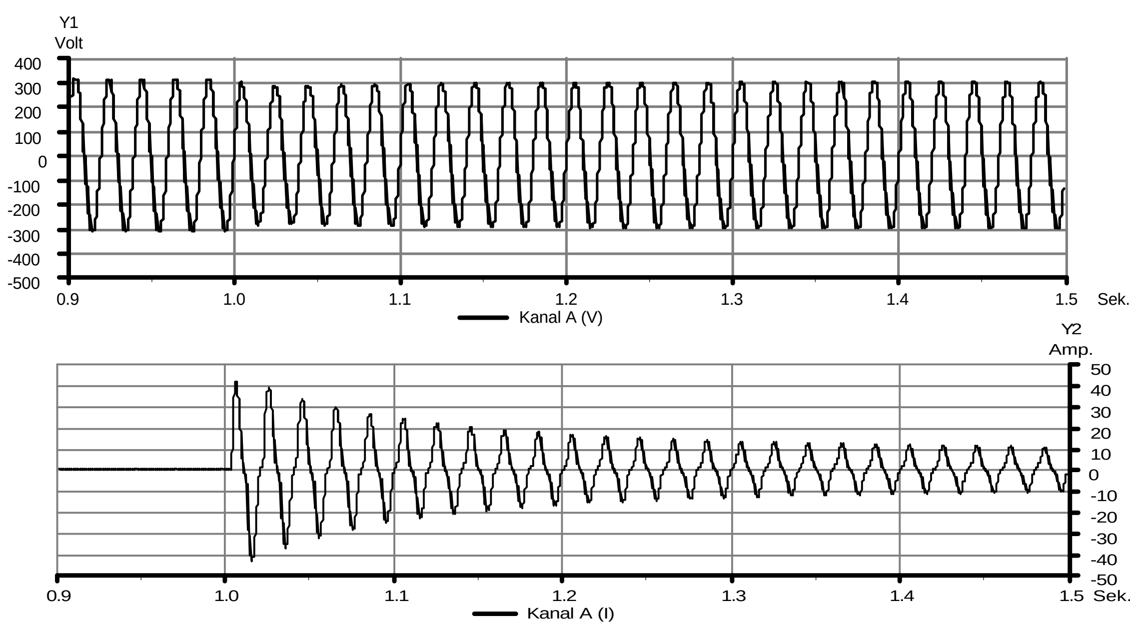

Figure 2. Voltage and Current Waveforms during a Motor Start.

Conversely, if the sag originated from the source side, then the current will usually increase slightly, stay the same, or decrease. If the load is a rectified-input, switched-mode power supply such as found in most electronic equipment, a decrease in the source voltage below the voltage level on the storage capacitor after the rectifier inside the power supply will result in no current flow, as long as that condition remains.

Voltage and current data taken during the sag can be also used to determine an approximation of the source and load impedances. The IEEE Emerald book shows that the approximation of the source impedance can be calculated by taking the voltage at two different levels and the corresponding current. [9] The difference in the voltages divided by the difference in the currents will yield this approximation. To be the actual source impedance, the current would have to contain a full harmonic spectrum. But for solving many PQ problems, this approximation is adequate. By averaging the calculations over a number of points, a more accurate value can be obtained.

Generally, the lower the source impedance, the "stiffer" the system, hence, the system should have less severe voltage sags for the same load changes. The source impedance to load impedance ratio of single phase circuits should be minimum of 1:20 (0.5 ohm source w/10 ohms load). This means that the energization of a load with a 10A inrush current on a 120V circuit would produce a voltage decrease to 0.96 p.u.. This should be adequate for other equipment on same circuit to operate properly. However, if three similar loads start at the same time, the resulting sag to 0.875 p.u. may be detrimental to other sensitive loads, such as having a contactor drop-out.

Ohm's Law and Kirchoff's Laws also work well when trying to solve harmonic problems. Attention is often focused on the harmonic voltages, when it is really the harmonic currents times the harmonic impedances that are at the root of the problem. It is the current draw of non-linear loads that are normally the cause of the harmonics. The resulting voltage harmonics merely distribute the problem to other loads that may be vulnerable to the potential zero crossings, increased losses in inductive devices, overloading of the neutral conductors, lower power factor and reduced ride-through of power supplies.

A quick examination of the voltage waveshape can indicate if even harmonics are presented. If the two halves or two quarters of the waveform (referenced about 180 or 90 degrees) are not symmetrical, then there is most likely even harmonics present. Most systems do not have significant even harmonics, unless there is a half wave rectifier on the circuit. An FFT of a half-wave rectified signal will have only even harmonics. A large banking facility in New York City found such a waveshape coming from the output of their uploaded UPS, and determined that half of their full wave bridge rectifier was damaged and non-functional before it was called on to provide back-up power.

Determining which harmonic currents are present can often lead to the load that is the source of them. A single phase, rectified input, switched mode power supply will usually have odd harmonic current with an amplitude that is proportional to the inverse of the harmonic number (1/3, 1/5, 1/7, 1/9,..). The harmonic content of multi-pole converters can be found from the equation: h=n*p +/- 1, where h is the harmonic number, n is an incrementing integer, and p is the number of poles or paths of conduction. For example, a three phase, full wave rectifier has six poles. The harmonic currents from such would be the 5^{th} and 7^{th}, 11^{th} and 13^{th}, 17^{th}

and 19th, and so on. A waveform from a six-pole converter and its harmonic content can be seen in Figures 3 and 4.

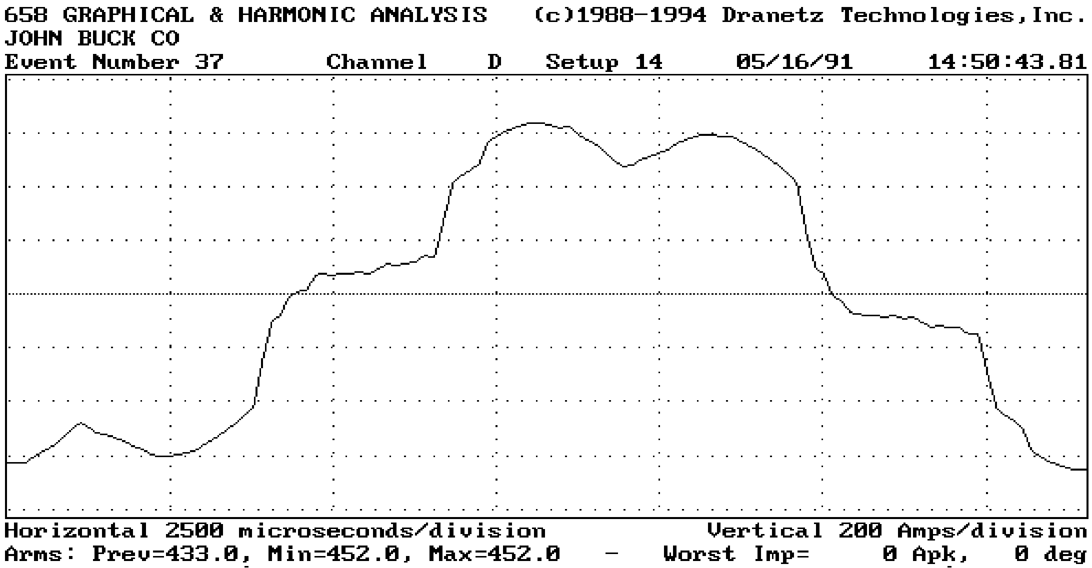

Figure 3. Current Waveform from 6-pole converter.

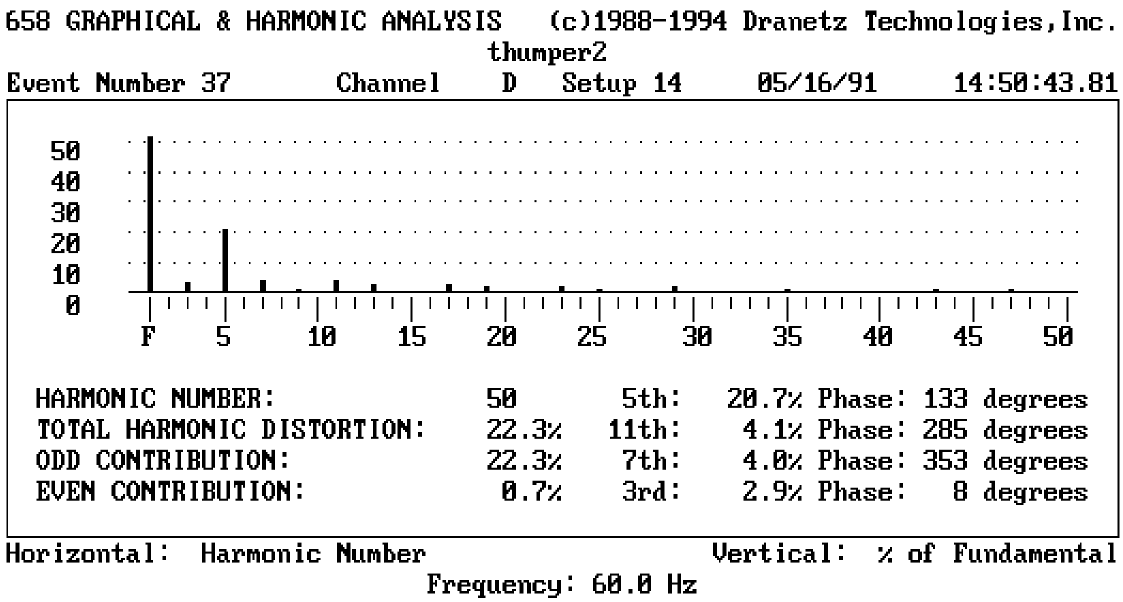

Figure 4. Harmonic Spectrum from Figure 3.

The harmonic currents multiplied by the harmonic impedances of the source will result in harmonic voltages drops, in the same was that the load currents caused voltage sags. The harmonic voltages will distort the original voltage waveform supplied to other loads on other circuits from the same source. While the harmonic currents do not propagate to the other circuits, their effect does through the distorted voltage. In extreme examples, it may be a neighboring facility that is the source of harmonic problems within a facility. For this reason, harmonic current and voltage limits have been established in both the IEC1000-3-X series [3] and IEEE 519-1992 [4] standards.

Distortion is not just limited to the harmonic currents. Interharmonic currents from asynchronous converters can result in equipment malfunctions. Sub-harmonics are a special set of interharmonics, with frequency components below the fundamental frequency. When these components are of adequate amplitude and frequency, the resulting voltage fluctuations can produce light flicker. Though this tends not to result in equipment mis-operation, it can have significant effect on the human operators.

Obviously, not all PQ-related problems are load side. Weather (lightning, wind, ice), animal contact, contamination of insulators, construction accidents, motor vehicle accidents, falling or contact with tree limbs can result in voltage sags. Such faults may be 3-phase, line-to-line, or single line-to-ground (SLTG). Though 3-phase faults are the most severe, they are relatively rare compared to the SLTG faults. The key to identifying the cause of source-side sags is to have a basic understanding of the operation of the fault protection system of the electric utility supplying the facility.

Preliminary results from the EPRI study indicate that most important cause of momentary voltage sags is lightning strikes. In the majority of sags, the voltage drops to about 80% of nominal value on the parallel feeders, while the faulted feeder may have a lower sag value, or may result in an interruption on the faulted circuit if the fault cannot be cleared. Distribution system sags tend to cluster around several duration ranges, based on the fault protection schemes: 6-20 cycles (typical distribution fault clearing times, 30-60 cycles (the instantaneous reclosing time for breakers) or 120-600 cycles (the delayed reclosing time for breakers). Figure 5 shows the voltage waveform caused by a fault resulting the operation of a distribution breaker.

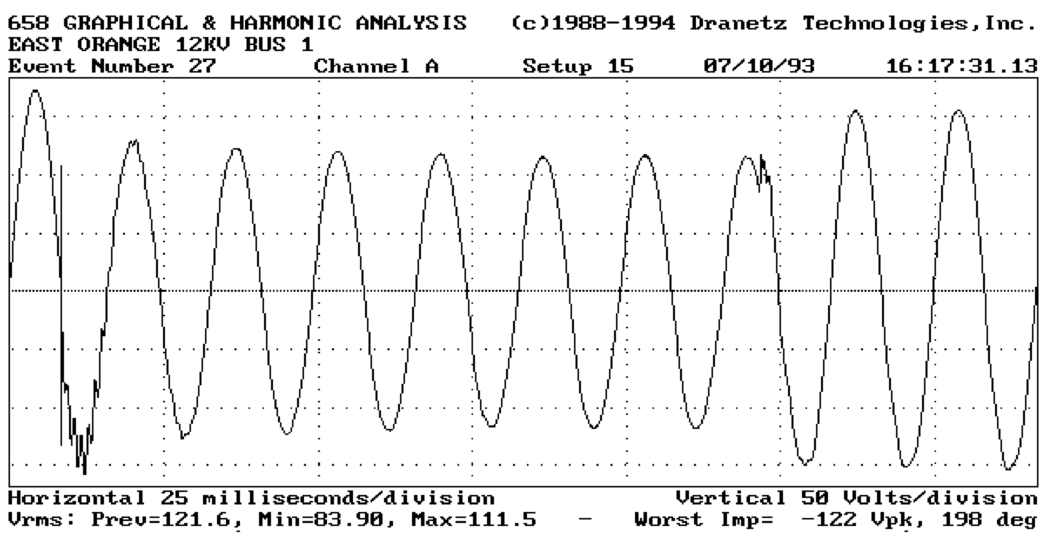

Figure 5. Voltage Sag From Distribution Level Fault

One of the most common source-side causes of transients is power factor correction capacitor switching, which may occur at a certain time each day or at a prescribed load level. These can usually be easily identified by examining the waveform. They usually exhibit a negative transient of up to 2 p.u. in magnitude, followed by an oscillation between 400-1400 Hz, depending on impedance of system. Figure 6 shows an example of such. This is in contrast to the lightning waveform, which is generally characterized with a very fast rise time (1.2 usec) of a unipolar transient (50usec decay time), and can be either negative or positive in polarity.

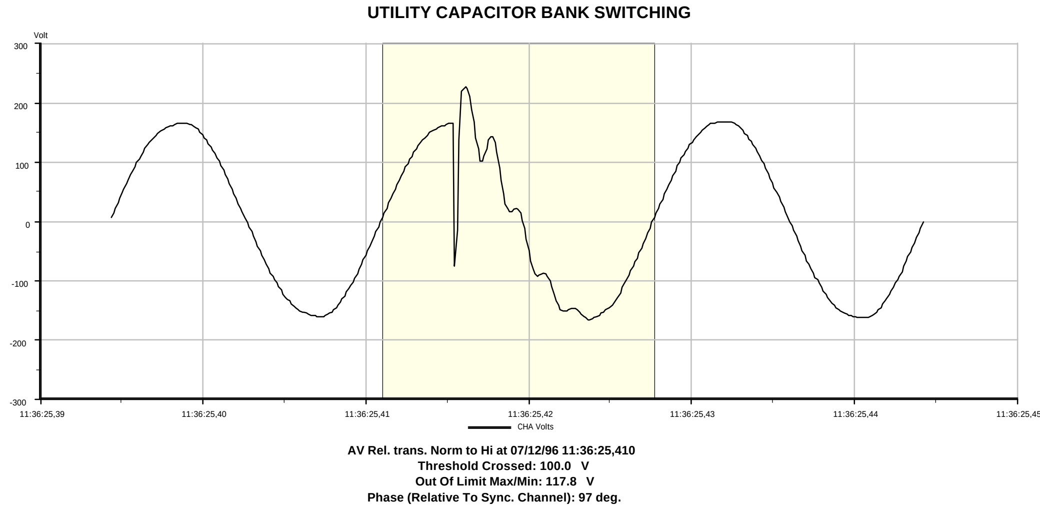

Figure 6. Power Factor Correction Capacitor Switching Transient.

6. Summary

Since most power quality problems originate within a facility, it makes sense in many cases to start at the load when searching for the cause. One of the most useful senses is vision. A visual examination can detect wiring problems, such as missing or improper grounds. Observing what happens in a facility and keeping a log of such will also help in performing the forensic-type analysis. Did the lights blink, and if so, where? What time was the process interrupted? If transients are suspected, were thunderstorms in the area? Was the humidity level low, which can lead to ESD (electrostatic discharge) problems?

Often, processes run properly until a change is made in facility. It may be change in the wiring, new loads, or the placement of loads. The process may run fine until a new ASD is placed on the circuit, and an increase in harmonic levels and notching are observed. If the circuit has excessive neutral-to-ground voltage of a grounded system, a laptop computer may work properly, but replacing it with a desk top computer that references the power supply to the third-wire ground may malfunction.

The more sophisticated power quality monitors can determine the type, magnitude, period and duration of the disturbance. They can clearly capture a periodic voltage sag on a single phase line occurring approximately every 30-60 seconds accompanied by a sharp increase in resistive current and/or a sharp increase in the neutral-to-ground voltage, which is probably due to a laser printer, copy machine or similar type load. Was there a step change in voltage at beginning and end of event (such as with a breaker operation)? Did the voltage recover gradually as a large increase in current gradually decays to a steady state condition (as one would find with a motor start?) Having the information available to answer these questions can lead to the bigger answers of “why was the process interrupted?”.

It can be very difficult to find the answer to these questions when only data collected is at the PCC or the distribution substation level, or inadequate monitoring equipment is used that only captures and saves part of what really happened. While information from these locations is also valuable, the facility managers should be sure that the quality of the power at the critical loads within their facilities is known, especially when there is an unscheduled process interruption that results in a significant financial loss. Equally important is the susceptible of the equipment powered by such. Both sets of information are needed to keep the process running uninterrupted.

References

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BIOGRAPHY

Richard P. Bingham is the manager of technology and products for Dranetz-BMI. 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 also serves on the NFPA 70B committee and co-authored the forthcoming chapter on Power Quality, as well as being a member of the IEEE 1159 Taskforces and other power quality related committees. He has written a number of papers and given numerous presentations worldwide in the electric utility and power quality instrumentation fields.