SIMPLE RULES FOR SOLVING POWER QUALITY MYSTERIES

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ABSTRACT

The typical power quality problem starts with a frantic call to the facility's engineer or electric shop supervisor concerning some malfunction that has either shut down production or caused a computer-based system to reset. After the fact, forensic-type investigations are probably the most difficult way to track down the source of a problem related to the quality of power. Following several simple rules can allow persons charged with such responsibilities quickly to mitigate most of such problems. It requires only a basic knowledge of electricity and how the various parameters relate in the presence of changes caused by loads, utility-switching, and other sources of power quality phenomena. It also requires a power quality monitor capable of reliably capturing the necessary information.

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1. BACKGROUND

The increase in power quality related problems are evident with such high visibility incidents as the recent disruptions at the stock exchanges and the air traffic control system in the United States. To those involved with power quality on a daily basis, this comes as no surprise. The increase dependence on computer-based and other electronic equipment with a lower tolerance to various types of power quality phenomena is a large factor.

This increased susceptibility is based on a number of factors, including the lower logic voltage levels, increased clock frequencies, interconnection of equipment through LANs, and escalating percentage of nonlinear loads. Just as important is the restructuring within industrial/commercial and electric utilities that have dispersed and sometimes eliminated the PQ experts within these organizations. The result is that there are more problems for less experienced people to handle.

There are two different approaches to solving power quality related problems: preventative/predictive maintenance and forensic-type investigations. Due to lack of understanding and increased workloads, the after-the-fact investigations still seem to dominate, though they are clearly the most difficult to solve. Both approaches can use simple rules that will help solve most power quality related problems. While the more complex causes will probably require the knowledge of the experienced person, fortunately, these are the minority of cases.

Before going into the simple rules and procedures, a common set of terms needs to be defined. In North America, the predominate source of these is the IEEE 1159 Recommended Practice on Power Quality Monitoring [1]. In Europe, EN50160 coupled with the UNIPEDE Voltage Characteristic documents are good sources. While both are very useful, the IEEE 1159 currently has a more thorough set of definitions for power quality phenomena, so it will be used here, as defined in Appendix A.

2. PREVENTIVE MAINTENANCE APPROACH

The preventive maintenance or pro-active approach has been used by many companies to prevent significant financial burdens from lost productivity. Whether it is monitoring the outputs of a UPS while off-line or harmonic levels of a transformer that needs to be derated to prevent shortening its life, this approach is clearly the preferred method. However, it often difficult to get implemented, as many do not see the benefits until after the disaster occurs.

Doing a preventive maintenance monitoring program usually involves the following steps: plan/prepare, inspect, monitor, analyze, and implement a solution. This is often an iterative process, as the first solution may only mitigate part of the problem. One of the more difficult tasks for the less experienced person is the analysis of the data. Numerous papers have been written on the other steps, so the following discussion will focus on the analysis step. The following preventive maintenance program concentrates on steady state conditions, though many rules apply to intermittent conditions as well.

It is assumed that a power quality monitor that can make an accurate survey is used. To do such, the monitor should have the ability to simultaneously capture RMS variations on a cycle-by-cycle basis, transients down to the microsecond level, and harmonic distortion at least to the fourthieth. The measuring voltage inputs should be high-impedance, differential inputs that can be used in both wye and delta circuits without assuming balanced conditions.

Current transformers should have an adequate bandwidth to capture both steady state and transient waveforms. This is often not so when CTs are clamped on the secondary of metering current transformers. Often today, voltage transients are clamped by surge-suppression devices, so the way to reliabily detect transients is through the triggering and monitoring of current transients.

The monitoring period should last at least one business cycle. A “business cycle” is how long it takes for the facility to repeat the pattern of operation. In industrial locations that run three identical shifts, seven days per week, monitoring may only take eight hours. Most facilities will find that a business cycle is one week. It may be necessary to repeat the survey several times per year due to seasonal changes, such as increases in ESD in the winter months in colder climates.
Monitoring should also be done at various places throughout the facility. Typically, the survey begins at the point-of-common- coupling (PCC), which is where the electric utility service meets the building service. Next, monitoring is done at the distribution panels on each floor, followed by outlets at the end of each branch circuit. Data at critical loads in the facility should also be included. While this may seem like a lot of data, having this baseline and profile of the facility will be extremely helpful when future disturbances happen.

Once the data has been collected, it is typically transferred into desktop or laptop computers for analysis using PC software programs. Limits on what is acceptable values can be found in such publications as the FIPS PUB 94 - Guideline on Electrical Power for ADP Installations, shown in Appendix B. Local safety agencies or equipment manufacturer’s specification should be observed, especially if they are more restrictive.

What the effect of being outside these limits would depend on the susceptibility of the equipment, the “stiffness” of the power system, and what other factors are present at the same time. These are not absolute limits, but rather references to raise questions. The neutral-to-ground voltage in a 120V, single phase system, is recommended to be between 0.5 and 3 Vrms. [2] If the voltage is near zero volts, then the presence of an illegal neutral-to-ground bond should be suspected. If the voltage is very high, then the absence of a reliable neutral or ground connection should be looked for.

The presence of voltage modulation (or fluctuation) can result in light flicker, depending on the frequency of the modulation. Based on EN60868, a variation of less than 1% at 9Hz with incandescent lighting can be noticeable.[3] In NEMA MG-1 and IEEE Std 112, they recommend a 10% derating of an electric motor with just a 3% voltage imbalance [4,5]. With proliferation of nonlinear loads, such as PCS and printers, being placed throughout facilities often without regard for maintaining balanced loading, a 3% voltage unbalance is non uncommon.

Analysis of several other parameters is useful. The harmonic distortion for both current and voltage should be reviewed. IEEE 519 Recommended Practice on Harmmonics in Power Systems and the IEC 1000-4-7 should be consulted for limits specified for individual harmonic amplitudes and total harmonic distortion value. Is the harmonic distortion severe enough that transformers and other inductive devices need to be derated?

A look at the harmonic spectrum from a FFT or DFT can give clues about what type of equipment is operating on the circuit and is it operating correctly. For example, if there is a high percentage of even harmonics, this would suggest the presence of half-wave rectification. If the equipment on the circuit utilizes such, then that may be an acceptable value. However, if the equipment only has full-wave rectifiers in the power supplies, this may indicate that part of the semiconductor bridge circuit is not operating properly.

The harmonics for multi-pole converters usually show up as harmonic pairs, $h=p*n+/-1$, where h is the harmonic number, p the number of poles, and n is an integer from one on. For example, a six-pole converter (three phase full wave bridge rectifier) would have harmonics at the 5th and 7th, 11th and 13th, 17th and 19th, and so on.

Two other parameters to look at are the source and load impedance. Source impedance is considered as the equivalent impedance of all of the wiring and transformer impedances (plus any loads) looking back toward the source. The load impedance is defined here as the equivalent impedance of all the loads and circuits looking away from the source.

A reasonable approximation of these values can be derived using the formula's presented in the IEEE Std 1100, Recommended Practice for the Grounding and Powering of Sensitive Electronic Equipment, also known as the Emerald Book [6]. Based on Ohm's Law, which states that Voltage = Current * Impedance, Load Impedance equals V line-to-neutral divided by I line-to-neutral. While the value is not an exact value unless signals from the entire frequency spectrum are present, it is useful for determining the effect of loads switching on and off.

Similarly, the source impedance is an approximation derived by taking the difference between two voltages at different times and dividing that value by the difference between two currents at the same time, or (V1-V2)/(I1-I2). This will give a value useful for determining how "stiff" the source is. It can also be used to calculate how severe a sag would result when various loads are turned on. For example, if the source impedance is 1 ohm on a 120Vrms circuit with 10A normal load, switching in a load that has an impedance of 11 ohms will result in a sag down to 100V. Source impedance values more than one ohm should be investigated.

If the power quality analyzer used records harmonic magnitudes and phase angles over time under various loading conditions, then harmonic impedances can also be calculated. This can be helpful in identifying potential resonances with system impedances, such as power factor correction capacitors.

During the preventive maintenance monitoring period, obtaining data is also possible as to the frequency of occurrence of power quality phenomena that are not steady-state conditions, such as sags, swells, transients and interruptions. This data can be either compared directly against the susceptibility specifications if supplied by the equipment manufacturer, or statistically compared against the various survey results that have been published in recent years. How to analyze the cause of the disturbance will be covered in the next section.

In North America, there are three recent studies that are useful in comparing against what is considered "normal", as far as the frequency of different types of power quality phenomena. The National Power Laboratories (NPL) survey was done at the point-of-utilization, the Canadian Electric Association (CEA) study was done at the point-of-common-coupling, and the Electric Power Research Institute (EPRI) survey was done at the distribution voltage levels. [7] Most European countries have also done such surveys, such as the Enel study in Italy, the East Midlands study in England, and the IQF study in France.

In summary, the preventive maintenance program can identify parameters that are likely to result in long-term system degradation or make the system vulnerable to power quality phenomena, such as low nominal line voltage that can be corrected with a transformer tap change. With many power quality monitors and software available in today's marketplace, such a program does not require much of the user's time nor effort.

3. INVESTIGATIVE ANALYSIS

To cover the analysis of power quality data for all of the potential causes of all the various types of disturbances would be a very lengthy dissertation. The following discussion is limited to sags, (or dips) as they are normally the most common and "are the most important power quality problem facing many industrial customers." [8]

The steps in undertaking an investigative analysis are similar to the preventive maintenance steps. At the analysis step, the first thing to do when determining the cause of sags is usually to determine if the cause was from the source side or the load side. This is also referred to as upstream or downstream, respectively, from the monitoring point. The source side would usually be the electric utility, if monitoring at the PCC. If monitoring at the end of a branch circuit, the source could be other branches off the same feeder, other feeders within the facility, or the electrical supply from the utility or back-up system.

3.1 SOURCE GENERATED SAGS

If one considers just source-generated sags recorded at the PCC, they can be the result of problems at the transmission, distribution, or even the generation level. From a study done in Northern Virginia, which experiences 40 thunderstorms in a typical year, the causes of distribution system sags are shown in Table 3.[10]

Other studies have shown similar results of lightning being the predominate cause of sags on distribution systems. Obviously, these percentages are different based on geographic location and the frequency of lightning-caused events. While the industrial/commercial facility manager usually has little recourse in preventing the occurance of such, it is normally not very difficult to determine that the fault occurred on the utility side with proper monitoring equipment. Appropriate mitigation actions can then be implemented to minimize the impact on the facility, such as installing UPS systems on critical loads.

To determine that the sag is the result of a utility system operation, knowledge of the fault-clearing scheme used the utility, along with an accurate monitoring of the voltage and current waveforms is needed. In the United States, most distribution breakers operate in 3-10 cycles with a high-current fault. They will also attempt to reclose 4-6 times before locking out. An example of such can be seen in Figure 1.

By determining if the current amplitude stayed constant, increased slightly, or decreased during the voltage sag, it can usually be determined that it was a source-generated sag, not a load-generated sag. With most switch-mode power supplies that are not heavily loaded, the voltage sag will reduce in input voltage to the power supply to a value less than the voltage level on the filter capacitor after the rectifying circuit.

While this condition remains, no current will be drawn. When the voltage on the capacitor is depleted below the voltage of the sag, then current will again be drawn. With a linear load, the current draw will go down proportionally to the decrease in the voltage. Constant power devices will increase the current drawn slightly, to maintain a constant power with the decreased voltage of the sag.

Knowing the transformer configuration at the service entrance (or any secondary transformer in series back toward the source), can also provide useful information in determining if it was a source generated sag. Single line-to-ground faults (SLTG) on the utility system are much more common than phase-to-phase or three-phase faults. [11] During such SLTG faults, for wye-wye and delta-delta connections, two phase-phase voltages will drop to 58% of nominal, while the other phase-to-phase voltage is unaffected. For delta-wye and wye-delta connections, one phase-to-phase voltage will be as low as 33% of nominal, while the other two voltages will be 88% of nominal. It is the circulating current in the delta secondary windings that results in a voltage on each winding. [12] Figure 2 illustrates this point, with Phase C-A sagging to about 33%, while phases A-B and B-C sag to about 88% of nominal.

If the monitoring point is downstream from the breaker that is attempting to clear the fault on a radial distribution system, than an interruption will be seen while the breaker is open, which is also illustrated in Figure 2. If the fault occurred on a parallel feeder, than the sag will end when the breaker opens.

If current is not monitored, there are some other clues that point to the source of the sag being a utility protection scheme operation. Since the contacts do not open or close cleanly, there will often be some voltage transients observed during the cycle at each end of the fault. Another clue is that the voltage usually drops abruptly and recovers abruptly. Since most industrial loads do not cycle on for 3-10 cycles only, and a motor start results in a voltage sag that recovers gradually, this type of fault is often readily discernible.

3.2 LOAD GENERATED SAGS

Though the electric utilities are frequently blamed for the source of sags, several studies, including the NPL study, have shown that “50% or more of the low/high RMS events are caused by load equipment in the building”.[10] “Sags found in industrial environments are generally due to the start-up of a load or a faulted circuit.” [13] Here is where Ohm’s and Kirchoff’s Laws are very useful in determining the cause the sag and the effects of loads starting up.

When loads normally start, there is an increase in current (I load) based on the load's impedance (Zload) and line voltage (Vsource). As mentioned before, the source and load impedances can easily be calculated if voltage and current are monitored on a cycle-by-cycle basis. Kirchoff's Laws states that the sum of the voltages around a closed loop must equal zero. An increase in current caused by a load change will result in an increased voltage drop across the source impedance(Vz = Iload * Zsource). Refer to Figure 3.

If the source voltage remains constant (which is a reasonable assumption if the source is considered as the electric utility generator), then the voltage across the load will decrease by the amount of the voltage drop across the source impedance. Figures 4 and 5 show an example of a sag caused the periodic cycling of the heating element in a laser printer. The top waveform is the Line-to-Neutral Voltage, the middle is the current, and lower is the Neutral-to-Ground voltage. Observe how the N-G voltage and current waveforms are very similar. If the source impedance is split between both legs feeding the load, then it can be easily seen how an increase in line current would develop a voltage drop in the neutral leg, which would result in the neutral-to-ground swell seen here.

With electric motors, the load impedance changes over time when energized, and results in the in-rush current waveform show in Figure 6. Note how the sag in Figure 7 begins as the motor starts, and then the voltage recovers somewhat as the load current achieves a steady state value.

4.0 SUMMARY

Using a power quality monitor to do preventive maintenance surveys and/or after-the-fact investigations requires the knowledge of Ohm's and Kirchoff's Laws. The data gathered from the survey is compared against acceptable limits to determine what parameters could be affecting the proper operation of equipment. For the forensic investigation, the direction of the power quality phenomena is determined first (source or load generated). Then, by analyzing the characteristics of the voltage and current waveforms and comparing them against those produced by different types of loads or system operations, the source in many cases can be quickly tracked down.

5. APPENDICES

5.1 Appendix A

Type of PQ Phenomena	Magnitude	Duration
Transient, Impulsive Oscillatory		
Short Duration RMS Variations		
Instantaneous, Interruption, Sag Swell	< 0.1 pu 0.1 - 0.9 pu 1.1-1.8 pu	0.5 - 30 cycles
Momentary, Interruption,	< 0.1 pu	

Sag, Swell	0.1 - 0.9 pu 1.1-1.8 pu	0.5 - 3 seconds
Temporary, Interruption, Sag, Swell,	< 0.1 pu 0.1 - 0.9 pu 1.1-1.8 pu	3 seconds - 1 minute
Long Duration RMS Variations, Interruption, Undervoltage, Overvoltage	< 0.1 pu 0.1 - 0.9 pu 1.1-1.8 pu	
Waveform Distortion		
Power Frequency Events		

IEEE 1159 Power Quality Phenomena [1].

5.2 Appendix B

Environmental Attribute	**Typical Environment**	**Normal**	**Critical**
Line Frequency	+/-0.1% - +/-3%	+/-1%	+/-0.3%
Over/under voltage	+/-5%, +6,-13.3%	+5%, -10%	+/-3%
Phase imbalance	2%-10%	5% max	3% max
Tolerance to low PF	0.85-0.6 lagging	0.8 lagging	less 0.6 lagging or 0.9 leading
Voltage THD	0-20% Total RMS	10-20% total, 5-10% largest individual	5% max total, 3% largest
Voltage Modulation	Negligible to 10%	3% max	1% max
Sags/Swells	+10%, -15%	+20%, -30%	+/-5%
Transient Impulses	2-3 times nominal peak value	Varies:1000-1500V	Varies:200-500V
Ground Currents	0-10Arms	0.001-0.5A	0.0035A or less

Some Representative Power Quality Attributes from FIPS PUB 94, pg 90.[13]

5.3 Appendix C

CAUSE	NUMBER OF SAGS	PERCENTAGE
Wind and Lightning	37	46%

Utility Equipment Failure	8	10%
Construction and Traffic Accidents	8	10%
Animals	5	6%
Tree limbs	1	1%
Unknown	21	26%

Table 3. Cause of Utility Distribution Sags

5.4 Appendix D - Figures

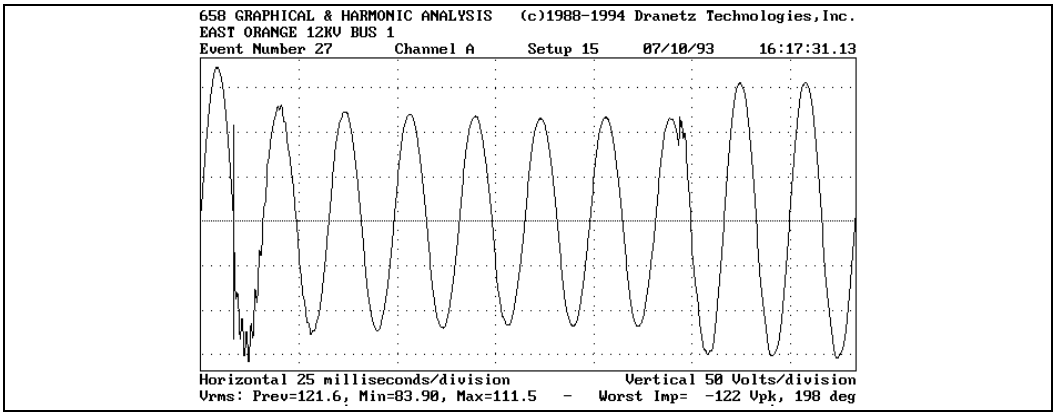
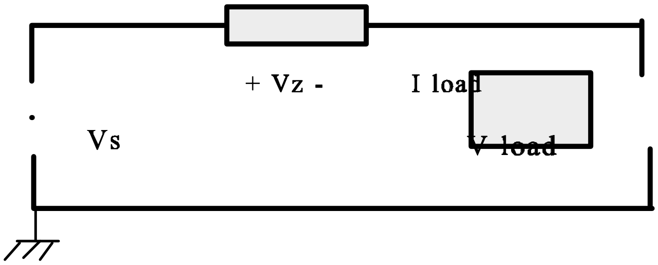


Figure 1. Sag Caused by Utility Distribution Breaker Operation



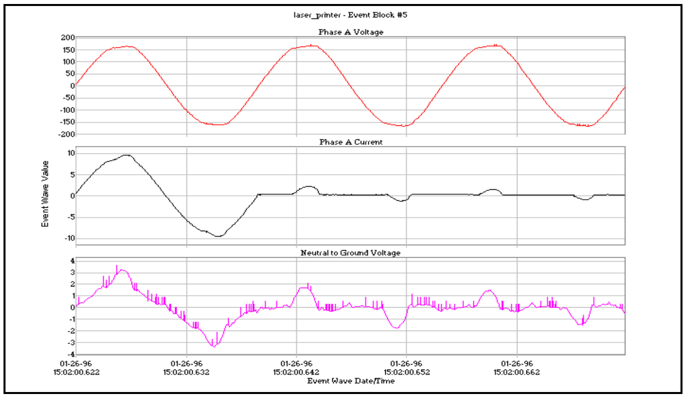
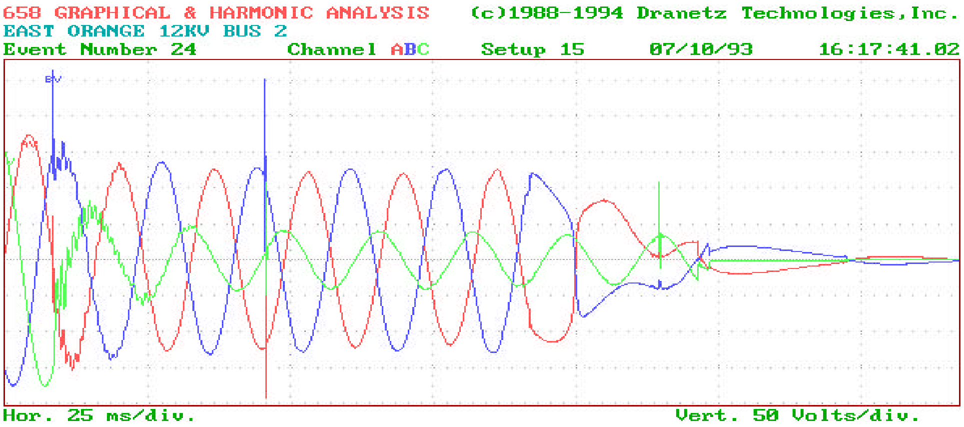


Figure 2. Single-Line-to-Ground Fault Sag then Interruption

Figure 3. Equivalent Impedance Diagram

Figure 4 and 5. Laser Printer Heating Element Cycling On and Off



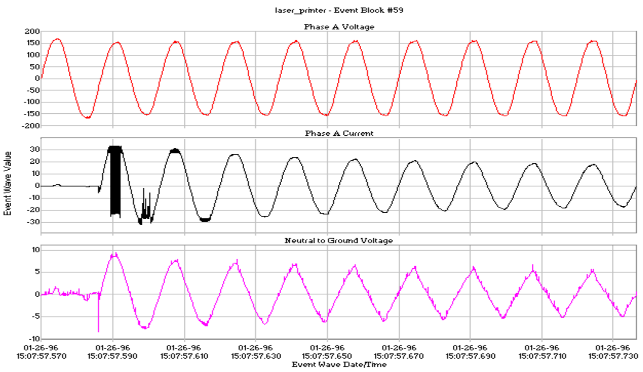


Figure 6 and 7 Inrush Current and Voltage Sag Caused by Motor Start

6. REFERENCES

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