CHAPTER 1

INTRODUCTION

1.1 General

Power electronics and power quality are irrevocably linked together as it strives to advance both broad areas. With the dramatic increases over the last 20 years in energy conversion systems utilizing power electronic devices, it is seen that the emergence of 'power quality' and simple control algorithm modification to this same technology can often play an equally dominant role in enhancing overall quality of electrical energy available to end-users.

Power electronics has given, as an industrial society, a plethora of new ways to manufacture products, provide services, and utilize energy. From a power quality impact viewpoint, applications such as

1. Switched-mode power supplies,
2. DC arc furnaces,
3. Electronic fluorescent lamp ballasts,
4. Adjustable speed drives, and
5. Flexible AC transmission components

are often cause for concern. From a utility supply system viewpoint, these converter-based systems can lead to operational and life expectancy problems for other equipment, possibly not owned or operated by the same party. It was from this initial perspective that the field of power quality emerged.
In most cases, the same devices and systems that create power quality problems can be used to solve power quality problems. 'Problem solving' applications such as

1. Active harmonic filters,
2. Static and adaptive var compensators, and
3. Uninterruptable power supplies

all utilize the same switching device technology as the 'problem causing' applications.

As the number of potentially problematic power electronic based loads have increased over time, the attention is given to enhanced converter control to maximize power quality. Perfect examples of these improvements include:

1. Unity power factor converters,
2. Dip-proof inverters, and
3. Limited-distortion electronic lamp ballasts.

While many studies suggest increases in power electronic-based energy utilization as high as 70-80% (of all energy consumed), it is equally clear that we are beginning to realize the total benefit of such end-use technologies. Power quality problems associated with grounding, sags, harmonics, and transients will continue to increase because of the sheer number of sensitive electronic loads expected to be placed.

1.2 Power quality

The term 'power quality' means different things to different people. To utility suppliers, power quality initially referred to the quality of the service delivered as 'measured' by the consumer's ability to use the energy delivered in the desired manner. This conceptual definition included such conventional utility planning topics as voltage and frequency regulation and reliability. The end-user's
definition of power quality also centers around their ability to use the delivered energy in the desired manner, but the topics considered can be much more specific and include magnitude and duration of different events as well as wave shape concerns. Fortunately, a good working definition of power quality has not been a point of contention, and most parties involved consider 'quality power' to be that which allows the user to meet their end use goals. The working definition is not complicated by particular issues; engineers are well aware that topics from many aspects of power engineering may be important. Power quality can be roughly broken into a few categories as follows:

1. Steady-state voltage magnitude and frequency,
2. Voltage sags,
3. Grounding,
4. Harmonics,
5. Voltage fluctuations and flicker,
6. Transients, and
7. Monitoring and measurement.

The remainder of this section discusses each of the major categories in turn.

1.2.1 Steady – State Voltage Frequency and Magnitude

In most areas of North America, steady-state frequency regulation is not a significant issue due to the sufficient levels of generating capacity and the strong interconnections among generating companies and control areas. In other parts of the world, and North America under extreme conditions, frequency can drive \( \frac{1}{4} \) to \( \frac{1}{2} \) Hz during periods of insufficient generating capacity. Under transient conditions, frequency can deviate up to 1-2Hz.

Frequency deviations can affect power electronic equipment that use controlled switching devices unless the control signals are derived from a signal
that is phase-locked with the applied voltage. In most cases, phase locks are used, or the converters consist of uncontrolled rectifiers. In either case, frequency deviations are not a major cause of problems. In most cases frequency deviations have more impacts on conventional equipment that do not use electronics or very inexpensive electronic devices. Clocks can run fast (or slow), motor speeds can drop (or rise) by a few revolutions per minute impact and are not considered a real power quality problem.

**Table 1.1 Ansi C84.1 Voltage Ranges**

ANSI C84.1 voltage ranges. Range A is for normal conditions, Range B is for emergency or short-time conditions.

<table>
<thead>
<tr>
<th></th>
<th>Service Voltage (%)</th>
<th>Utilization Voltage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Range A</td>
<td>114-125V</td>
<td>108-125V</td>
</tr>
<tr>
<td>Range B</td>
<td>110-127V</td>
<td>104-127V</td>
</tr>
</tbody>
</table>

Steady-state voltage regulation is a much more pronounced issue that can impact a wide range of end-use equipment. In most cases, utility supply companies do a very effective job of providing carefully regulated voltage within permissible ranges. In North America, ANSI Standard C84.1 suggests steady-state voltage ranges both at the utility service entrance and at the point of connection of end-use equipment. Further-more, equipment manufacturers typically offer equipment that is tolerant of steady-state voltage deviations in the range of ±10%. Table 2.1 shows the voltage ranges suggested by ANSI C84.1, with specific mention of normal (Range A) and contingency (Range B) allowable voltages, expressed in percent.

Virtually all equipment, especially sensitive electronic equipment, can be affected by voltage deviating outside the ±10% range. In most cases, over voltages above +10% lead to loss of life, usually over times; excessive over
voltages can immediately fail equipment. Under voltages below -10% usually lead to excessive current demands, especially for equipment that has a controlled output like an adjustable speed drive controlling a motor to a constant speed/torque point. The impacts of these prolonged excessive currents can be greater voltage drop, temperature rise in conductors. In the extreme, under voltages of more than 15-20% can cause the equipment to trip immediately. In most cases, such extreme under voltages are associated with system faults and the associated protection system. These extreme under voltages are so important that they are classified in a power quality category of their own, called voltage sags.

1.2.2 Voltage Sags

Other than improper grounding, voltage sags are probably the most problematic of all power quality problems. A number of standards-making bodies, including IEEE, ANSI, and IEC, are working on standards related to sags. In most cases, sags are generally agreed to be more severe and outside of the scope and they are temporary in nature due to the operation of system protection elements. Because the electrical system is a continuous electrical circuit, faults in any location will have some impact on voltages throughout the network. Of course, areas closer to the faulted area will see a greater voltage sag due to the fault than other, more (electrically) remote areas. Sags can originate anywhere in a system, but are more pronounced in utility distribution systems because of the greater exposure of low-voltage systems to the causes of short circuits.

Most utility companies implement distribution system protection in what is known as a 'fuse saving' methodology. In overhead distribution/system, two feeders (named 1 and 2) are supplied from the same substation transformer. Each primary circuit has its own automatic circuit recloser (ACR).

With the protection system set up based on fuse-saving methodology, any fault downstream of a fault will be cleared first by the substation recloser followed by a reclosing operation (re-energization of the circuit) \( \frac{1}{2} \) to 2 seconds
later. If the fault is still present, the closer fuse should blow to permanently isolate the fault.

For a fault on the load side of fused Tap 2, customers on Feeder 1 will see a voltage sag determined by the system land transformer impedance at the substation. Because this impedance is typically in the same order (or larger) as the feeder circuit impedance, a sag in substation bus voltage of 50% is common. This sag will persist until Feeder 2 is cleared by the recloser opening. When the recloser re-energizes the circuit, a permanent fault will still be present and the substation bus will again experience voltage sag. Of course, any sag in substation bus voltage will be delivered directly to all customers on Feeder 1, even though there is no electrical problem on that feeder.

Voltage sags are probably the most common power quality problem that is 'given' to the end-user by the supplying utility. However, improper equipment grounding is responsible for the vast majority of power quality problems on the customer's side.

Voltage sags cause interruption to the production with raw material loss in the production lines and damage in electronic boards. This has been a major complaint by big customers like large industrial firms. It may be ranked as the second complaint of power quality after the harmonics. However, the extent of damage and business interruption due to the voltage sag is higher than the harmonics. Most of the electronic equipments cannot be repaired locally and have to be imported from the manufacturer, which takes large time and cost high. The harmonics, damaging capacitors and cables, with higher occurrence than voltage sags, are more easy to repair by substitution from the local market. The problem is more severe in large industrial areas where cables and substation are highly loaded. In some cases where the voltage sag lasted to many cycles, damage to motors has been recorded. The use of reactive compensation is more feasible from
the economic point of easy installation and maintenance. (Fabio Tosato and Stefano Quaia 2001).

Voltage sag may be defined as momentary decrease from 0.1-0.9 p.u, in the RMS voltage magnitude at the power frequency for duration from 0.5 cycle to one minute. Its main reasons are large motor starting and electrical faults associated with heavily loading of cables and transmission systems. Due to their small duration, voltage sags do not cause damage to motor or large equipments, although they cause some stresses on the insulation and disturbance to the operation. However, they can disrupt electronic equipments such as variable speed drives, Personal Computers etc., thus disrupting the operation (McGranaghan et. al. 1993)

1.2.3 Grounding

Grounding of equipment was originally conceived as a personnel safety issue. However, the presence of an electrical conductor that is at zero potential has been widely used in many power electronic and microprocessor-controlled loads. The electrical systems in residential, commercial, and industrial facilities fall under the purview of the National Electric Code which establishes specific criteria for grounding of equipment. While it was once thought that proper grounding according to the NEC was detrimental to power quality concerns, these opinions have gradually faded over time.

From a power quality perspective, improper grounding can be considered of three broad categories:

1. Groups loops,
2. Improper neutral-to-ground connections, and
3. Excessive natural-to-ground voltage.
The group loop problem is a significant issue when power, communications and control signals all originate in different locations, but come together at a common electrical point. Transients induced in one location can travel through the created ground loop, damaging equipment along the way. Improper neutral-to-ground connections will create a 'noisy' ground reference that may interfere with low-voltage communications and control devices. Excessive neutral-to-ground voltage may damage equipment that is not properly insulated or that has an inexpensive power supply.

For any shift in ground potential for the power circuit, often caused by lightening, potentially large currents can flow through the grounding circuits and through the sensitive electronic equipment. Such currents can easily lead to equipment damage. Situations like these are common in

1. Residential areas, if power and telephone grounds are not the same, and
2. Commercial and industrial complexes consisting of multiple buildings with linking communications, computer, or control circuits when each building has its own power service (and therefore ground).

Load current returning in the neutral conductor will, at the point of improper connection to ground, divide between neutral and ground. This current flow in the ground conductor will produce a voltage at the load equipment, which can easily disrupt equipment operation.

For load equipment that produces significant voltage drop in the neutral, such as laser printers and copying machines when the thermal heating elements are on, the voltage from the neutral to the ground reference inside the equipment can exceed several volts. This voltage is sufficient to damage printed circuit boards, disrupt control logic, and fail components.
1.2.4 Harmonics

In most cases, power electronic equipment is considered to be the 'cause' of harmonics. While switching converters of all types produce harmonics because of the non linear relationship between the voltage and current across the switching device, harmonics are also produced by a large variety of "conventional" equipment including:

1. Power generation equipment (slot harmonics),
2. Induction motors (saturated magnetics),
3. Transformers (over excitation leading to saturation),
4. Magnetic-ballast fluorescent lamps (arcing), and
5. AC electric arc furnaces (arcing).

All these devices will cause harmonic currents to flow, and some devices actually directly produce voltage harmonics.

Any alternating current flow through any circuit at any frequency will produce a voltage drop at that same frequency. Harmonic currents, which are produced by power electronic loads, will produce voltage drops in the power supply impedance at those same harmonic frequencies. Because of this inter relationship between current flow and voltage drop, harmonic currents created at any location will distort the voltage in the entire supply circuit.

In most cases, equipment is not overly sensitive to the direct impacts of harmonic current flow. However, equipment heating is a function of the RMS value of the current, which can significantly exceed the fundamental frequency value when large harmonic components are present. It is because harmonic currents produce harmonic voltages that are a real power quality concern.

Most equipments can operate satisfactorily as long as the voltage distortion at the equipment terminals do not exceed around 5%. Exceptions to this general rule include ripple-control systems for converters (which are impacted by small even-order harmonics) and small harmonics at sufficiently high frequency to
produce multiple zero crossing in a wave-form. (Note that voltage notching due to simultaneous commutation of switching devices can also create multiple zero crossings).

Converters that have a time-limited firing signal can directly suffer from excessive voltage distortion. For a six-pulse converter, a maximum time of 1/(6x50) seconds is available to turn on a switching device. Similarly, for a twelve-pulse converter, a maximum of 1/ (12x50) is available to turn on a switching device. Considering that all switching devices have a short (but nonzero) turn-on time, manufacturers tend to design drive circuits that bring up the firing pulse for a limited amount of time.

For example, a firing pulse is maintained for 100 ps and the device must begin conduction at that time. In situations where voltage distortion is excessive, the device to be switched could be reverse biased during the first several milliseconds of the time available for device firing during which time conduction cannot begin. If the firing signal is removed before the certain classes of switching devices which are correctly biased, conduction will not begin at all. This situation, commonly called a 'misfire', can lead to equipment mis operation and failure.

Because some switching devices can conduct in both directions when the firing signal is applied (but only one direction is intended to carry appreciate current), applying the firing pulse at a time when the voltage is of the wrong polarity can destroy the device. Excessive voltage distortion can certainly lead to such a situation, and manufacturers typically design products to function only under limited-distortion conditions.

Because of the numerous potential problems with harmonic currents, standards exist for their control. The IEEE takes a more 'system-level' point of view and prescribes limits for harmonic currents for a facility as a whole, including one or more harmonic producing loads.
1.2.5 Voltage Fluctuations and Flicker

Voltage flicker is not directly caused by electronic loads except in the largest of applications. Voltage fluctuations, and the corresponding light flicker due to them, where are usually created by large power fluctuations at frequencies less than about 30 Hz. In most applications, only

1. Large DC arc furnaces and welders,
2. Reactive power compensators, and
3. Cyclo converters

are potentially problematic. Each of these types of end-use devices can create large, low-frequency (about 30 Hz or less) variations in the system voltage, and can therefore lead to voltage flicker complaints. At this time, the IEEE prescribes a 'flicker curve' based originally on research conducted by General Electric. The IEC, however, has adopted a different methodology that can consider voltage fluctuations and flicker that are more complex than those considered by the IEEE flicker curve.

Most equipment are not sensitive to the voltage fluctuations that cause flicker complaints. The change in output of incandescent lamps as viewed by human observers becomes objectionable at levels of change around 0.3%, but Electronic equipment will not be affected at all. Because most utility supply companies limit voltage fluctuations, regardless of the frequency of repetition, to less than a few percent, equipment malfunction or damage due to flicker is very rare.

Because of the advances in power electronics that have offered devices with higher power ratings, reactive compensation systems have been developed to compensate for voltage fluctuations by adding or removing reactive power from the supply circuit. These devices have allowed large flicker-producing loads like arc furnaces to be served from utility circuits. However, because the compensators
can directly impact system voltage, they can create flicker problems if they are not properly applied and controlled.

1.2.6 Transients

Transients, especially in the voltage supply, can create numerous power quality problems. The major sources of transients are

1. Lightning,
2. Utility circuit switching and fault clearing,

Lightning events can create the most severe over voltages, but these transients decay rapidly. A typical lightning transient has decayed to zero in a few hundred microseconds, but it can reach a peak magnitude of several hundred percent if not controlled with surge suppression devices. Other categories of transients associated with power system switching are much smaller in magnitude, but at least in the order of several hundred milliseconds. Considering the energy available in a transient, therefore, there is considerable overlap in the range of severity of lighting and switching transients. It is the available energy that typically determines whether or not equipment will be affected or damaged. The device's protection system sees these over currents as a fault, and trip the drive. Similarly, the over voltage at the terminals can be passed through to the DC bus and accumulate, where the drive may trip due to over voltage on the DC bus.

1.2.7 Monitoring and Measurement

To consider or to diagnose power quality related problems, it is imperative to measure various power quality parameters. Several different categories of monitoring and measurement equipment exist for these purposes, with various costs for fully equipped disturbance analyzers.

The most basic category of power quality measurement tool is the hand-held voltmeter. It is important that the voltmeter be a true-rms meter, or
erroneous readings will be obtained, that incorrectly suggest low or high voltage when harmonics are present in the signal. It is especially important to have true rms capability when measuring currents; voltage distortion is not typically severe enough to create large errors in the reading of non-true-rms meters. Virtually all major measurement equipments are true-rms meters.

The next step up from the basic voltmeter is a class of instruments that have come to be called 'power quality analyzers'. These instruments are hand held and battery powered. These instruments can measure and display various power quality indices, especially those that relate to harmonics like THD, etc., and can also display the input waveform. New models feature 20MHz (and higher) bandwidth oscilloscopes, inrush measurements, time trending, and other useful features. Manufacturers such as Fluke, Dranetz, BMI, and Tektronix offer these types of instruments.

In most power quality investigations, it is not possible to use handheld equipment to collect sufficient data to solve the problem. Most power quality problems are intermittent in nature, so some type of long-term monitoring is usually required. More advanced long-term monitors can record numerous power quality events and indices, including transients, harmonics, sags, flicker, etc. These devices are often called 'line disturbance analyzers'.

It is important to use the right instrument to measure the phenomenon that is suspected to cause the problem. Some meters record specific parameters, while others are more flexible. With this flexibility comes an increased learning curve for the user, so it is important to spend time on them before going out to monitor, to make sure all aspects and features of the equipment are understood.

It is equally important to measure in the correct locations. The best place to measure power quality events is at the equipment terminals that are
experiencing problems. With experience, an engineer can evaluate the waveforms recorded at the equipment terminals and correlate them to events and causes elsewhere, in the power system. In general, the farther away from the equipment location the monitoring takes place, the more difficult it can be to diagnose a problem.

1.3 Summary

The fundamentals of power quality are presented in this chapter.