Section 11: Power Quality Considerations

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Introduction

The term *power quality* may take on any one of several definitions. The strict definition of *power quality* is "the concept of powering and grounding electronic equipment in a manner that is suitable to the operation of that equipment and compatible with the premises wiring system and other connected equipment" [1]. In practice, however, the term *power quality* is often used to denote the proximity of the system voltage to its sinusoidal form at the nominal voltage level. Deviation from this sinusoidal norm therefore denotes a power *quality issue*. Strictly speaking, this deviation is actually a *power disturbance*, defined as "any deviation from the nominal value (or from some selected thresholds based upon tolerance) of the AC input power characteristics" [1]. The most common power disturbances are, as defined by [1]:

Overvoltage: An RMS increase in the AC voltage, at the power frequency, for a period of time greater than 1 min. Typical values are 110%-120% of nominal.

Undervoltage: An RMS decrease in the AC voltage, at the power frequency, for a period of time greater than 1 min. Typical values are 80-90% of nominal.

Swell: An increase in RMS voltage or current at the power frequency for durations from .5 cycle-1 min. Typical values are 110%-180% of nominal.

Sag: An RMS reduction in the AC voltage, at the power frequency, for durations from _ cycle to a few seconds.

Interruption: The complete loss of voltage. A *momentary interruption* is a voltage loss (<10% of nominal) for a time period between .5 cycles and 3 seconds). A *temporary interruption* is a voltage loss (<10% of nominal) for a time period between 3 seconds and 1 min. A *sustained interruption* is the complete loss of voltage for a time period greater than 1 min.

Notch: A switching (or other) disturbance of the normal power system voltage waveform, lasting less than _ cycle; which is initially of opposite polarity to the waveform, and is thus subtractive from the normal waveform in terms of the peak value of the disturbance voltage. This includes a complete loss of voltage for up to _ cycle.

Transient: A subcycle disturbance in the AC waveform that is evidenced by a sharp discontinuity of the waveform. May be of either polarity and may be additive to, or subtractive from, the nominal waveform.

Flicker: A variation in input voltage, either magnitude or frequency, sufficient in duration to allow visual observation of a change in electric light source intensity.

Harmonic Distortion: The mathematical representation of distortion of the pure sine waveform. This refers to the distortion of the voltage and/or current waveform, due to the flow of non-sinusoidal currents.

Electrical Noise: Unwanted electrical signals that produce undesirable effects in the circuits of the control systems in which they occur. Noise may be further categorized as transverse-mode noise, which is measurable between phase conductors but not phase-to-ground, and common-mode noise, which is measurable phase-to-ground but not between phase conductors. This noise may be conducted or radiated. Also referred to as RFI (radio-frequency interference) or EMI (electro-magnetic interference).

The causes of the common power disturbances listed can vary greatly. Common causes are listed in Table 11-1:

Table 11-1: Common power disturbance causes

Disturbance	Common causes
Overvoltage	Voltage regulator malfunction Improperly set transformer taps Improperly-applied power factor correction capacitors
Undervoltage	Voltage regulator malfunction Improperly set transformer taps Large source impedance ("weak" system)
Voltage Swell	Recovery of system voltage following a fault Remote switching (capacitors, etc.)
Voltage Sag	Remote fault Cold-load pickup (motor starting, transformer energization, etc.) Large step loads
Transient (Typically voltage surges)	Lightning strikes Close-in switching (capacitors, etc.) Complex circuit phenomena such as current chopping, restrikes, system resonance, etc.
Flicker	Arcing loads such as arc furnaces Also same sources that cause voltage sags and swells
Notches and Harmonic Distortion	Power electronic converter equipment such as rectifiers, inverters, drives, etc., which produce non-sinusoidal load current and commutation notches
Interruptions	Faults causing overcurrent protective device operation Utility maintenance activities
Electrical Noise	Power electronic converter equipment such as drives Conductors and power equipment which carry large amounts of current Arcing in overcurrent protective devices

Power disturbances can greatly affect utilization equipment. For example, sensitive electronic medical equipment can malfunction, adjustable speed motor drives may trip off-line, etc. Interruptions can cause microprocessor-based equipment such as computers to lose data. In extreme conditions, such as for voltage surges caused by direct lightning strikes, both power equipment and utilization equipment may be subject to failure. With the high reliability requirements imposed upon power systems, it is imperative that power system disturbances, or potential disturbances, be mitigated to avoid down-time, equipment failure, and risk to human life.

Power quality metrics

There are various methods for categorizing the severity of power disturbances. The most typical indices for measuring power quality disturbances are:

Distortion Factor: The ratio of the root square value of the harmonic content to the root square value of the fundamental quantity, expressed as a percentage of the fundamental, also known as total *harmonic distortion* [1].

$$Distortion\ Factor(THD) = \sqrt{\frac{\sum_{h=2}^{n} V_h^2}{V_1^2}} \times 100\% \qquad (11\text{-}1)$$

where

V_h is the RMS harmonic voltage (or current) value at a frequency of n times the fundamental frequency
V_1 is the RMS fundamental-frequency voltage or current

Alternate forms for the distortion factor are given in [2] as percentages of the nominal voltage or demand load current for the system under consideration, for use in evaluation of the harmonic content of the system voltage or current. These are referred to as Total Harmonic Distortion (THD_{Vn}) and Total Demand Distortion (TDD), defined as follows:

$$THD_{Vn} = \sqrt{\frac{\sum_{h=2}^{n} V_h^2}{V_n^2}} \times 100\% \qquad (11\text{-}2)$$

$$TDD = \sqrt{\frac{\sum_{h=2}^{n} I_h^2}{I_L^2}} \times 100\% \qquad (11\text{-}3)$$

where

- V_h is the RMS value of the n[th] harmonic component of the voltage
- V_n is the RMS nominal fundamental voltage value
- I_h is the RMS value of the n[th] harmonic component of the current
- I_L is the maximum demand load current, typically the average maximum monthly demand over a 12-month period

Crest Factor: The ratio of the peak value of a periodic function to the RMS value, i.e.:

$$crest\ factor(cf) = \frac{y_{peak}}{y_{rms}} \qquad (11\text{-}4)$$

where

- y_{peak} is the peak value of a periodic function
- y_{rms} is the RMS value of the function

Because power system voltages and currents are nominally sinusoidal, the nominal crest factor for these would be √2, which is 1.414 (see "Electric Power Fundamentals" section (section 2) for details).

Notch Area: A notch in the power system voltage (or current) is illustrated in figure 11-1 [2]:

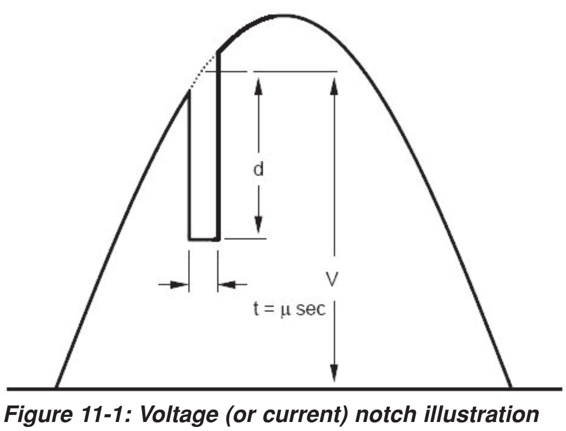

Figure 11-1: Voltage (or current) notch illustration

The notch area for the notch as illustrated in figure 11-1 is defined as:

$$A_n = t \cdot d \qquad (11\text{-}5)$$

where

- A_n is the notch area in volt-microseconds
- t is the notch time duration in microseconds
- d is the notch depth in volts

Recovery time: This is the time needed for the output voltage or current to return to a value within the regulation specification after a step load or line change.

Displacement Power Factor: The ratio of the active power of the fundamental wave, in watts, to the apparent power of the fundamental wave, in volt-amperes. This is the traditional definition of power factor.

Total Power Factor: The ratio of the total input power, in watts, to the total volt-ampere input. This includes the effects of harmonics.

K Factor: A measure of a transformer's ability to serve non-sinusoidal loads. The K factor is defined as:

$$K = \sum_{h=1}^{h_{max}} \left(I_{h(pu)}^{2} \cdot h^{2} \right) \qquad (11\text{-}6)$$

where

I_h	is the harmonic component at h times the fundamental frequency
h	is the harmonic order of Ih in multiples of the fundamental frequency
h_{max}	is maximum harmonic order present

Voltage surges

The causes of voltage surges may be split into two major categories: Power system switching and environmental [1]. Both exhibit decaying oscillatory transients. Capacitor switching close to the point under consideration is the most common cause of switching surges, while lightning is the most common cause of environmentally-induced voltage surges. Both can cause severe damage to unprotected power system components, with the potential for lightning damage being the most severe; in the worst case, lightning damage can be catastrophic.

Surge arrestors, as described in Section 7, are typically used to protect against voltage surges. On low voltage systems transient voltage surge suppressors (TVSS), also described in Section 7 are also used. For motors, surge capacitors are an option. In severe cases, custom-designed R-C snubber circuits may be required as well.

Voltage sags, swells and interruptions

Voltage sags, swells and interruptions have many causes. Remote switching or lightning strikes can cause voltage swells, as can the recovery of the system voltage after a fault. Voltage sags can be caused due to transformer or motor inrush or large step loads, especially on systems without large amounts of available fault current. Voltage interruptions are generally caused due to protective device operation.

Protection of sensitive equipment against voltage sags and swells can be difficult. Fast-acting voltage regulators offer the one means of defense against these phenomena, although any voltage regulator must be properly applied to avoid worsening the problem. Fast-acting voltage regulators can generally be classified as tap-switching, buck-boost, or ferroresonant (also known as CVT "constant voltage transformer") types [1]. New solid-state tap switching technologies for voltage regulators provide faster response than older, electromechanical switching technologies. Other devices, such as "power line conditioners" which combine some TVSS functions with voltage regulation and noise reduction, and motor-generator sets, are also used [1].

Protection of sensitive loads against voltage interruptions is best performed with an *uninterruptible power supply* or UPS. This device is available in several different topologies and is crucial where microprocessor-based devices are to be powered. UPSs are discussed in more detail in a later section of this guide.

Harmonic distortion

Harmonic distortion is a subject of great interest in modern power systems. Harmonic distortion results from non-sinusoidal load currents. These currents are the result of non-linear loads, such as drives, which employ power electronic devices to rectify the AC waveform. These devices draw non-sinusoidal currents which, in turn, cause non-linear voltages to be developed in the system.

IEEE Standard 519-1992 [2] gives recommended limits for current distortion due to consumer loads and voltage distortion in the utility supply voltage. Both are referenced at the point on the utility system where multiple customers can be served, referred to as the Point of Common Coupling (PCC). The requirements from [2] for current distortion limits on general distribution systems 120 V - 69 kV are given in table 11-2. Table 11-3 shows the corresponding utility voltage distortion limits.

Note that the current limits are given both as limits on the individual harmonic levels and a limit on the TDD, and that as the ratio Isc/IL increases the limits also increase. The reason for this is that the current distortion limits are designed to limit the voltage distortion at the PCC, and the voltage distortion for a given current distortion worsens with a larger source impedance ($\overline{V} - \overline{I} \bullet \overline{Z}$).

Table 11-2: IEEE 519-1992 Harmonic current distortion limits for general distribution systems 120 V through 69 kV (essentially same as [2] table 10-3)

Maximum harmonic current distortion in percent of I_L						
Individual harmonic order (Odd harmonics)						
I_{sc}/I_L	<11	11<h<17	17≤h<23	23≤h<35	35≤h	TDD
<20*	4.0	2.0	1.5	0.6	0.3	5.0
20<50	7.0	3.5	2.5	1.0	0.5	8.0
50<100	10.0	4.5	4.0	1.5	0.7	12.0
100<1000	12.0	5.5	5.0	2.0	1.0	15.0
>1000	15.0	7.0	6.0	2.5	1.4	20.0
Even harmonics are limited to 25% of the odd harmonic limits above.						
Current distortions that result in a DC offset, e.g. half-wave converters, are not allowed.						
*All power generation equipment is limited to these values of current distortion, regardless of actual I_{SC}/I_L						
where I_{SC} = maximum short-circuit current at PCC I_L = maximum demand load current (fundamental frequency component) at PCC						

Table 11-3: IEEE 519-1992 Harmonic voltage distortion limits (essentially same as [2] table 11-1)

Bus voltage at PCC	Individual voltage distortion (%)	THD_{Vn} (%)
69 kV and below	3.0	5.0
69.001 kV through 161 kV	1.5	2.5
161.001 kV and above	1.0	1.5

Note: High voltage systems can have up to 2.0% THD where the cause is an HVDC terminal that will attenuate by the time it is tapped for a user

Mitigation of harmonic distortion is generally accomplished by one of the following means:

- Passive tuned filters
- Use of phase multiplication on power conversion equipment
- Active filters

Passive tuned filters are simple series L-C filters. A single tuned passive filter can effectively mitigate one harmonic frequency. They are generally tuned to a value below the harmonic frequency to be attenuated to avoid a resonance condition at that frequency. These are custom-engineered solutions that must be designed specifically for the circuit in question. Passive filters are also used for power factor correction. However, there is a limit to their effectiveness and if higher-order harmonics must be attenuated their use is generally not cost-effective. Care must be taken in all cases to balance the harmonic and power factor correction considerations.

Phase multiplication operates on the principle that if *m* six-pulse rectifiers are shifted 60/*m* degrees from each other, are controlled by the same delay angle, and are loaded equally, the only harmonics present will be:

$$h = kq \pm 1 \qquad (11\text{-}7)$$

where

h	is a harmonic order present
q	= 6*m* and is known as the *pulse number* of the circuit
k	is any integer

Thus, for standard 6-pulse rectifiers the harmonic orders present will be 5, 7, 11, 13,…, etc. 18-pulse rectifiers are the current state-of-the-art; for an 18-pulse rectifier (*m*=3), the harmonic orders present are 17, 19, 35, 37, …, etc. For an 18-pulse converter, the lower-order harmonics are thus eliminated. For systems with large numbers of phase-multiplied converters the harmonic current limits in table 10-3 are increased by the factor $(q/6)^{1/2}$, where q is the pulse-number of the predominate non-linear load on the system. In this case the limits for the harmonic orders that do not fit equation (11-7) for the q of the predominate non-linear load are multiplied by a factor of 0.25. Phase-shifting transformer connections are used to achieve the 60/*m* degree phase shift between 6-pulse rectifier units.

Active filtering technology is a still-evolving art. Current state-of-the-art designs measure the current, filter out the fundamental frequency of the measured current, and inject current that is the negative of the result into the system to cancel the harmonics up to a given harmonic order. These systems are generally used in existing installations that have existing 6-pulse drives where replacing the drives is not a cost-effective solution, or where multiple smaller 6-pulse drives are utilized since phase multiplication for a drive below 100hp is generally not cost-effective. State-of-the-art units can also dynamically correct the power factor, and are advantageous vs. passive filters both in their effectiveness and their flexibility in power factor correction.

Power quality monitoring

Power quality monitoring is vital when sensitive equipment is to be powered, and also for the over-all reliability of the system. Microprocessor-based technology allows the most common power-quality instrumentation to be combined into a single monitoring device which incorporates wave-form capture, measures of the power quality metric values per the above discussion, and conventional current, voltage, power, and energy measurements, with min/max logging capabilities. These devices are typically true RMS-reading instruments, with measurements up to a given harmonic (typically 31st harmonic or higher).

The inclusion of power monitoring equipment in the initial power system design will make diagnosis of any subsequent power quality issues, should they arise, much easier and more efficient. Reference [3] contains much information on power quality monitoring and should be consulted for further reference.

References

[1] IEEE Recommended Practice for Powering and Grounding Electronic Equipment, IEEE Std. 1100-1999, March 1999.

[2] IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems, IEEE Std. 519-1992, June 1992.

[3] IEEE Recommended Practice for Monitoring Electric Power Quality, IEEE Std. 1159-1995.