A Guide to Power Quality Testing

Megger

Power on

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What is power quality?

Power quality is defined in several ways.

The IEC defines power quality as the characteristics of electricity at a given point on an electrical system, evaluated against a set of reference technical parameters.

This definition is based on the assumption that there is a standard set of parameters that the power quality phenomenon must meet. This definition is applicable where a set of standards are implemented whether through utility standards, contract or government policies.

The IEEE defines power quality as the concept of powering and grounding sensitive equipment in a manner that is suitable to the operation of that equipment.

This means that if equipment is operating correctly, then there is no power quality issue. If the equipment is not operating correctly due to the power it is receiving, then there is a power quality issue.

In the IEEE definition there is no predefined set of parameters that power quality must meet. Instead, the state of the power quality is determined by the operation of the end user equipment.

Power quality phenomenon

Power quality phenomenon are the circumstances that cause voltage or current deviations from its ideal waveform. These disturbances can cause failure of loads or equipment.

As technology progresses, the modern power grid is changing. The addition of green energy sources like solar and wind energy, and the reduction of coal bulk generation plants, are beneficial to the environment but also result in more power quality phenomenon.

As loads increase with the introduction of new technologies, like electric vehicles, the intermittent nature of solar power coupled with wind energy, voltage stability suffers. The implementation of smart grid technology is a way to help combat overload and make the grid more efficient and resilient. However, smart grid communications can also contribute to power quality phenomenon.

There are a variety of different types of power quality phenomenon, including under-voltage, over-voltage, dips (sags) and swells, transients, unbalance, flicker, harmonics (THD/TDD), inter-harmonics, RVC, as well as mains signaling issues. Each of these presents its own set of challenges to the end user. Megger's MPQ1000 and MPQ2000 Power Quality Analyzers help identify each of these phenomena so that they can be corrected.

Under-voltage

Under-voltage is a decrease in RMS voltage less than 0.9 pu (90%) for longer than one minute. Typical values of under-voltage are between 0.8 pu and 0.9 pu. This power quality phenomenon can occur for several reasons including, overloaded circuits, loads switching on, capacitor banks switching off or bad connections.

Under-voltage conditions can cause problems and failures in motors, appliances as well as lighting systems. Many appliances have single phase motors.

For a motor to drive a fixed load, it must draw a fixed amount of power. When the voltage decreases, the current must increase to provide the same amount of power. If that current exceeds the motor's current rating, the heat generated will end up overheating the coils.

Low voltage can also cause low light output levels in incandescent lighting. Fluorescent lamps may have difficulty starting. Low voltage conditions can also cause the lamp to flash off and on without starting. Over time this will deteriorate the lamp's electrodes.

Low voltage will cause room heaters and water heaters to heat at a slower rate.

Over-voltage

An over-voltage is an RMS increase in AC voltage greater than 1.1 pu for longer than one minute. Typical values associated with over-voltage are 1.1 pu to 1.2 pu. It occurs when the voltage in a circuit is raised above its upper design limit.

Over-voltage can be the result of load switching (switching off a large load like motors), variations in the reactive compensation (switching of cap banks), poor system voltage regulation capabilities or controls, as well as incorrect tap settings on a transformer.

It can cause problems and failures in motors, appliances as well as lighting systems. Over-voltage conditions on a motor can drive the magnetic portion of the motor into saturation. This causes the motor to draw excessive current, which, in turn, causes excessive heat that can damage the coils over a period of time.

Over-voltages will cause incandescent lighting to burn out prematurely.

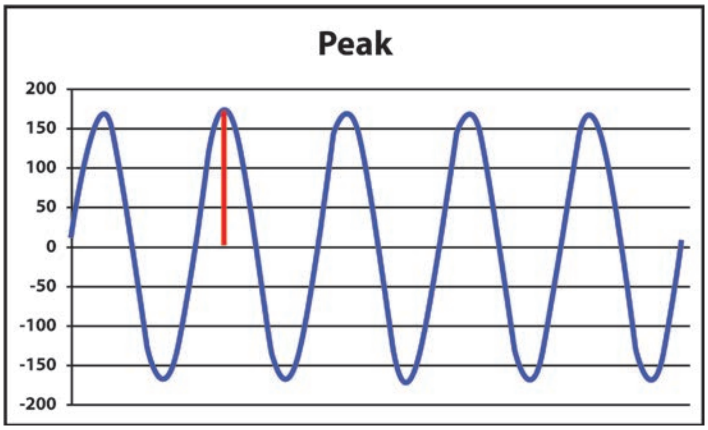
Over-voltages will cause resistive loads. Room heaters and water heaters will draw more current, causing them to run hot. This will lead to premature failure.

RMS voltage

RMS voltage is defined as the root mean square.

RMS is equal to the value of a direct current that will produce the same average power dissipation in a pure resistive load.

In a perfect sine wave, the RMS would be equal to the peak voltage times 0.707.



Peak = 169.68

RMS = 169.68 x 0.707

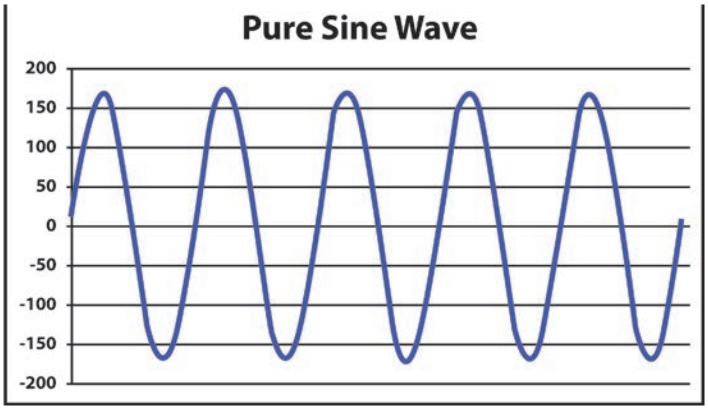
TRMS = 120.0

RMS (Root Mean Square) by definition is the square root of the arithmetic mean of the squares of the values.

$$RMS = \sqrt{\frac{\sum_{i=1}^{n}(Samples_i)^2}{n}}$$

When RMS is calculated in this manner, it is referred to as TRMS (True RMS).

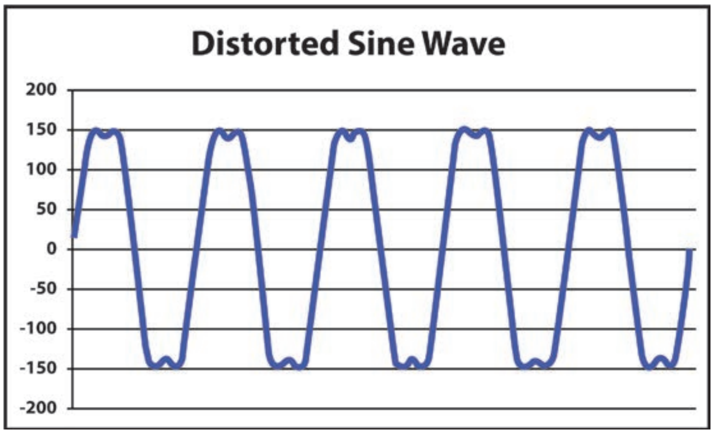
This is because when the waveform is a perfect sine wave, RMS will equal TRMS.



RMS = 120.0

TRMS = 120.0

However, when there is waveform distortion trying to calculate RMS by multiplying the peak of the waveform by 0.707, it will give the wrong result.



RMS = 103.9

TRMS = 121.6

In the real world, no voltage or current waveform is a perfect sine wave. There is always some level of harmonics providing waveform distortion. The greater the waveform distortion, the greater the error of a peak measurement times 0.707 will be. This is why TRMS (True Root Mean Square) measurements are used.

Voltage dips (sags) and swells

Voltage dips (sags) and swells are two of the most common power quality events that occur. Dips and swells cannot be prevented on power systems. As impedances change throughout the course of the day, so does the voltage - if only momentarily. Even the most instantaneous dips can cause operations to shut down and require hours to restart. Voltage swells are a common cause of tripping breakers and equipment tripping off line.

Voltage dips (sags)

Voltage dips (sags) can be caused by source voltage changes, or load side changes, including inadequate wiring.

On the load side, when a large load turns on, there is an abrupt decrease in impedance. This leads to an abrupt increase current known as a current in rush. When this occurs the current inrush can lead to a dip or sag in the voltage.

Source side faults that can cause voltage dips / sags include the following:

Single-Line-to-Ground (SLG) Fault - A single-line-to-ground fault is one of the most common types of faults. It is an asymmetrical fault that occurs when one conductor drops to the ground or comes in contact with the neutral conductor. These can occur due to high-speed wind, falling tree limbs and lightning.

Line-to-Line (LL) Fault - A line-to-line fault, or asymmetrical fault, occurs when two conductors are short circuited. These can be due to high winds causing adjacent lines to come into contact.

Double-Line-to-Ground (DLG) Fault - A double-line-to ground fault is an asymmetrical short circuit that occurs simultaneously between two phases along with the earth.

Three Phase (3P) Fault - A three phase fault is a symmetric fault which means it is a balanced fault. It affects each of the three phases equally. This is much rarer than the asymmetrical fault. When looking at transmission line faults, roughly 5% are symmetric faults. Although these faults are rarer they can result in severe damage to equipment.

Different types of dips / sags

Dips or sags, as they are referred to in some regions, can be classified differently depending on the standard. A voltage dip is also referred to as sag. The two terms are considered interchangeable.

The IEC61000-4-30 defines a voltage dip as a temporary reduction of the voltage magnitude at a point in the electrical system below threshold.

IEC 61000-4-30 defines an interruption as a special case of a voltage dip. An interruption is a reduction of voltage at a point in the electrical system below the interruption threshold.

Based on their duration and RMS magnitude, IEEE1159 categorizes dips / sags as follows:

Instantaneous dip / sag - A short duration voltage variation that lasts from 0.5 cycles to 30 cycles. The voltage during an instantaneous sag will vary from 10% to 90% of nominal.

Interruption - A short duration voltage variation that lasts from 0.5 cycles to 3 seconds. The voltage during an interruption will fall to less than 10% of nominal.

Momentary dip / sag – A short duration voltage variation that lasts from 30 cycles to 3 seconds. The voltage during a momentary sag will vary from 10% to 90% of nominal.

Temporary interruption instantaneous dip / sag - A short duration voltage variation that will last from 3 seconds to 1 minute. The voltage during this sag will fall to less than 10% of nominal.

Voltage swells

A voltage swell is basically the opposite of a voltage dip /sag. It is a temporary increase in RMS voltage.

Like voltage dips and sags, voltage swells are categorized differently by different standards.

A voltage swell is defined by IEC61000-4-30 as a temporary increase of the voltage magnitude at a point in the electrical system above a threshold.

Voltage swell is defined by IEEE 1159 as the increase in the RMS voltage level to 110% to 180% of nominal, at the power frequency for durations of ½ cycle to 1 minute.

Like sags, IEEE categorizes voltage swells by their duration and RMS magnitude, as follows:

Instantaneous swell - A short duration voltage variation that lasts from 0.5 cycles to 30 cycles. The voltage during an instantaneous swell will vary from 110% to 180% of nominal.

Momentary swell – A short duration voltage variation that lasts from 30 cycles to 3 seconds. The voltage during a momentary swell will vary from 110% to 140% of nominal.

Temporary swell - A short duration voltage variation that will last from 3 seconds to 1 minute. The voltage during this swell will vary from 110% to 120% of nominal.

Like voltage dips / sags, voltage swells can be caused by either source voltage changes, or load side changes as well as poor neutral connections.

A single line to ground fault (SLG) on an ungrounded system will result in a voltage swell on the ungrounded phases.

A voltage swell can also be caused when a large load turns off on the load side. The abrupt interruption of current can generate a large voltage due to the inductance of line and the sudden change in the current flow.

Voltage swells can cause breakers to trip, equipment to drop off line. They can damage sensitive electronics equipment. Repeated voltage swells can lead to insulation breakdown and cause components to fail.

Class A – RMS (1/2 cycle) measurement

The RMS voltage measurement for voltage dip (sag) and swell detection is measured over one cycle, beginning at a fundamental zero crossing, and refreshed each half-cycle. This value is used only for voltage dip (sags), swells, interruption, as well as RVC detection and evaluation.

Class A – swell detection

On a single-phase system, a swell begins when the Urms (1/2) voltage rises above the swell threshold. The swell ends when the Urms (1/2) voltage is equal to, or below, the swell threshold minus the hysteresis voltage.

On poly-phase systems, a swell begins when the Urms (1/2) voltage of one or more channel rises above the swell threshold. The swell ends when the Urms (1/2) voltage on all measured channels are equal to, or below, the swell threshold minus the hysteresis voltage.

Class A – dip (sag) detection (poly-phase)

The dip/sag begins when the Urms (1/2) voltage of one or more channels is below the dip threshold. It ends when the Urms (1/2) voltage on all measured channels is equal to, or above, the dip threshold plus the hysteresis voltage.

Transients

Transients are a momentary variation in voltage or current that last less than a cycle.

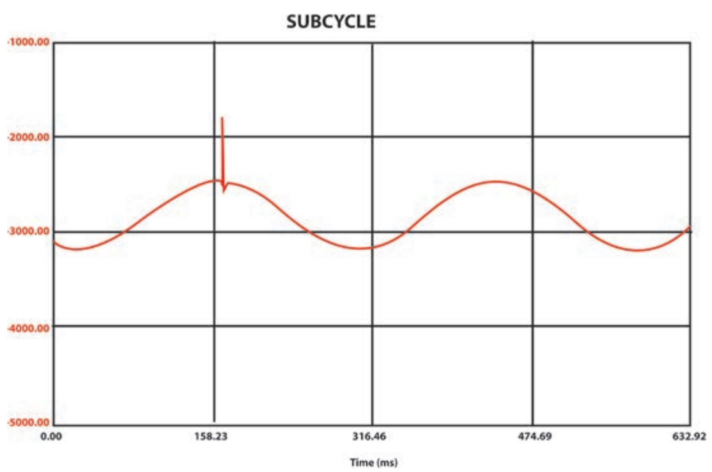
IEC60050-161 defines a transient as pertaining to, or designating, a phenomenon or a quantity which varies between two consecutive steady states during a time interval short when compared with the time-scale of interest.

IEEE1159 categorizes transients as either impulse transients or oscillatory transients.

IEEE1159 defines an impulse transient as a sudden non-power frequency change in the steady-state condition of voltage or current that is unidirectional in polarity – primarily positive or negative.

IEEE1159 defines an oscillatory transient as a sudden, non-power frequency change in the steady-state condition of voltage, current that includes both positive and negative polarity values. An oscillatory transient is a voltage or current whose instantaneous value changes polarity in a rapid fashion.

The impulse transient is a high frequency transient with frequency components in the few-hundred-kilohertz region and is typically caused by lightning and inductive loads.



Oscillatory transients have a characteristic oscillation or ringing as shown in the following table. The frequency of the oscillation can be anywhere from less than 5KHz up into the megahertz. The frequency can give a clue to the origin of the disturbance.

Osillatory Transients	Spectral Content	Typical Duration	Typical Voltage Magnitude
Low Frequency Med. Freqency High Frequency	<5 kHz 5 - 500 kHz 0.5-5 MHz	0.5 to 50 ms 20 µs 5 µs	0 - 4 pu 0 - 8 pu 0 - 4 pu

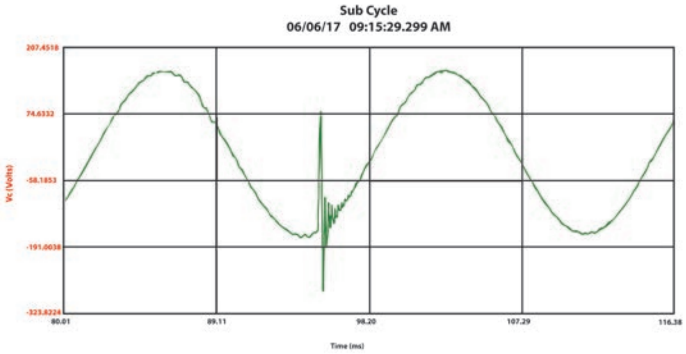
Low-frequency oscillatory transients originate primarily due to capacitor bank energization.

Oscillatory transients with fundamental frequencies less than 300 Hz can be observed due to transformer energization or ferroresonance.

Medium-frequency oscillatory transients can occur when a capacitor bank is switch in close electrical proximity to another capacitor bank that is already energized.

Other causes include cable switching and a system's response to an impulsive transient.

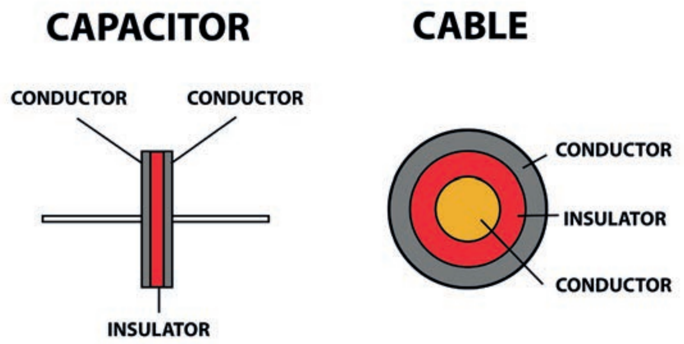
High-frequency oscillatory transients can be linked with the high speed switching of power electronics such as switching power supplies. These can repeat several times per cycle. Like medium frequency transients, high speed oscillatory transients can also be caused by the system's response to an impulsive transient.



Transients can cause damage

Transient voltages can result in degradation or immediate dielectric failure in all equipment classes. High magnitude and fast rise time contribute to insulation breakdown in electrical equipment like those found in switchgear, transformers and motors. By repeatedly applying a lower magnitude of transients to equipment, slow degradation, as well as eventual insulation failure and decreasing mean time between failures may occur.

Transients can damage insulation because insulation has capacitive properties like those found in wires. Both capacitors and wires have two conductors separated by an insulator. The capacitance provides a path for a transient. If a single transient has enough energy it will damage that section of insulation. Repeated lower energy transients will degrade the insulation over time and lead to a failure.



How transients interact

Transients on a coil

Transients on a coil of a motor or a transformer will dissipate a majority of its energy in the first few coils, damaging the insulation that surrounds them. Each subsequent coil, beyond the first few, present more resistance and capacitance to the transient. This reduces its magnitude and increases its period, in turn reducing energy.

Transients and motor leads

Transient voltages can interact with the distributed inductance and capacitance of motor leads, resulting in peak voltage at the motor terminals which stresses and degrades the insulation around the stator winding of the motor. The smaller the motor is, the longer the lead, resulting in a greater peak voltage. This is why it is recommended to avoid long motor leads.

Lightning and transients

Lightning is a common cause of impulse transients. Lightning strikes or high electromagnetic fields produced by lighting can induce voltage and current transients in power lines and signal carrying lines. These are known as unidirectional transients.

High speed transients

High speed transients have rise and fall times of just nanoseconds. They are caused by arcing faults, like bad brushes in motors, and are rapidly damped out by a few meters of distribution wiring. Standard line filters that come with nearly all electronic equipment can remove high speed transients.

The effect of high speed transients in distribution systems are limited because they are typically low energy due to their short duration. In distribution systems the cable lengths will dampen them out.

Joules = Watts * Seconds

If a 500V transient occurs for 1000 microseconds that drives a current of 10A, this will deliver an energy of 5 joules.

5 joules = (500 * 10) * (1000 *(10)^ (–6))

If a 500V transient occurs for 1 microsecond that drives a current of 10A, this will deliver an energy of:

0.005 joules.

.005 joules = (500 * 10) * (1 *(10)^ (–6))

High speed transients will cause issues in areas with short cable runs, like those found in off shore platforms. We can also see their impacts in residential and commercial locations operating solar panels without battery back-up. Solar panels respond nearly instantaneously to changes in solar radiation. This can lead to high speed transients in these systems. Over time, these repeated transients can break down filters and cause failures in sensitive electronics. This leads to reduced mean time between failure (MTBF) of this electronic equipment.

IEC transient detection methods

The IEC has several suggested methods to detect transients:

Comparative method: Detecting a transient when a fixed, absolute threshold is exceeded.

When the comparative method is used an absolute threshold is set by the user. Each sample is then compared to the limit. If the sample exceeds the limit a transient event begins. The transient event ends when a following sample falls below the threshold.

Envelope method: Similar to the comparative method, but with the fundamental removed prior to analysis.

When the envelope method is used, an absolute threshold is set by the user. The fundamental waveform is filtered out then each sample is compared to the limit. If the sample exceeds the limit, a transient event begins. The transient event ends when the next sample falls below the threshold.

Sliding-window method: When the instantaneous values are compared to the corresponding values on the previous cycle.

When the sliding window method is used each sample is compared to the corresponding sample of the previous cycle. If the difference between these samples exceeds the limit then a transient event begins. The transient event ends when the difference between a following sample and its corresponding sample of the previous cycle falls below the threshold.

Unbalance

Unbalance is a power quality phenomenon in poly-phase systems where the RMS values of the line voltages and/or the phase angles between consecutive line voltages are not all equal, per IEEE 1159 and IEC 61000-4-27.

Voltage unbalances typically are a result of unbalanced loads. Large single-phase loads, like single-phase arc furnace, draw all their current from one phase. This can create unbalanced voltage. These unbalanced voltages can cause excessive heating in three phase motors.

A voltage unbalance of 2% can lead to a current unbalance of up to 20% in a three phase motor. This can lead to coils overheating.

Current unbalance can also cause heat effects in transformers and increased current in neutral lines.

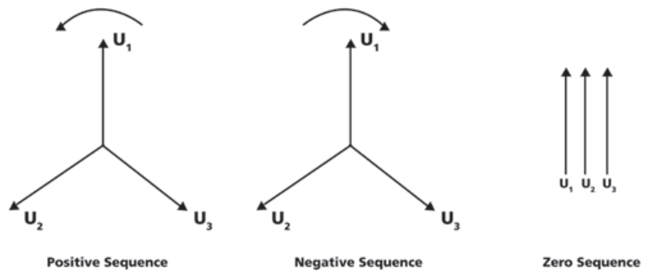
Unbalance can be measured using different techniques. There is the ANSI method of unbalance measurement. In this method the phase to phase RMS measurement is taken of all phases. These are then averaged together, each individual phase is then compared to the average. The percentage of deviation of the phase that deviates the most is then used as the unbalance measurement. The problem with this method is it is just an estimate, since it only looks at the effect of the most unbalanced phase, while it ignores all other phases.

The IEC method of unbalance utilizes symmetrical components. By using symmetrical components the three phase system can mathematically break down the system into three balanced systems – a positive sequence, a negative sequence and a zero sequence.

Balancing a system

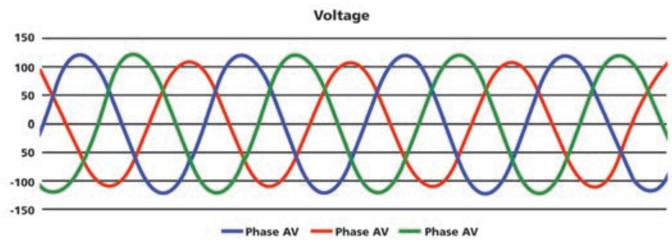
In a perfectly balanced system, all the voltages and phase angles need to be equal.

Symmetrical components refer to the rotational component of the magnetic field. The positive sequence component rotates in the same direction as the fundamental. The negative sequence component rotates in the opposite direction of the fundamental. The zero sequence component has no rotation.



The sequenced components are calculated based on Fortescue's principles. Phases B and C are shifted by 120 degrees and 240 degrees respectively. Any change in magnitude or phase will then be detected.

In a perfectly balanced system, the negative sequence component of all the phases will cancel out when they are added together. However, any deviation in any phase magnitude, or any phase angle will create a negative sequence unbalance. So by measuring the negative sequence unbalance we can get a direct measurement of unbalance for all phases.



Viewing the negative sequence factor allows us to view the unbalance as a percentage of the positive sequence. So a 2% unbalance in the negative sequence factor is reflective of all phases while an ANSI 2% unbalance is only representative of the most unbalanced phase.

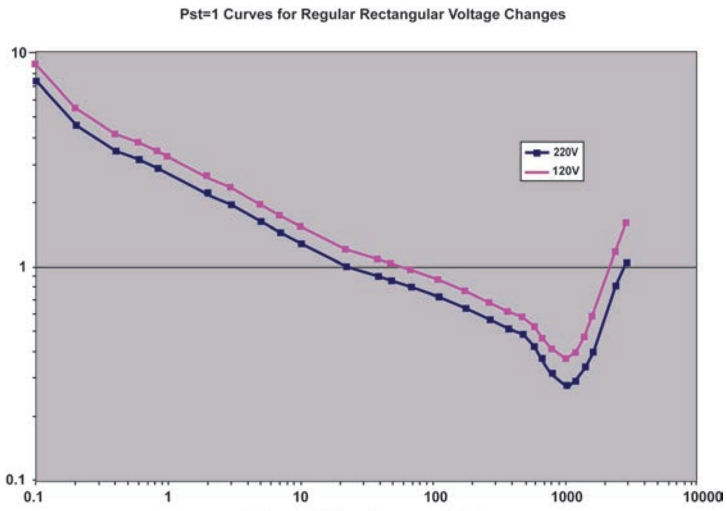
Flicker

Flicker is defined by IEC and IEEE as the impression of unsteadiness of visual sensation induced by a light stimulus whose luminance or spectral distribution fluctuates with time.

Flicker is a very specific problem related to human perception and incandescent light bulbs. It is not a general term for voltage variations. Our perception of light flicker is almost always the criteria for controlling small voltage fluctuations.

Voltage fluctuations are changes in voltage magnitude over varying periods of time. These fluctuations in voltage can cause periodic changes in the output of lighting. The impact on our visual sensitivity will depend on the severity of the change of lighting output which will depend on the magnitude and frequency of the voltage fluctuation and the type of lighting.

Studies using incandescent lighting at 115V/60Hz and 230V/50Hz have shown that when the voltage fluctuation is at 8Hz a minimal voltage fluctuation is noticeable. As the frequency of the voltage fluctuations get less than, or greater than, 8Hz the voltage fluctuations need to be greater for the lighting changes to be noticeable.



A weighted curve was developed which gives more weight to fluctuations at 8Hz and less weight to fluctuations below and above 8Hz. This curve was based on the incandescent light and is used in the flicker measurement algorithm.

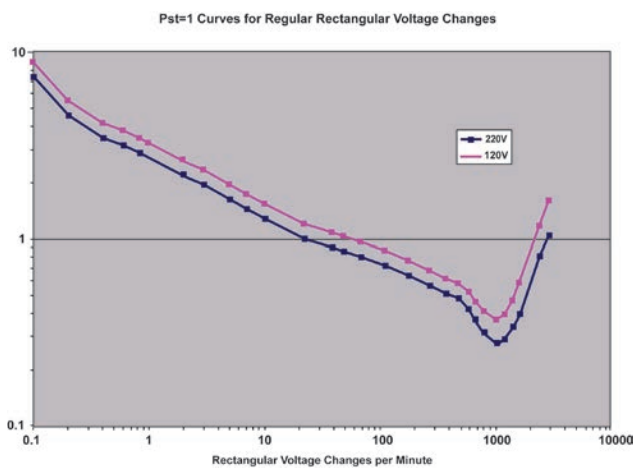
Measuring flicker

Flicker is measured using IEC methodology (IEC6100-4-15). In this methodology, instantaneous voltage is taken and compared to a rolling average voltage. The deviation between these two is multiplied by a value in a weighted curve. The curve is based on the sensitivity of the human eye at 120V/60Hz or 230V/50Hz. Once this is determined, the end value is called a percentile unit. The percentile units go through a statistical analysis in order to calculate two values.

Types of flicker

Short term flicker (Pst) is calculated based on the flicker percentile unit. Pst is based on a 10-minute interval.

Long term flicker or (Plt) is calculated based on the Pst. Plt is based on a two-hour interval.



How to know if flicker levels are good or bad

Reaction to flicker is subjective. Different individuals may perceive flicker severity differently. For some people a long term flicker value (Plt) of 1.0 may cause annoyance, whereas in other cases higher levels of Plt may be noticed without annoyance.

Below are some recommendations on flicker limits:

- The European standard EN50160 requires that the long term flicker should be less than or equal to 1.0 for 95% of the time, under normal operating conditions
- In the US, the IEEE, as defined in IEEE1453, recommends the following for low voltage systems:
  - Short term flicker (Pst) should be less than or equal to 1.0 for 95% of the time
  - Long term flicker (Plt) should be less than or equal to 0.8 for 95% of the time
  - The planning levels for medium voltage systems 0.9 for Pst and 0.7 for Plt
  - The planning levels for high voltage systems 0.7 for Pst and 0.6 for Plt

Sources of flicker

Flicker is caused by voltage variations. These variations can be caused by many different sources. These sources include, but are not limited to, the operation of ovens, welders, cranes, mills, arc furnaces, inrush currents from loads turning on as well as poor wiring and bad connections.

In certain cases, inter-harmonics, even at low levels, give rise to flicker, or cause interference in ripple control systems. These would be low frequency inter-harmonics equal to or below the 2nd order.

Harmonics

Harmonics are a sinusoidal component of periodic waves that have frequencies that are multiples of the fundamental frequency. Harmonics can cause many problems, including the overheating of neutral wires, motors and transformers, as well as electronic failures.

According to IEEE 519, a harmonic is a component of order greater than one of the Fourier series of a periodic quantity. An example of this would be in a 60Hz system, the harmonic order 3, also known as the “third harmonic,” is 180Hz.

IEC 61000-4-30 defines a harmonic frequency as a frequency which is an integer multiple of the fundamental frequency.

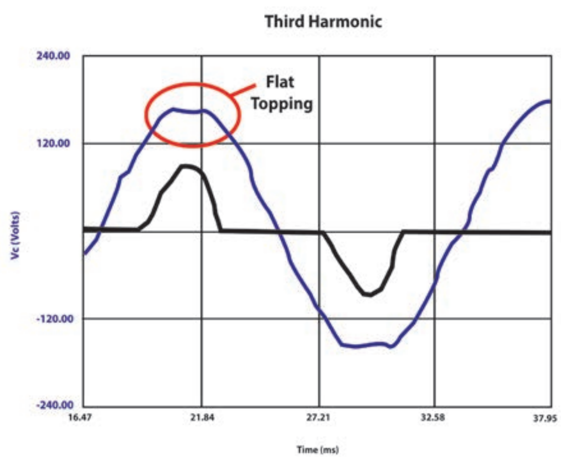
Loads and how they affect harmonics

Linear loads, like incandescent light and motors, draw current equally throughout the waveform. Non-linear loads, like switching power supplies, draw current only at the peaks of the wave. Non-linear loads are the ones that cause harmonics.

Harmonics and propagation

Current harmonics do not propagate through transformers, but do create heating effects in cables, transformers and motors.

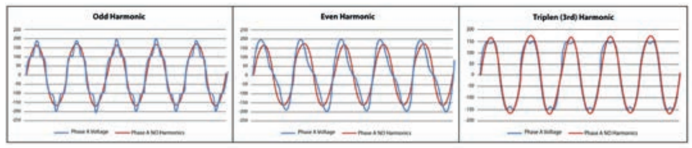
If current harmonics get high enough they can cause voltage harmonics. In the example below we see a common condition referred to as flat topping. The current harmonics have gotten high enough to cause a distortion at the peak of the voltage waveform. This is an example of a third harmonic.



Although current harmonics do not propagate through transformers, voltage harmonics can pass through transformers.

Characterizing harmonics

Harmonics are characterized based on their order. Odd harmonics are those with odd order numbers. These are the normal harmonics we expect to see. These are created due to non-linear loads. Even harmonics are those with even order numbers. Even harmonics are non–symmetrical and not normal. The presence of even harmonics is a sign that there is a faulty rectifier on the system. Triplens are odd harmonics that are a multiple of three. This includes 3rd order, 9th order, 15th order, etc. Different order harmonics will tend to cancel each other out due to different peaks and valleys. Triplens do not cancel out. They add together and can cause very high neutral currents.



Harmonics can also be characterized as a set of sequence components. These sequence components are based on the rotation of their magnetic field.

Positive sequence harmonics create a magnetic field in the direction of rotation. The fundamental frequency is considered to be a positive sequence harmonic.

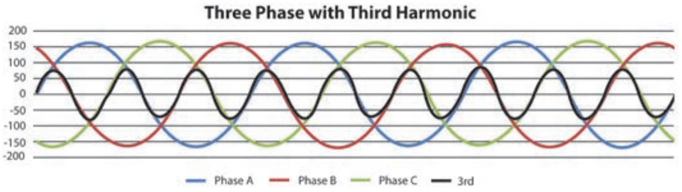
Negative sequence harmonics develop magnetic fields in the opposite direction of rotation. This reduces torque and increases the current required for motor loads. Negative sequence harmonics also create counter rotational currents in motors that can cause motor vibration.

Zero sequence harmonics create a single-phase signal that does not produce a rotating magnetic field of any kind. These harmonics can increase overall current demand as well as generate heat.

60Hz Harmonics Frequencies				50Hz Harmonics Frequencies		
Harmonic	Frequency	Note		Harmonic	Frequency	Note
0	0	DC		0	0	DC
1	60	Fundamental		1	50	Fundamenta
2	120	Negative sequence		2	100	Negative sequence
3	180	Zero sequence		3	150	Zero sequence
4	240	Positive sequence		4	200	Positive sequence
5	300	Negative sequence		5	250	Negative sequence
6	360	Zero sequence		6	300	Zero sequence
7	420	Positive sequence		7	350	Positive sequence
8	480	Negative sequence		8	400	Negative sequence
9	540	Zero sequence		9	450	Zero sequence
10	600	Positive sequence		10	500	Positive sequence
11	660	Negative sequence		11	550	Negative sequence
12	720	Zero sequence		12	600	Zero sequence
13	780	Positive sequence		13	650	Positive sequence
14	840	Negative sequence		14	700	Negative sequence
15	900	Zero sequence		15	750	Zero sequence
The fundamental has a positive				*The fundamental has a positive*		

Three-phase system

In three-phase systems, the fundamental currents cancel each other out and add up to zero amps in the neutral line. A zero sequence harmonic (the third harmonic) will be in phase with the other currents of the three-phase system. Since they are in phase, they sum together and can lead to high neutral currents.



Harmonic effects

Excessive harmonic distortion can cause many power quality problems, due to the heat generated by harmonics. Some of these problems include neutral wires, transformers and motors overheating.

Triplen and zero sequence harmonics can cause neutral lines to overheat because they do not cancel out, but rather add together on the neutral line.

When all three phases are balanced and there are no harmonics, the neutral lead will not have current present. When the third harmonic is added, the neutral current flows. By adding the 9th harmonic to this the neutral current increases. As current increases, so does the heat in the neutral.

$$Winding\ Loss = I^2 x\ Z$$

$$Z = \sqrt{R^2 + X_L^2}$$

$$X_L = 2\pi f L$$

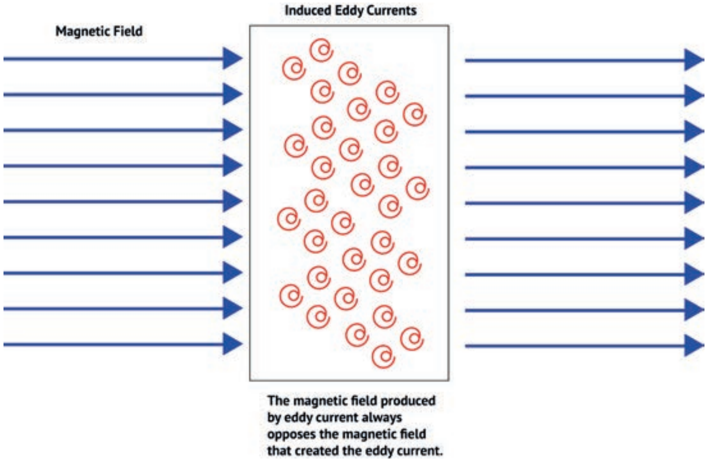
Harmonics and transformers

Harmonics cause heating effects in transformers. Winding loss, also known as copper loss, also causes heating in transformers. High order harmonics cause core loss in transformers. As the harmonic content increases due to increasing non-linear loads, possible overheating and failure can occur.

Harmonic order

Higher harmonic order means higher frequencies. These higher frequencies increase the inductive reactance, which increases the impedance. As the impedance increases so does the winding loss.

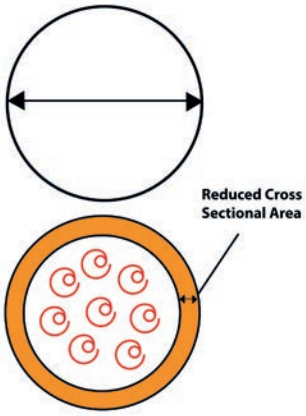
Higher-order harmonic currents cause both copper loss and core loss. This is primarily due to eddy current.



What is skin effect?

Eddy currents cause a phenomenon known as "skin effect" in transformer windings. The tendency of AC current to be distributed in a conductor so that the density is greatest near the surface of the conductor.

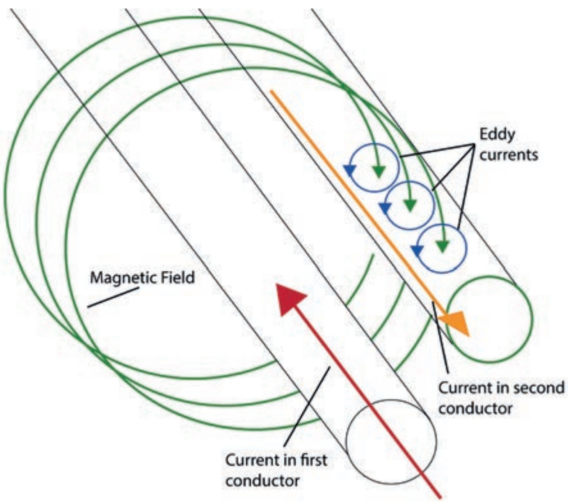
Eddy currents induced in wire create a magnetic field that opposes the magnetic fields that generated them. This opposition increases the resistance in the center of the conductor, causing the current density to be greater near the surface, reducing the effective cross sectional area of the wire, resulting in a higher resistance and greater winding loss.



At low frequencies skin effect is minimal. At higher harmonic frequencies, the skin depth becomes smaller, further increasing the conductor resistance and winding loss.

Harmonics and proximity effect

Proximity effect occurs when an AC current flows through a conductor that is in close proximity to another conductor – like a coil. Because of the induced eddy currents in the adjacent wire, the current density becomes constrained to a smaller region on the side of the wire. As the AC current flows through the first coil it generates a magnetic field that induces longitudinal eddy currents in the adjacent coil.



The eddy currents create a magnetic field that oppose the magnetic field that created it, increasing the resistance of the conductor. This causes the current density in the adjacent coil to be greater, while reducing the effective cross sectional area of the conductor that increases it.

Harmonics and core losses

Due to heat generated in the core from eddy currents and hysteresis, higher-order harmonic currents can cause magnetic core losses. These losses are dissipated as heat in the core. Eddy currents in the core are reduced through lamination of the core. Instead of a solid iron, the core is arranged in layers.

Each layer is separated by an insulator (lamination) in which the magnetic field will pass through, but the eddy currents will not. The lamination does not eliminate the eddy currents; however, it does reduce them. Although the eddy currents still circulate within the individual plates of the laminated core, their net heating effect is greatly reduced.

Hysteresis and harmonic effects

Hysteresis is the change in the magnetic domains within the core. It is not associated with eddy currents. As the magnetic force changes polarities, energy is created and is dissipated as heat in the core. Total power loss of the core is equal to the eddy current losses, plus the hysteresis losses.

Transformer de-rating

Transformers need to be de-rated based on their harmonic content to avoid overheating and failure. The measurement used to determine the transformer de-rating is called K-factor.

What is K-factor

K-factor defines the non-linear load a transformer can tolerate without overheating. The K-factor number is proportional to the heating effect of harmonics. The K-factor calculation takes into account the eddy currents created in the windings of the transformer and not the core.

$$K = \sum_{i-0}^{n} (I_n * h)^2 / \sum_{i=0}^{n} I_n^2$$

One amp of 13th harmonic current creates far more heat than 1 amp of 5th harmonic current.

If we square the harmonic currents (including the fundamental), and we square the harmonic orders, we then sum the products to get K-factor.

A K-factor of 1.00 will mean there are no current harmonics. The higher the K-factor number the greater the harmonic current content.

The K-factor is based on ANSI C57.110 and is an accepted means of de-rating transformers for non-linear loads even though the term does not appear in the standard.

The K-factor rating

The K-factor rating describes the winding heating effects compared to normal. A K-2 reading would mean that the stray loss heating effects are twice normal. A standard transformer is a K-1 transformer. Transformers come in basic K-factors such as 4, 9, 13, 20, 30, 40 and 50.

Harmonics and their effect on motors

Excessive current harmonics can cause motors to not only run inefficiently and overheat, but also vibrate.

Negative sequence harmonics can create vibrations in motors because they produce magnetic fields in the opposite direction of the fundamental frequency, reducing torque and increasing the current required for motor loads.

Overheated motors

Motors subjected to harmonics experience winding loss (copper loss) just like a transformer. Eddy currents are induced in the conductors of the windings by alternating magnetic fields. These currents induce magnetic fields that are opposite from the magnetic fields that created them. The repulsion of the magnetic fields increase the resistance in the winding, creating heat and loss of power. Higher frequency harmonics will increase the energy of the eddy current.

Vibration in motors

Positive-sequence harmonics create magnetic fields that go in the same direction as the fundamental frequency produces.

Negative-sequence harmonics produce magnetic fields in the opposite direction of the fundamental frequency.

The interaction of these opposing fields can produce vibration in the motor shaft.

When the vibration produced reaches the resonant frequency of the shaft, it greatly amplifies the vibration that can damage the shaft.

Recording harmonics

The IEC 61000-4-7 method captures and records harmonics and inter-harmonics continuously.

Each harmonic order consists of 3 (5Hz) bins that are centered on the frequency of the harmonic order. They are grouped into bins in 10 minute intervals.

For example, the center frequency of the 3rd harmonic on a 60Hz system will be 180Hz. Therefore, the 3rd harmonic bin on a 60Hz system will include all the frequencies from 172.5Hz through 187.5Hz.

In a 50Hz system, the 3rd harmonic is 150Hz. Therefore, the 3rd harmonic bin is from 42.5Hz through 57.5Hz.

Each harmonic will be an aggregation of the harmonic frequency, plus and minus 7.5Hz.

Inter-harmonics

Inter-harmonics have frequencies that are not multiples of the fundamental frequency. They are the aggregation of all the frequencies between the harmonic bins. The inter-harmonic order consists of all the frequencies between the order ‘n’ and ‘n+1’. Therefore, the 3rd inter-harmonic will be an aggregation of all the frequencies between the 3rd and 4th harmonic bins.

Inter-harmonics can effect mechanical low frequency oscillations, lamp flicker as well as disrupt equipment that is synchronized to the supply voltage zero-crossing. It can also cause telecommunication interference and resonance.

Low frequency inter-harmonics below the 2nd order can cause lamp flicker in sufficient magnitude.

Inter-harmonics can be generated at any voltage level in the network and can be injected from HV and MV systems into the LV or from the LV and MV into HV systems.

The magnitude of inter-harmonics are typically low, although higher levels can occur under resonance conditions.

Inter-harmonic generation

Inter-harmonic can be caused by rapid changes in current magnitudes and/or phase angle. This can cause sidebands at the fundamental frequency that can lead to voltage fluctuations. These can be generated by loads operating in a transient state and when an amplitude modulation of currents and voltages occur.

Sub-harmonic generation

Sub-harmonic generation is inter-harmonic frequencies below the fundamental frequency. They can cause amplitude modulation that results in voltage variation. Series line compensation capacitors can cause sub-harmonic currents.

Line compensation capacitors have both natural frequencies and base frequencies. These frequencies will appear on a generator rotor as a modulation of the base frequency. If the sub-harmonic frequency interacts with one of the natural frequencies of the turbine-generator shaft, a self-excitation can occur and damage the shaft. Motors with variable-torque loading or adjustable-speed drives can also be a source of sub-harmonics.

Asynchronous switching

Inter-harmonics can be generated by asynchronous switching that is not synchronized with the power system. These inter-harmonic frequencies can be located anywhere in the frequency spectrum.

Typical sources of asynchronous switching:

- Variable-load electric drives
- Static frequency converters
- Arcing loads
- Ripple controls

Most common effects of inter-harmonics

The most common effects of inter-harmonics are variations in RMS voltage magnitude. This can be seen in flicker in both incandescent and fluorescent lamps. Variations of the voltage can be the result of sideband frequencies that modulate voltage.

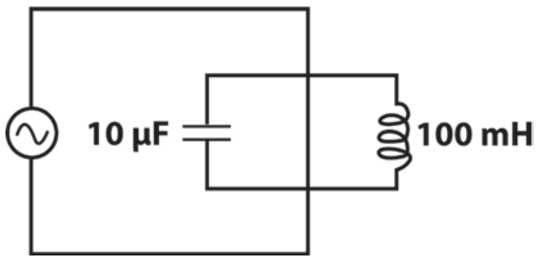
The influence of inter-harmonics on voltage fluctuation is most prevalent at lower frequencies. The influence on voltage fluctuation of inter-harmonics with frequencies higher than twice the fundamental is small.

Resonance

Resonance is the condition in which an electric circuit or device produces the largest possible response to an applied oscillating signal.

This oscillation can create high currents that can lead to catastrophic failures.

Resonant conditions occur when inductive reactance equal capacitive reactance.



In this example at 159Hz, Xc = 100Ω and XL =100Ω.

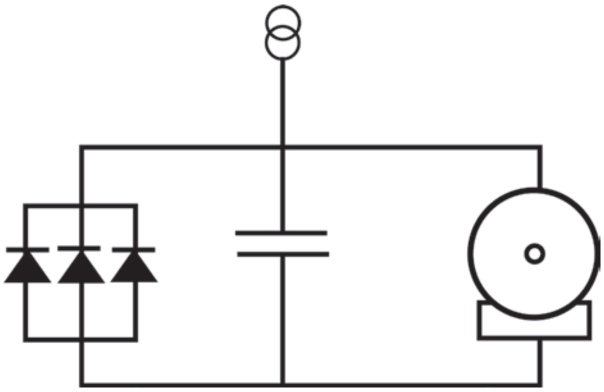
Circuits that have capacitive and / or inductive loads have impedances that will vary with frequency.

As motors turn on the inductive reactance will increase on the circuit. This will lower the power factor.

To counter the low power factor capacitor banks are turned on. This increases the capacitive reactance.

A resonance condition will occur when the capacitive reactance equals the inductive reactance.

In these cases high currents can flow through the circuit and lead to catastrophic failures.



If harmonic or inter-harmonic frequencies approach the resonance frequency of the system a resonance oscillation will occur.

This oscillation may cause humming or buzzing or lead to catastrophic failure.

THD and TDD

Total harmonic distortion (THD) is the measure of the sum of the harmonic components of a distorted waveform.

THD is the RMS (root-mean-square) sum of the harmonics, divided by one of two values: either the fundamental value, or the RMS value of the total waveform.

THD is typically represented as a percentage of fundamental amplitude.

Both IEC and IEEE have specifications and recommendations for both THD as well as individual harmonics values.

THD can be calculated for either current or voltage.

THD works very well when analyzing voltage harmonics, however it can be misleading when analyzing current harmonics.

THD is typically referenced to the amplitude of the fundamental.

The voltage fundamental value is always present in non-faulted conditions. This is not necessarily true for current.

The current amplitude will fluctuate with the loads impedance.

As loads turn off, the fundamental current amplitude decreases.

If the current being drawn by the load is low (near zero) then the THD value will appear to be very high.

If the sum of the squares of the total harmonic current is 0.2A and the square of the fundamental current being drawn by the load is 200A then the THD will equal 3.16%.

$$THD = \sqrt{(0.2 \div 200) \times 100} = 3.16\%$$

If the square of the fundamental current being drawn by the load then drops to 200mA then the THD will equal 100%.

$$THD = \sqrt{(0.2 \div 0.200) \times 100} = 100\%$$

This is deceiving because the current THD level appears to be high, but this is only because there is little to no current being drawn.

Total demand distortion (TDD) measurements should be used for total current harmonic measurements.

The total demand distortion references the total root-sum-square harmonic current distortion, to the maximum average demand current recorded during the test interval.

Therefore, the reference value is the same throughout the test interval and it is a valid value.

Total demand distortion should be calculated in accordance with the IEEE 519 document, "Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems", published by the IEEE Standards Association.

The power quality industry has developed certain index values to assess the distortion caused by the presence of harmonics.

The two values most frequently indexed are THD and TDD.

Individual harmonic values are also indexed in different specifications, such as the North American IEEE 519 document and the European Standard EN50160 on power quality; issued by the European Committee for Electrotechnical Standardization (CENELEC).

Rapid voltage change (RVC)

A rapid voltage change is a fast rise or fall of the RMS voltage. In general, it causes changes in lighting but will not cause damage to electrical equipment, although equipment may trip off line.

Residential households are most commonly effected by RVC especially if they are in a weak network. A small reduction in voltage can result in a noticeable reduction in light intensity. This can be most noted as light changing in intensity continuously.

What triggers an RVC

RVC events can be caused by switching on a specific load or a sudden change in source voltage. Sudden source voltage changes can occur in solar grids when the sun is obscured by clouds. Additionally, source voltage changes can occur in wind farms when wind speed decreases.

How to capture an RVC event

In order to capture an RVC event, a nominal voltage of the system under test must be declared, and an RVC threshold must be defined, this is typically 3% of nominal. For an event to be classified as a rapid voltage change, the voltage must not fall below the lower voltage limit. If the voltage falls below the lower tolerance limit, it is classified as a voltage dip (sag).

Before an RVC event can be triggered a steady state voltage must be established. An RVC event will then be triggered when the RMS value drops below the RVC threshold. The RVC event will end once the RMS voltage falls within the RVC threshold plus the hysteresis value for a full second.

Calculations

The 1 cycle RMS voltage is calculated every ½ cycle, Urms (1/2 cycle).

This is a 1 cycle RMS value that utilizes a ½ cycle sliding window.

The RVC Interval in a 50Hz system is the average of 100 consecutive Urms (1/2 cycle) intervals.

The RVC Interval for a 50Hz system uses a 100 cycle sliding window with a ½ cycle slide.

The RVC Interval in a 60Hz system is the average of 120 consecutive Urms (1/2 cycle) intervals.

The RVC interval for a 60Hz system uses a 120 cycle sliding window with a ½ cycle slide.

In either case, the interval duration is 1 second.

Triggering an RVC Event

Before an RVC event can be captured, a steady state must be achieved.

100 / 120 consecutive Urms (1/2 cycle) intervals do not deviate more than the user defined RVC threshold.

An RVC event will be triggered when a single Urms (1/2 cycle) interval deviates by more than the RVC threshold.

The RVC event will end when a steady state condition returns.

Mains signaling

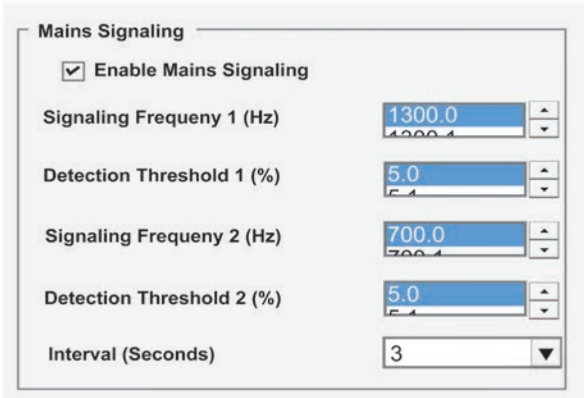
Power-line communication (PLC) carries data on a conductor that is also used simultaneously for AC electric power transmission or electric power distribution to consumers. It is also known as power-line carrier, power-line digital subscriber line (PDSL), mains communication, powerline telecommunications or power-line networking (PLN).

One method of power-line communications is known as mains signaling. Mains signaling can be used to turn on and off remote equipment using two different frequencies. Mains signaling are ripple control signals in the frequency range of 110Hz to 3000Hz.

Utilities can use mains signaling to turn on and off customer loads during peak demand periods. Mains signaling can be used to switch on and off of public lighting. Some reported complaints that have attributed to mains signaling include: light flicker, noise from electrical appliances (due to resonance effects) street lights not switching on and off properly.

To detect mains signaling, the operator must select the frequencies being used. This is done as part of the analyzers configuration in the PC software.

Megger PQ software configuration



The mains signaling function looks for two separate frequencies. One frequency (signal frequency 1, for example) could be to turn off a piece of equipment, while the other frequency (signal frequency 2, for example) is to turn on that piece of equipment.

Signal Frequency 1 (Hz): Set this to the desired frequency in Hz.

Detection Threshold 1 (%): This is the trigger that initiates the event detection. This is measured as a percentage of the declared voltage.

Signal Frequency 2 (Hz): Set this to the desired frequency in Hz.

Detection Threshold 2 (%): This is the trigger that initiates the event detection. This is measured as a percentage of the declared voltage.

Interval (Seconds): This defines for how long the frequency must be detected.

If one of these frequencies pass their trigger threshold for more than the defined interval, then a mains signaling event will occur. The analyzer will record when the signal occurred and capture the waveform containing the mains signal.

Leading and lagging phase angles

Loads can be resistive like an incandescent light bulb. Loads can be inductive - like a motor. Loads can also be capacitive - like a capacitor bank.

Inductive loads, like coils and motors, are resistive to changes in AC current. This causes a time shift between the voltage and the current.

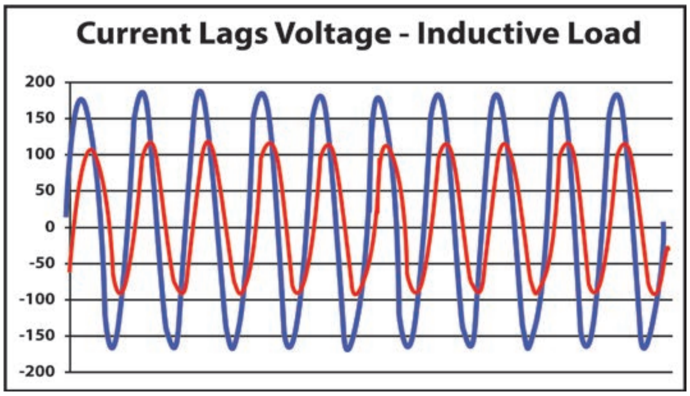
The rise and fall time of the current lags the voltage because of the coils resistance to changes in current.

A capacitive load allows current to pass, but is resistive to voltage changes. It takes time for a cap to charge up.

In this case, the current leads the voltage.

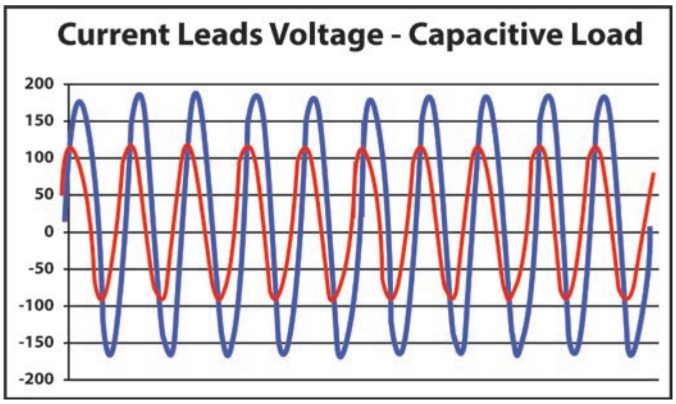
This can be remembered by the phrase ELI the ICE man.

In an inductive load (L) current (I) lags the voltage (E). (ELI)



The greater the inductive load the more the current lags the voltage.

In a capacitive load (C) current (I) leads the voltage (E). (ICE)



The greater the capacitive load, the more the current leads the voltage.

NOTE: We always reference leading and lagging from the point of view of the current. The current either leads or lags.

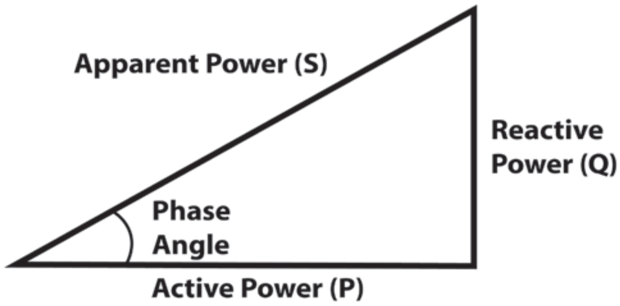
Power triangle

Active power (P) is the power that performs actual work and is measured in watts.

Reactive power (Q) is the power that does not perform actual work. It is stored energy like that stored in a capacitor or in the magnetic field of a motor. It is required for the equipment to function but does not perform actual work. Reactive power is measured in VARS.

Apparent power (S) is the sum of the active power (P) and the reactive power (Q).

Together these form the power triangle.



$$S = \sqrt{P^2 + Q^2}$$

Apparent power (S) equals the square root of the sum of the active power (P) squared plus the reactive power (Q) squared.

When there is 0 phase shift between the voltage and the current then the active power (P) will equal the apparent power (S) and the reactive power (Q) will be zero.

As the phase shift between the voltage and current increases, so does the reactive power (Q). As the reactive power (Q) increases, active power (P) decreases.

For example, as motors start up during the day, the inductive load increases. As the inductive load increases, the more the current lags the voltage. The greater the phase shift.

Reactive power (Q) will increase and active power (P) will decrease. This means there is less energy to do work. If left unchecked the active power (P) could drop to such a low value that there is not enough power to perform the work required. This will lead to an under voltage event.

In order to reduce the lagging phase shift and reduce the phase shift between the voltage and the current, capacitor banks are turned on. This will reduce the reactive power (Q) and increase the active power (P), avoiding the potential under voltage event.

Power factor

The power factor is a direct measurement of the phase shift between the current and the voltage. There are different power factor measurements. The displacement power factor (DPF) and the true power factor (TPF).

The displacement power factor (DPF) is the cosine of the phase angle between the voltage and the current. The value can be between -1.0 and 1.0.

A DPF of ±1.0 indicates there is no phase angle between the voltage and current. The voltage is in phase with the current. As the phase angle between the voltage and the current increases, the DPF decreases. The sine of the DPF indicates whether the current is leading or lagging the voltage.

A positive DPF indicates the current is lagging the voltage, the load is inductive.

A negative DPF indicates the current is leading the voltage, the load is capacitive.

The displacement power factor (DPF) only provides the power factor of the fundamental.

Harmonic effects on power / energy and power factor

Everything discussed to this point is assuming purely sinusoidal waveforms. In the real world, we have waveform distortion caused by harmonics.

The power triangle only holds true when the voltage and current harmonics are purely sinusoidal. As soon as harmonic distortion is introduced the power triangle formula does not hold true.

For this reason apparent power (S), active power (P) and reactive power (Q) cannot be calculated but need to be directly measured.

Apparent power (S) will be the measured voltage RMS times the current RMS, measured in volt amps (VA).

Active power (P) is the aggregated sum of all the voltage times current samples. These are aggregated over a selected time interval, typically 15 minutes. This is measured in watts (W).

Reactive power (Q) is the aggregated sum of all the voltage time current samples, shifted 90°. These are also aggregated over a selected time interval, typically 15 minutes. This is measured in Vars (VAR).

True power factor (TPF) = Active power (P) / Apparent power (S).

True power factor (TPF) gives the power factor inclusive of the harmonics.

The TPF has a range from 0 and 1.0. This value is always positive.

If the displacement power factor (DPF) is nearly identical to the true power factor (TPF) this is an indication of little harmonic distortion on the system.

If the larger difference is between the displacement power factor (DPF) and the true power factor (TPF) there will be greater harmonic distortion on the system.

Compliance testing

Compliance testing is a testing technique which is done to validate whether a system meets a utilities or a government set of prescribed standards.

These types of tests are generally performed using a Class A piece of equipment. This is to ensure that the measurements technique is known and valid.

When a compliance test is performed the power quality analyzer is programmed with a predefined set of limits. A power quality recording is performed for a minimum period of time. The recorded data is then compared to a predefined standard.

EN50160

EN50160 testing is a common compliance test that is performed throughout Europe. This is a government standard that ensures that individual loads do not cause excessive distortion in a power system. This testing is performed using a Class A instrument. Some analyzers have an EN50160 configuration pre-programmed. This allows the user to simply select the proper configuration. The recording is done for a minimum of 1 week. Then the data is analyzed. Some PC software will have a pre-programmed EN50160 analysis and/or report.

Power factor studies

A power factor study is done to determine if the load is drawing too much reactive power (KVAR). As inductive loads increase so does the phase angle between the voltage and current. This in turn increases the reactive power (KVAR) in a system and decreases the active power (KW). As active power decreases the ability to perform work decreases. If left uncorrected the power generation would need to increase to produce more apparent power (KVA) in order to compensate. This is why capacitor banks are switched into circuits to compensate for the inductive load and reduce the overall phase shift.

Displacement power factor (DPF) is the cosine of the phase angle. If the voltage and current have no phase shift (the phase shift = 0°) then the DPF = cosine of 0° = 1.0. If an inductive load causes a phase angle of 20° between the current and the voltage then the DPF = cosine of 20° = 0.939.

A power factor study allows the operator to see how the loads are changing and when to add capacitance to a system in order to improve overall efficiency.

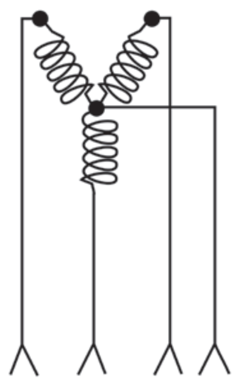
APPENDIX A

Common power configurations and energy measurement methods

There are many power configurations and each of them have advantages and disadvantages. This section will cover some common configurations and the energy measurement methods.

4 wire wye 3 wattmeter

The 4 wire wye 3 wattmeter configuration is one of the most common configurations in the world.



Some of the advantages of the 4 wire wye 3 wattmeter configuration include:

- The neutral connection provides safety
- Lower insulation stress
- Can be connected phase-to-neutral or phase-to-phase, providing two different voltage levels

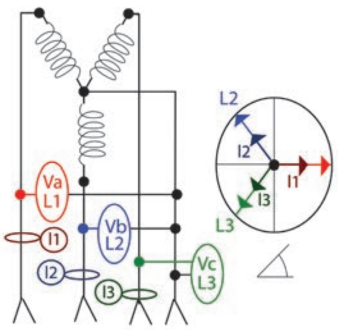
Some of the disadvantages of the 4 wire wye 3 wattmeter configuration include:

- A fault can lose a phase voltage
- Susceptible to zero sequence harmonics
- Phases can be unbalanced
- Can have high neutral currents from unbalance or zero sequence harmonics
- Higher cost (more material)

Measuring power and energy on a 4 wire wye 3 wattmeter configuration

Since we are measuring line voltage and line currents the measurement of power on this type of system is very straight forward.

This configuration requires 3 wattmeters, one on each phase.



The voltage and current channels are connected as follows:

Analyzer Channel	Analyzer Label	Type of Connection	Connect to
1	Va	Voltage	Between Va and Neutral
2	Ia	Current	Clamp on Phase A
3	Vb	Voltage	Between Vb and Neutral
4	Ib	Current	Clamp on Phase B
5	Vc	Voltage	Between Vc and Neutral
6	Ic	Current	Clamp on Phase C

3 wire delta 2 wattmeter

The 3 wire delta 2 wattmeter configuration are also very common configurations.

Some of the advantages of the 3 wire delta 2 wattmeter configuration include:

- Suppression of zero sequence harmonics
- A fault will not lose a phase
- Will remain balanced in the presence of unbalanced single phase loads
- Lower cost

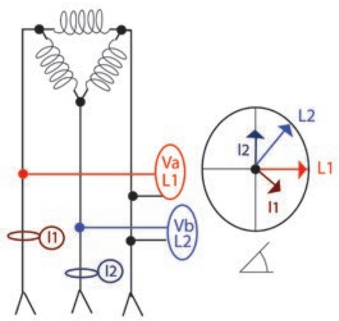
Some of the disadvantages of the 3 wire delta wattmeter configuration include the following:

- Lost phase will raise the voltage on the other phases, creating over voltage conditions
- Higher insulation required
- Reduced safety due to no neutral

Measuring power and energy on a 3 wire delta 2 wattmeter configuration

Since we are measuring phase voltage and line currents there is a 30° phase shift introduced into this system.

This configuration requires 2 wattmeters.



The voltage and current channels are connected as follows:

Analyzer Channel	Analyzer Label	Type of Connection	Connect to
1	Vac	Voltage	Between Va and Vc
2	Ia	Current	Clamp on Phase A
3	Vbc	Voltage	Between Vb and Vc
4	Ib	Current	Clamp on Phase B

This method will measure the total power and energy on a delta system and complies with Blondel's theorem.

Blondel's Theorem

Blondel's theorem states that the total power in a system of (N) conductors can be properly measured by using (N) wattmeters or watt-measuring elements.

Therefore, in a 3 wire delta 2 wattmeters are required.

The potential coils are connected between the conductors and a common point and there should be one current coil on each of the two conductors.

Converting delta to a wye

A delta can be measured by mathematically converting the delta to a wye. This is done by mathematically changing the phase voltage (line-to-line) to a virtual line-to-neutral voltage.

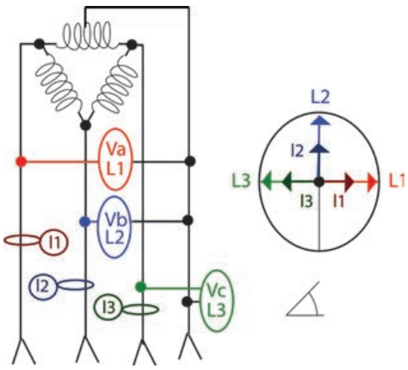
V_ln=V_ll/√3

Converting delta to a wye enables the operator to view power values per channel.

The disadvantage of converting delta to a wye is that deltas can become unbalanced when phase shifts are introduced.

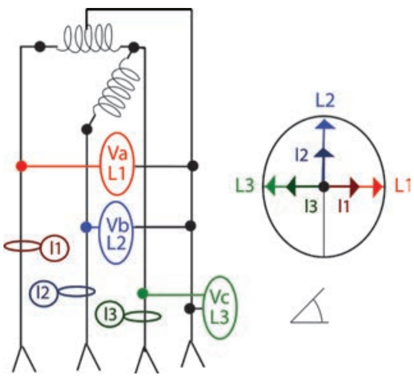
Red leg delta (wild leg / high leg)

To measure this configuration, a 4 wire wye 3 wattmeter configuration is used.



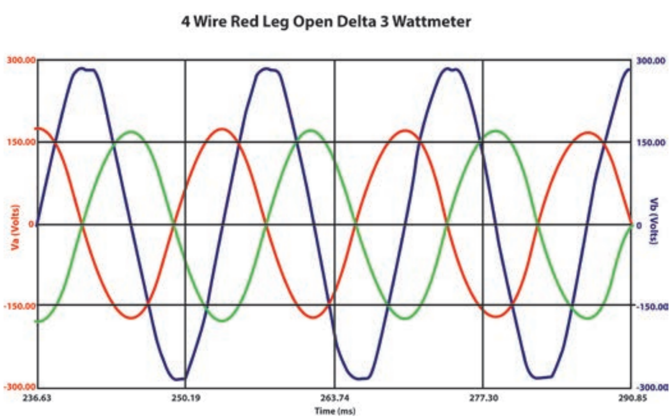
Although a 3 wattmeter approach is used, note that the phase angle between phases is 90° not 120°.

The red leg delta can also be a 4 wire open red leg delta.



NOTE: A 3 wattmeter system is still used per Blondel's theorem. (4 wires – 1 = 3 wattmeters)

Red leg or wild leg configurations will also have one leg that is higher than the others.



Some of the advantages of the 4 wire red leg delta configuration include:

- Can supply 3 different voltages, 240V, 208V and 120V
- Where the three-phase load is small, two individual transformers may be used instead of the three providing a variety of voltages at reduced cost

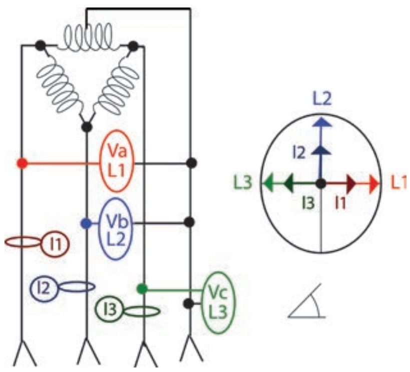
Some of the disadvantages of the 4 wire red leg delta configuration include:

- They can be unbalancing due to large single-phase loads
- High-leg to neutral load limit
- More complicated network design

Measuring power and energy on a 4 wire red leg delta 3 wattmeter configuration

Since we are measuring line voltage and line currents, the measurement of power on this type of system is very straight forward.

This configuration requires 3 wattmeters, one on each phase.

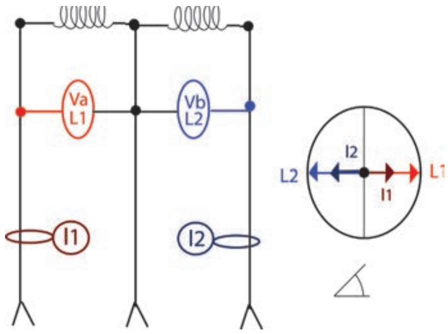


The voltage and current channels are connected as follows:

Analyzer Channel	Analyzer Label	Type of Connection	Connect to
1	Va	Voltage	Between Va and Neutral
2	Ia	Current	Clamp on Phase A
3	Vb	Voltage	Between Vb and Neutral
4	Ib	Current	Clamp on Phase B
5	Vc	Voltage	Between Vc and Neutral
6	Ic	Current	Clamp on Phase C

3 Wire split phase 2 wattmeter

The 3 wire split phase 2 wattmeter configurations is a common residential connection.



Some of the advantages of the 3 wire split phase 2 wattmeter configuration include the following:

- Provides 240V and 120V, for residential applications
- Low cost

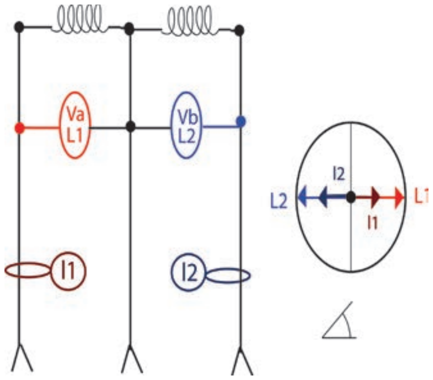
Some of the disadvantages of the 3 wire split phase 2 wattmeter configuration include:

- Can become unbalanced
- Susceptible to zero sequence
- Can see high neutral current from unbalanced loads as well as zero sequence harmonics

Measuring power and energy on a 3 wire split phase 2 wattmeter configuration

Since we are measuring line voltage and line currents, the measurement of power on this type of system is straight forward.

This configuration requires 2 wattmeters, one on each phase. (# wires -1 – 2 wattmeters)



The voltage and current channels are connected as follows:

Analyzer Channel	Analyzer Label	Type of Connection	Connect to
1	Va	Voltage	Between Va and Neutral
2	Ia	Current	Clamp on Phase A
3	Vb	Voltage	Between Vb and Neutral
4	Ib	Current	Clamp on Phase B

APPENDIX B

Troubleshooting

In this section several various types of power quality issues will be examined. We will examine some common problems and common causes.

Solar

We have seen an increase in the use of solar panels in both residential and small commercial facilities. This has been facilitated by government incentive programs, energy savings as well as the move toward clean renewable energy. The grid to which these solar systems are connected is a dynamic system. As equipment is added to the grid, it has an impact on the grid and vice versa.

Over-voltage:

Most grids were designed as radial systems. This means that they were designed to deliver power in one direction, from the source to the load. When power is delivered from the source, we see a small voltage drop at the residence due to grid impedance. When a PV system is used, power is generated at the residence and flows back into the grid, this can cause a voltage rise at the residence. The magnitude of the voltage rise will depend on different factors, including cable lengths and diameters, as wells as the amount of power being fed back into the grid.

These higher voltages can lead to equipment problems, such as premature motor failures. There are many different types of motors, and many turn on and off multiple times per day. These can include the motors in air conditioners, washing machines, refrigerators and more. When a motor turns on, it draws a high inrush current during start up. As voltages increase so does the inrush current. When motors draw higher inrush current they generate more heat. Over time, this will degrade the motors and can lead to a premature failure.

PV installations can also experience some momentary high over-voltage conditions due to load rejection. This occurs when there is a sudden loss of load. PV systems can be islanded in the case of system faults or excessive over voltage. Anytime the PV system is islanded it will experience a sudden loss of load (or load rejection) at the inverter. A sudden loss of load can cause momentary high voltage conditions that can last several cycles. These can lead to protection equipment tripping or equipment damage.

Unbalance:

When there are multiple PV systems on a branch this can lead to unbalanced scenarios. When multiple PV systems are hooked up to the same phase this can lead to unbalanced voltages on the grid. The phases with the PV systems will have a higher voltage. Unbalanced voltage can cause large current unbalances in 3 phase systems. Typically transformer tap changes would need to be changed in order to compensate for this unbalance.

Power reversal:

Since the grid was engineered as a radial system, it is designed to have power delivered in one direction, from the source to the load. With the advent of distributed generation, power can be generated on the load side and flow in the reverse direction back to the substation. This can be done via PV systems as well as other DC devices. When power is reversed, we can see issues with protection devices tripping as well as premature tap changer failures. Transformer tap changers are mechanical devices that can be rated for several thousand switching cycles. In systems where the power is continuously reversing direction these tap changers can fail in relatively short amounts of time.

Transients:

Another issue we run into with PV systems is the speed at which its output voltage can change. When the solar radiation changes, due to clouds, pollution or other causes, the output from the PV changes nearly instantaneously. If the system is not designed for this then it can create high-frequency transients on the system. These high frequency transients can lead to premature failure of equipment such as microwave ovens and other electronic devices.

Harmonics:

The inverters used on PV systems create high frequency voltage and current harmonics. These typically have orders from the 39th harmonic through the 49th harmonic.
The higher the frequency of the harmonic the higher the heating effects on cables, due to the increased eddy currents generating greater skin effect. In sufficient magnitudes these high frequency harmonics can lead to premature insulation failure.

PQ analysis:

When testing solar panels there are several power quality phenomenon we want to be sure to examine.

1. Voltage regulation. We want to be sure we are not experiencing voltage swells that can lead to premature failures.

2. Rapid voltage change (RVC). When analyzing solar panels we also want to enable RVC. This will allow us to examine the stability of the voltage. Unstable voltage can lead to phenomenon such as light flicker.

3. Unbalance. We want to be sure we are recording unbalance at the point of common coupling. This will allow us to determine if the PV system is creating unbalanced conditions on the distribution system that could affect others on the system.

4. Transients. High-speed transients should be examined as these can cause premature failures of electronic devices in the residence.

5. Harmonics. Always examine harmonics. Typically the harmonics created by the inverters will be higher frequency harmonics between the 39th and 49th harmonic orders. In excess these harmonics can lead to cable heating and premature failure of insulation in cables, motors as well as transformers.

Wind

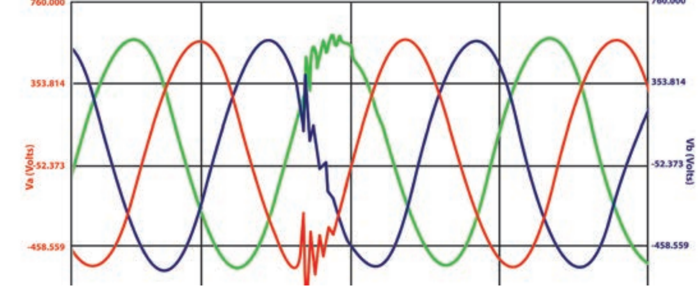
Wind farms have become commonplace in rural areas. These produce an abundance of renewable energy. They also introduce some power quality issues as well.

Rapid voltage change (RVC):

The power produced in a wind farm will change with the available wind. As the wind changes so does the output voltage. The RMS voltage stability can be affected by this. This can lead to lighting issues as well as nuisance tripping.

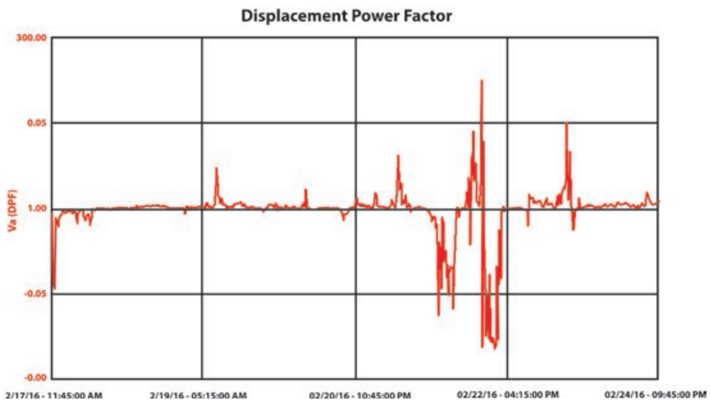
Transients:

Wind turbines are large inductive devices. Each has power factor correction capacitors in them. As these switch in and out we see transients occurring through the system. Repeated transients can cause insulation to breakdown over



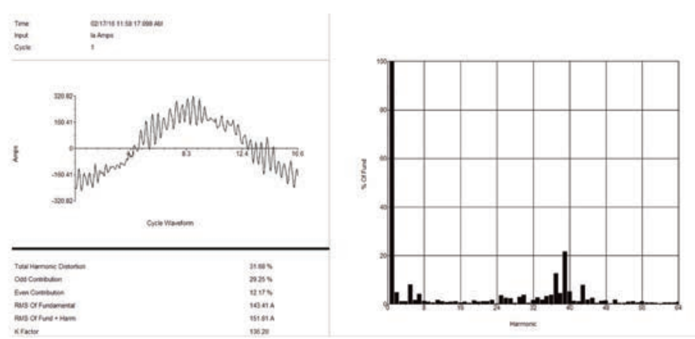
Power factor:

Wind turbines use induction generators. These require reactive power to generate a magnetic field. When the wind is blowing the turbine is creating active power (KW). This leads to good power factor values. However, when the wind is not blowing, the turbine can be drawing reactive power and not generating any active power. This can lead to very poor power factors that can result in under voltage events on the transmission lines.



Harmonics:

The inverters used in wind farms create high frequency voltage and current harmonics. These can typically have orders from the 39th harmonic through the 49th harmonic. The higher the frequency of the harmonic the higher the heating effects on cables, due to the increased eddy currents generating greater skin effect. With sufficient magnitudes, these can lead to premature insulation failure.



Resonance:

Every turbine consists of an induction generator and a pad mount transformer. This represents a great deal of inductance. Each turbine also has capacitor banks plus there are miles of cable in wind farms. This leads to a great deal of capacitance. Resonance conditions can occur that can create high currents and generate excessive heating effects.

PQ analysis:

When testing at wind farms there are several power quality phenomenon we want to be sure to examine.

1. Voltage regulation and rapid voltage change. Be sure not only to record RMS voltage but to also enable rapid voltage change (RVC). This will allow us to examine the stability of the voltage. Unstable voltage can lead to phenomenon such as light flicker.

2. Transients. In these highly inductive environments we will see capacitor banks switching in and out creating transient voltages. Be sure to enable sub-cycle recording to capture these low frequency transients.

3. Power factor. Wind farms can experience very low power factors under the right conditions. Be sure to enable demand recording so both displacement power factor (DPF) and true power factor (TPF) is recorded.

4. Harmonics: Always examine harmonics. Typically the harmonics created by the inverters will be higher frequency harmonics between the 39th and 49th harmonic orders. In excess, these harmonics can lead to cable heating and premature failure of insulation in cables, motors as well as transformers.

5. Inter-harmonics: In wind farm environments we always want to be sure to record inter-harmonics. Resonance will occur when the inductive reactance equals the capacitive reactance. Inter-harmonic frequencies can lead to resonance at the right frequency.

Lightning

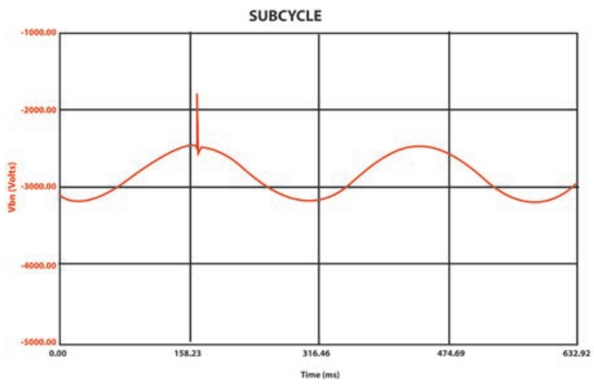
A bolt of lightning can be miles long, reach temperatures in excess of 50,000 degrees Celsius and be in the millions of volts. Lightning strikes kill approximately 100 people per year in the US alone and account for billions of dollars in damage.

Lightning can cause power interruptions. It can blow fuses, melt or damage wiring, cause equipment to drop off line or fail, corrupt data and cause systems to re-boot.

High current swells and transients due to lightning can enter buildings through overhead power lines underground power lines, telecommunications cables or other external equipment.

In many cases where lightning has caused electrical devices to fail, the owner is entirely unaware of the cause of the damage.

This is because a lightning strike does not have to hit something to cause a power quality problem. A bolt of lightning will create a magnetic field that will induce an impulse transient on a wire.



These can have large surges of current that damage equipment. They may also have lower current levels but repeated application of these transients will wear down insulation and cause failures in systems. When the equipment fails it may not be obvious that the cause is due to repeated lightning strikes.

Typical lightning protection consists of lightning rods that are connected by heavy cables to grounding equipment. This is typically metal rods driven into the earth. This provides a path for the lightning current to travel safely to ground. Lightning rods will allow a path for the current down the outside of a building and into the ground beneath it.

However, lightning rods may not provide absolute lightning protection. The current running through the lightning protection will create a magnetic field. This will induce an impulse transient on wires. This can cause damage especially to sensitive electronics. This issue will be exacerbated when the lightning protection has worn, corroded or poor connections.

Surge protectors are commonly used to protect electronics and have specific ratings to handle different amounts of current. This is typically rated in joules. The main component in most surge protectors is the metal oxide varistor. These will typically respond to transients in a few microseconds. However, metal oxide varistors do wear out and surge protectors can fail. Large transients that exceed their rating can damage them as well as sustained over-voltage conditions.

Tripping breakers

Current swells, voltage swells or transients are the most common cause of tripping breakers. Current swells are caused by inrush current or load switching. Voltage swells are caused by utility faults and load switching. Transients can result from lightning strikes, capacitor bank switching, load switching, loose wires and arcing.

Ground Fault Interruptors, or GFI, devices will trip when the leakage current on the earth gets too high. These monitor the current differential between the neutral line and earth. When investigating GFI trips, the neutral and ground currents need to be monitored.

Transformer problems

Transformer failures can be due to overheating and insulation breakdown. Overheating can be caused by current harmonics. AC currents produce eddy currents within the coils. These create both a skin effect and proximity effect that lead to the heating of the coils.

The higher the frequency or the magnitude of the harmonics, the greater the heating effect. This can cause insulation to overheat and coils to short. Common causes include non-linear loads such as power supplies and VFD’s.

Transformers can be de-rated using a K Factor. K Factor de-rated transformers can have larger coils or larger neutrals to better deal with harmonics currents. By measuring the K Factor of the current we can determine if the K Factor of the transformer is sufficient.

Unbalance creates high neutral currents that will cause heating as well. Heat is a function of the square of the current. Common causes of unbalance include large single-phase loads such as arc furnaces.

Transients break down insulation. Repeated transients will slowly break down insulation over time. This can lead to shorted coils. In many cases, a short due to transients will be seen in the first few coils.

This is because the transient will dissipate its energy in the first few coils. Common causes of transients include lightning, load switching, cap bank switching and loose wiring.

Computer problems

Computer problems can be most associated with sags and swells. Transient voltages and high harmonic levels can result in computer lock-ups, garbled data or even damaged equipment. Voltage sags can be caused by source voltage changes, inadequate wiring as well as inrush currents. Voltage swells are caused by utility faults and load switching.

Equipment tripping out

Sags and swells play a large role in equipment tripping out. Transient voltages can result in degradation or immediate dielectric failure in all classes of equipment. These are often caused by lightning strikes, capacitor bank switching, load switching as well as loose wires/arcing. Voltage sags, also a cause of tripping equipment, are source voltage changes, inrush currents and inadequate wiring. Utility faults and load switching cause voltage swells.

Motor problems

Motors experience PQ failures. Oftentimes, they are caused by voltage sags that occur for more than one minute – causing motor controllers to dropout. The dropout voltage of motor controllers is typically 70% to 80% of nominal voltage. Long duration voltage sags can cause heating in induction motors because of the increased current drawn by the motor.

Common causes of voltage sags include source voltage changes, inrush currents as well as inadequate wiring. Long duration sags are caused by faults. Voltage imbalance can cause overheating of motors and transformers. Phase current imbalance to three-phase induction motors varies almost as the cube of the voltage imbalance applied to the motor terminals. A three-and-one-half percent voltage imbalance, therefore, results in 25% added heating in motors. A voltage imbalance greater than 2% can affect motors. Three-phase induction motors should be de-rated when operated with imbalanced voltages.

When harmonic frequencies increase, so do eddy currents, which lead to greater skin effect and a smaller cross sectional area of the wire being utilized by the current, resulting in greater heating effects. This is why higher frequency harmonics tend to generate more heat in wires, motors and transformers.

Some common causes of harmonics include electronic loads and SCR/rectifier loads, while transients can cause the insulation to breakdown in motors.

Fast-changing PWM (pulse width modulation) voltage pulses can interact with the distributed inductance and capacitance of motor leads. This can result in an amplified peak voltage as high as 1600V at the motor terminals. This peak voltage stresses and degrades the insulation around the stator winding of the motor. The peak voltage magnitude at the motor terminals depends on the motor lead characteristics and the surge impedance of the motor, the smaller the motor and longer the leads, the greater the peak voltage.

Frequency variations can cause motor problems in some systems. The power system frequency is directly related to the rotational speed of the generators on the system. It depends on the balance between the load and the capacity of the available generation. When this dynamic balance changes, small changes in frequency occur. This can cause shaft damage. Frequency variations can be caused by generators isolated from the utility system that use a governor. Abrupt load changes may not be adequate to regulate the speed of the generator and the frequency will vary.

APPENDIX C

Performing a Power Quality Analysis

Below are the 8 general steps in performing a power quality investigation.

Plan and prepare

Asking the proper questions can yield a wealth of clues to the source of the problem.

What are the reported symptoms?

Relays tripping out, lights dimming, periodic humming, equipment tripping off line, capacitor bank fuses blowing, motor failures. These can help us determine what power quality phenomenon may be causing the problem.

How often does the symptom occur?

Is it cyclic or intermittent? This helps us determine how long to record.

Can any patterns be recognized? Can any correlations be made?

For example, if a breaker is tripping every morning it would indicate a possible start up sequence issue. Where during the start of the work day too much equipment may be turning on too quickly causing a large current inrush that is tripping the breaker.

Has there been any changes to the equipment or the power system?

If a change has been made recently this may very well be a factor in the reported problem.

Receive input from all those involved

Always try to receive input from multiple sources. Different people may report different facts or symptoms that can lead to clues to the problem.

Inspect

Inspecting the system will not only allow you to determine where safety hazards may be, but may help you determine if the problem is due to poor connections or poor grounding.

- Check for safety hazards
- Check everything is to code
- Check for bad connections

NOTE: Thermal imaging can help find bad connections.

Where to connect

Selecting the proper location for monitoring will make locating the root cause far simpler.

PCC (Point of Common Coupling): This is the point where the utilities input power meets the customer's building. Monitoring at this point helps to determine if the problem is a customer or load side issue or if the issue is on the incoming utility side.

If troubleshooting a piece of equipment, then connect as close to failing equipment as possible: If a piece of equipment is tripping off line or failing, then place the monitor as close to the input to that equipment as possible. This way the operator can see the actual signals that the equipment is seeing. If monitoring from further away, other impedances may effect the measurement.

Long motor leads can amplify transients. Connect as close to the motor as possible. Cables act as capacitors and can store a charge. Motors also store a charge in the form of a magnetic field. Depending on the grounding, a transient signal could cause the magnetic field of the motor to collapse and add to the charge on the cable. This means that the signal seen at the output of the drive may not be the signal seen at the input of the motor.

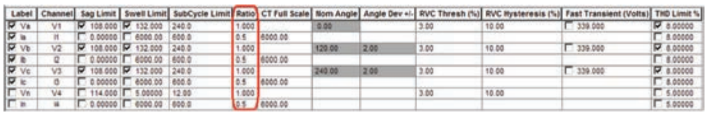
Take the environment into account. Verify the instrument is rated for the temperature, moisture and humidity levels in the location being recorded. Ensure current clamps are also rated properly for the environment where they will be used.

Select the proper current transducer. Determine the proper range. If the selected CT range is too low, there is a risk of saturating the CT when large loads turn on. If the selected CT range is too high, then it may give a poor resolution. This will introduce false noise into the recording.

Do you want to use a flexible or split core CT?

A flexible CT (Rogowski coil) can fit into tight locations better. They can also have multiple ranges. Flexible CTs work very well on high voltages. However, since they have an air core they have a low permeability. This means at low levels they may have poor resolution and poor phase response.

Increase the sensitivity of a flexible Rogowski coil by wrapping it around the cable twice. This will double its output level. If this is done, set a ratio of 0.5 in the analyzer's configuration. This will tell the analyzer to multiply the measured input from the Rogowski coil by 0.5 (In essence dividing the value by 2). Since the double wrapped Rogowski coil is outputting double the value by having the analyzer, divide that value by two you end up recording the actual real value, but get more sensitivity out of the flexible Rogowski coil.



Label	Channel	Sag Limit	Swell Limit	SubCycle Limit	Ratio	CT Full Scale	Nom Angle	Angle Dev +/-	RVC Thresh (%)	RVC Hysteresis (%)	Fast Transient (Volts)	THD Limit %
Va	V1	108.000	132.000	240.0	1.000		0.00		3.00	10.00	339.000	8.00000
Ia	I1	0.00000	6000.00	600.0	0.5	6000.00						8.00000
Vb	V2	108.000	132.000	240.0	1.000		120.00	2.00	3.00	10.00	339.000	8.00000
Ib	I2	0.00000	6000.00	600.0	0.5	6000.00						8.00000
Vc	V3	108.000	132.000	240.0	1.000		240.00	2.00	3.00	10.00	339.000	8.00000
Ic	I3	0.00000	6000.00	600.0	0.5	6000.00						8.00000
Vn	V4	114.000	5.00000	12.00	1.000				3.00	10.00		5.00000
In	I4	0.00000	6000.00	600.0	0.5	6000.00						5.00000

Flexible current clamps (Rogowski coils) develop a voltage across them when placed on a line. This value needs to be integrated. Therefore flexible current clamps require circuitry to perform this integration. This circuitry needs power. Therefore, some flexible current clamps require batteries, others may be powered by the analyzer to which they are connected. If your flexible current clamp requires batteries then be sure to place fresh batteries in the current clamps before starting the recording.

Are you performing a test on a medium voltage system where you are connecting to current transformer secondaries? If the secondary current being measured is just a few amps then it is recommended to use a split core CT.

Split core current clamps have iron cores. These have high permeability. This means they transfer magnetic field more efficiently. So at these low levels you will not only get more accurate current measurements, but more accurate phase measurements as well.

NOTE: If you are recording off a secondary of a current transformer, you may have limited frequency response. This is because the current transformers used in these step down applications typically have low bandwidths. This means that higher frequency harmonics may be attenuated. Typically when recording off the secondary of a current transformer harmonic accuracy will start falling off after approximately the 11th order.

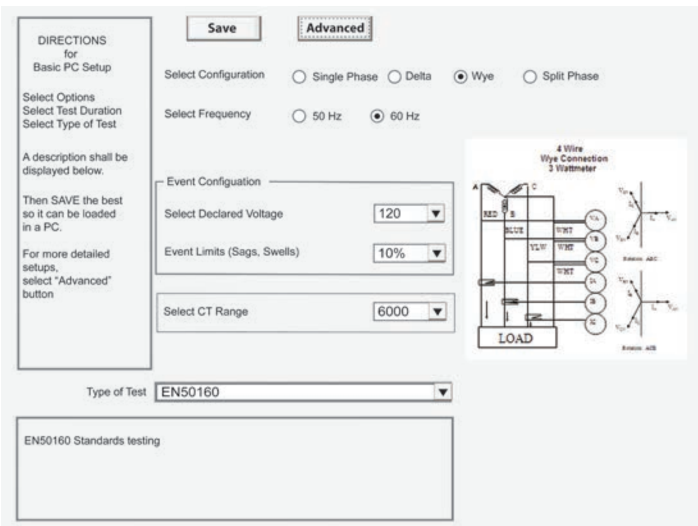
Are you recording DC? If yes, then you must use Hall effect CT. Both split core current clamps and flexible current clamps require an alternating magnetic field in order to develop a changing field within them. They cannot measure direct current. In fact if an iron core CT is placed on a DC line, the core will be magnetized and you may not be able to easily remove the CT. On DC lines, you need two current clamps that utilize Hall effect sensors. Named after the physicist Edwin Herbert Hall, a Hall effect sensor is a transducer that varies its output voltage in response to a magnetic field. The Hall effect sensor works on either AC or DC currents. In order for the Hall effect sensor to operate it also requires power. So always be sure to change the batteries before performing an extended recording.

Verify the PQ analyzer is configured properly

Verify the proper power configuration is selected, whether it be a 4 wire 3 wattmeter wye, a red leg delta, a 3 wire delta, a three wire split phase, or a single phase configuration. If the proper configuration is not selected then the recorded power and energy measurements will be incorrect.

Verify the proper event triggers are selected. Different problems can be caused by different PQ phenomenon. For example, tripping breakers can be caused by current swells or transients. Light variation can be due to dips (sags), swells, RVC, inter-harmonics, etc.

A configuration wizard in the software is very helpful in these cases. Simply select the problem you are troubleshooting and let the software set the proper PQ limits.



Verify the CT range in the analyzer configuration is set to match the current clamps to be used. If the value in the setup file does not match the value of the CT being used, then the analyzer will use the wrong slope and record the wrong values.

Connect the PQ analyzer

Use PPE (Personal Protection Equipment).

Verify voltage leads are connected per power configuration diagrams. If these are not connected properly, then the recorded voltages, as well as power and energy values will be incorrect.

Verify CT ranges are set correctly and are in the proper direction. Power flows from the source to the load. When the KW are positive, then the power is flowing in the proper direction. If the KW is negative this is an indication of either a reverse power flow (from the load to the source) or a backwards current clamp.

An analyzer with auto CT detection and configuration verification helps ensure that both the current clamps range is correct and the power analyzer connections are correct.

Verify unit power setting is correct. Some power quality analyzers have multiple methods of powering themselves. An analyzer can either be powered off of a battery in the case of chart recording of just a few hours. Others require an AC source. This may be in the form of an AC power cord or an AC to DC power adapter. Either way, these need to be plugged in to an electrical outlet. Other power quality analyzers can be powered off of the Phase A input. This means they do not need to be plugged into an AC outlet. They will get power directly from the lines they are measuring.

Whichever method you choose to use, verify any switch settings on the instrument are set appropriately (Phase A or AUX power).

Ground the unit. Whenever performing a PQ analysis the instrument should always be grounded for safety reasons. This will prevent any part of the instrument from becoming live should an internal fault occur.

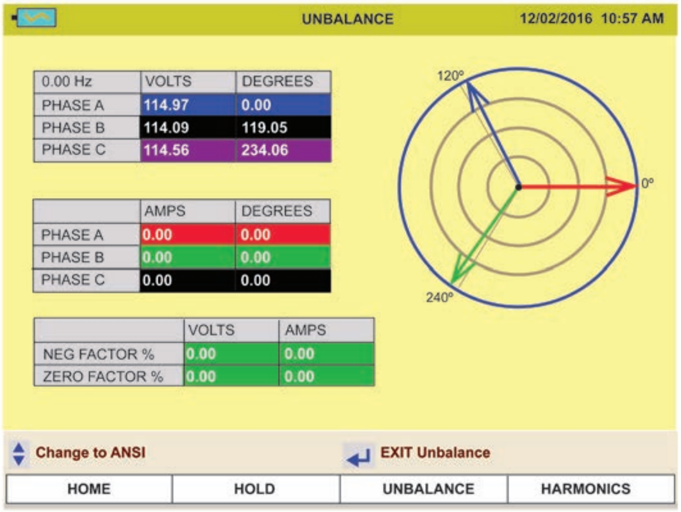
Lock up the unit. If leaving an instrument in a location where it can be seen, it is wise to lock up the analyzer. Some analyzers come with Kensington locks, similar to those on laptop computers. Some have lids that can be closed and locked using a padlock. They can be secured in place.

Review the data before starting the recording

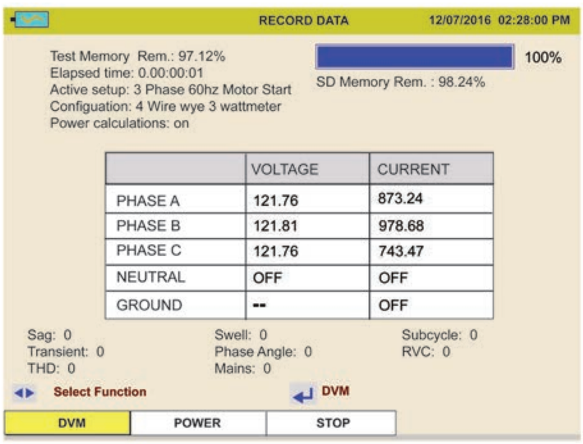
Verify the RMS voltage and current values are reading properly.

Verify the KW is positive. If it is negative this is a sign a current clamp is backwards.

Verify phase angles are correct per the connection diagrams. Reference manuals for proper configurations. An instrument with configuration verification helps ensure the connections are correct.



Verify the unit is recording before leaving the site



Allow the analyzer to record for at least one complete problem cycle. For example, if it is reported that a breaker trips every couple days, then the minimum amount of recording time would be two days. If the problem happens only once a week, then record for at least a full week.

Analyze data

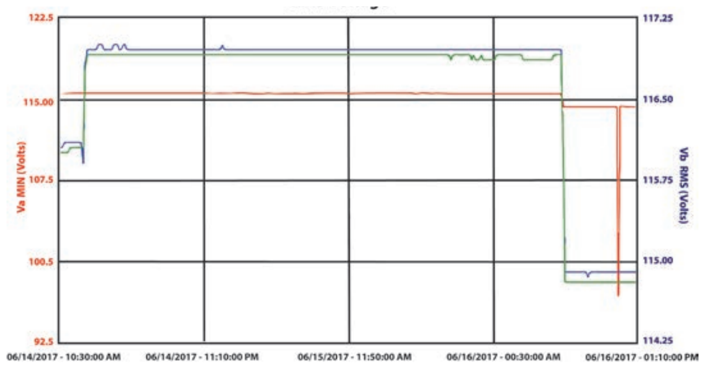
If failure repeated itself then look for events that occurred at the time of the failure.

Review the data for events that can cause the reported symptoms such as dips (sags) / swells / transients / unbalance / harmonics / RVC, etc.

Analysis of voltage fluctuations

Voltage fluctuations, also referred to as variations, are variations of the RMS voltage. This can be cyclic changes or intermittent. The magnitude of these changes do not normally exceed 5% of the nominal voltage.

Voltage variations are typically associated with the dimming and swelling of lighting sources. This is not to be confused with the PQ phenomenon flicker. The term flicker refers to the perceived lighting intensity that is a result of voltage fluctuation.



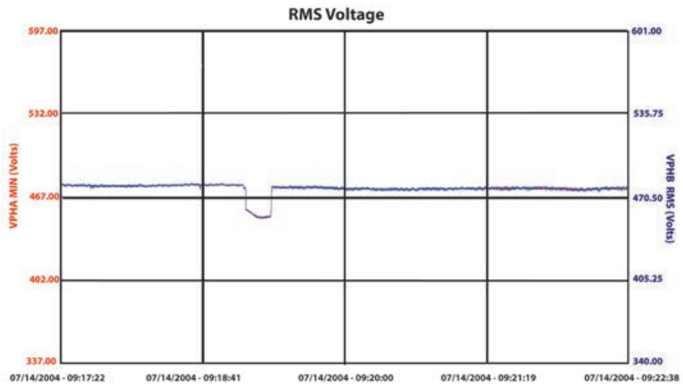
The European EN50160 standard requires that the RMS voltage remains within 10% of nominal for 95% of the time and within +10% and -15% of nominal for 100% of the time. This is under normal operating conditions.

Causes of voltage fluctuations can be due to either source variations or load variations. The most common source of voltage fluctuations are loads turning on and off. These can be cyclic such as air conditioner units turning on and off or they can be intermittent, like the turn on of an industrial process.

Analysis of dips (sags)

Check the RMS chart for dips (sags).

A dip or sag is defined as a drop in voltage below 90% of the fundamental. Sags can be caused by faults on the utility side or by the starting of large loads, such as motors. If you are having issues with equipment tripping off line it is important for mitigation reasons to understand what dip (sag) level and what duration can cause that piece of equipment to trip.



Single phase or three phase dip

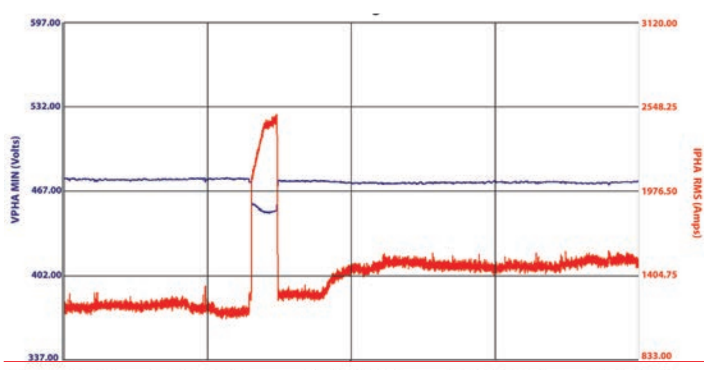
Single phase dips (sags) are common and often caused by single line to ground faults (SLG) on the utility side. This can be due to down lines or faulty insulators due to weather conditions such as lighting, heavy rains or winds, snow and ice, etc. Insulation failures in equipment can also cause these faults.

Single phase dips (sags) can also be caused by large single phase loads starting.

Three phase faults are less common, but typically more severe. These can be caused by faults on the transmission or distribution side or by large 3 phase loads starting up.

What was the current doing during this dip?

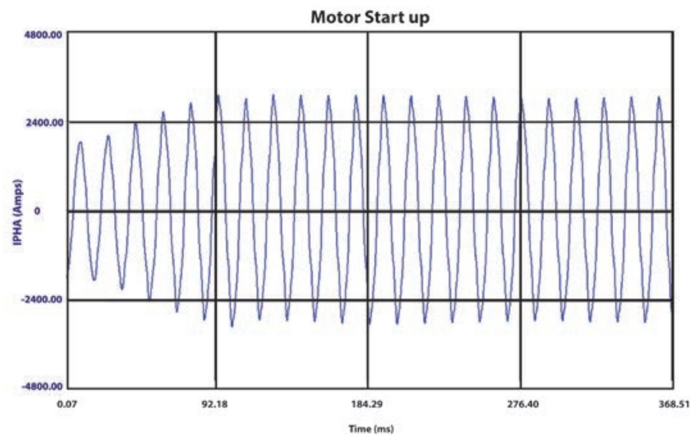
This can be an indicator or the source of the dip (sag). When a large load starts up we will see an inrush of current and this can lead to a dip or sag in voltage. However, this is dependent on the load.



When examining the voltage versus the current of this voltage dip (sag), we see the current increased while the voltage decreased. This could be an indicator of a load side start up. However, we must know our load. A swell in current could be seen if there is a dip (sag) in the voltage while the motor is running. This would cause the motor to pull more current to maintain its torque.

Examining the waveform can provide more information.

In this case, we can see the cause of the dip (sag) was a motor starting up.



Analysis of voltage swells

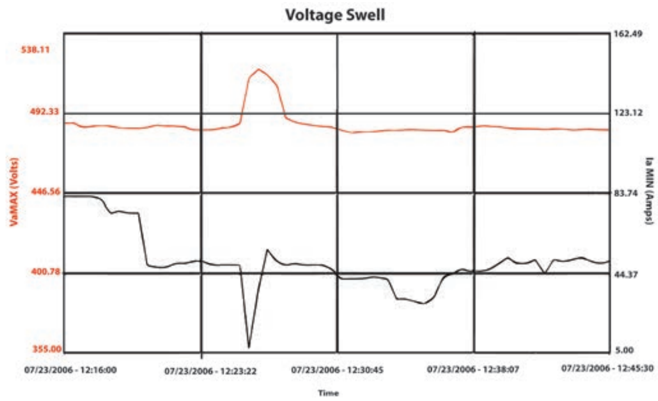
Voltage swells can cause equipment to trip off line and lights illumination output to swell.

Voltage swells can be due to either load side impedance changes or source side impedance changes.

Ungrounded systems such as delta systems are susceptible to swells due to a single line-to-ground fault (SLG). When a single line-to-ground (SLG) fault occurs on one phase of an ungrounded delta that phase voltage drops, however; the other phases will swell until the fault is cleared.

Voltage swells can also be caused by the de-energization of large loads on the load side. The voltage will equal the inductance time the change in current over the change in time. The larger the inductance or the more abrupt the de-energization, the larger the voltage swell.

Swells can also be caused by poor grounds.



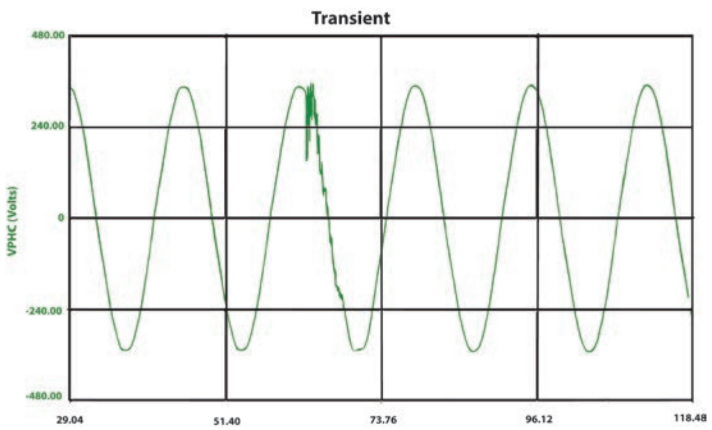
By examining the voltage and the current, we can see in the above case a large load turned off abruptly inducing a voltage swell.

Analysis of transients

Transients can cause a breakdown in insulation. This can happen due to a single large transient, but it is more commonly due to a repeated smaller magnitude transient. Transients can also cause small breakers to trip off line periodically.

Common causes of transients include lightning and high speed switching. This type of transient will be seen as a single ended sub-cycle surge.

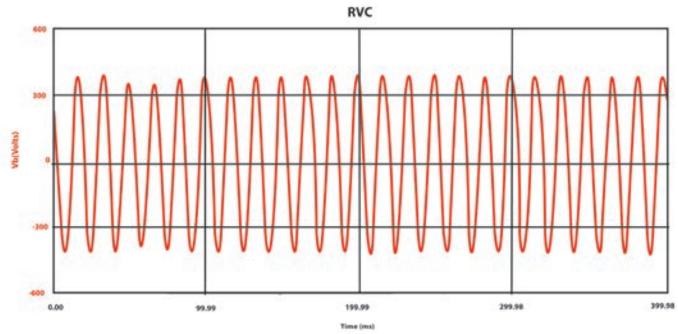
Another common cause of transients is the switching on of capacitor banks. When a capacitor bank switches on it creates an oscillatory transient that rings out.



Analysis of rapid voltage change (RVC)

Rapid voltage change can cause lights to flicker and be a general nuisance.

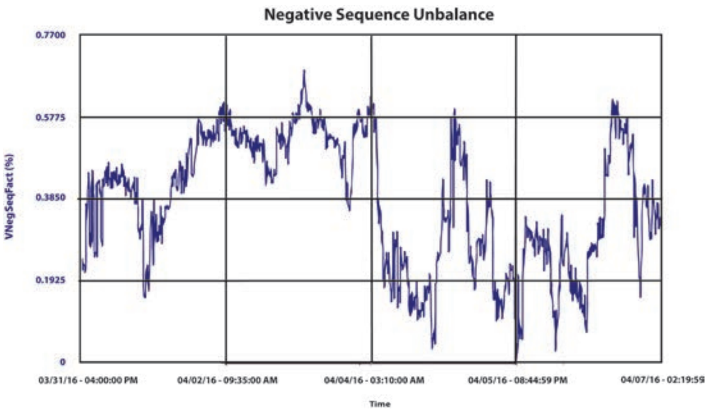
We will see rapid voltage changes as a fluctuation in the waveform amplitude.



RVC is typically caused by switching, welding equipment, induction cookers, renewable resources, such as wind and solar. The non-steady output of wind and solar can cause rapid voltage change.

Analysis of unbalance

The main issues with unbalance is it will cause high neutral currents and cause three phase motor heating. Just a 1% voltage unbalance on a 3 phase motor can create a 6 to 10% current unbalance. This can cause coils to overheat.



Examine the negative sequence voltage unbalance.

The European EN50160 standards limit voltage unbalance to 2%. North America also recommends a 2% limit on voltage unbalance.

Analysis of harmonics

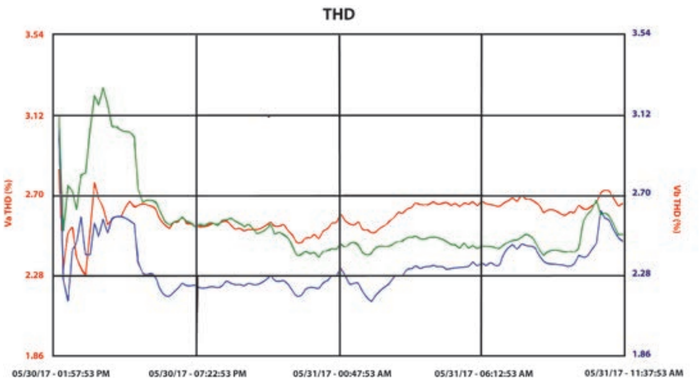
All non-linear loads produce harmonics.

Examples include computers, PWM drives, compact fluorescent lamps, switching power supplies, electric arc furnaces and more.

Harmonics cause heating effects in wires, motors as well as transformers. They can create disturbances with electronics and control systems. They can cause high neutral currents.

Harmonics can blow fuses in capacitor banks. If a harmonic occurs at a resonance frequency it can lead to catastrophic failures.

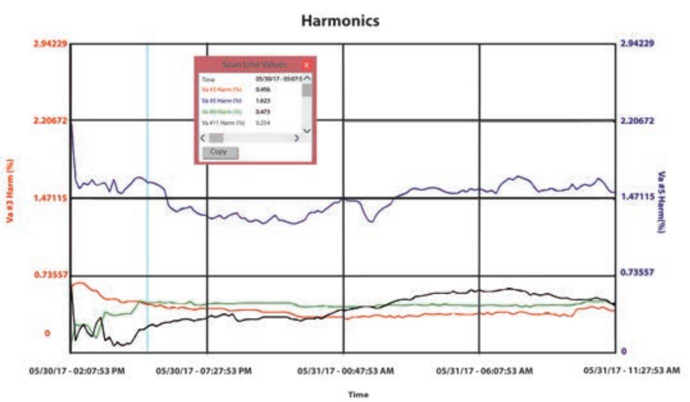
Examine the Total Harmonic Distortion (THD).



The European EN50160 standards and IEEE519 recommended practice both limits voltage THD to 8% on low voltage systems (<1kV). On medium voltage systems (1kV to 69kV) the European EN50160 standard limits the THD to 8%, while the IEEE519 recommended practice limits the voltage THD to 5%.

Examining Harmonic Orders

Harmonics – If you do see harmonics what order harmonics are you seeing?



All harmonics generate heat in wires, motors, transformers, etc. This is due to skin effect. The higher the frequency of the harmonic the greater the skin effect. Therefore, the greater the heating effects. Different order harmonics are generated by different types of equipment. Examining them provides us with more information.

Odd number harmonics are normal and what we expect to see generated by non-linear loads.

Even number harmonics (2, 4, 6, etc.) are not symmetrical and in general should not be present in any significant amplitude.

The European EN50160 standards limit the voltages 2nd harmonic content to 2.0% and the 4th harmonic content to 1%. The remainder are limited to 0.5%.

IEEE519 recommended practices limits all individual voltage harmonics to 5%. Current harmonics are referenced to the short circuit current of the system (see IEEE519). Even current harmonics are typically limited to 25% of the odd current harmonics.

Positive sequence harmonics have magnetic fields that rotate in the same direction as the fundamental. These harmonic orders include the 7th, the 13th and the 19th.

The European EN50160 standards limit the voltages 7th harmonic content to 5.0%, the 13th harmonic content to 3.0% and the 19th harmonic to 1.5%.

IEEE519 recommended practices limits all individual voltage harmonics to 5%.

Negative sequence harmonics can setup counter rotational magnetic fields in motors. This not only leads to energy loss, but can also lead to vibrations within the motor. Negative sequence harmonics include the 5th, 11th and 17th order. The 5th order harmonics are commonly caused by 6 pulse converters, such as those in 3 phase power supplies, while the 11th is commonly caused by 12 pulse converters.

The European EN50160 standards limit the voltages 5th harmonic content to 6.0% and the 11th harmonic content to 3.5% and the 17th order harmonic to 2.0%.

IEEE519 recommended practices limits all individual voltage harmonics to 5%.

Zero sequence harmonics produce high neutral currents. This creates losses through heat. Zero sequence harmonics include the 3rd, 9th and the 15th. The 3rd order harmonic is very common and typically caused by commercial power supplies found in computer systems and everyday consumer electronics.

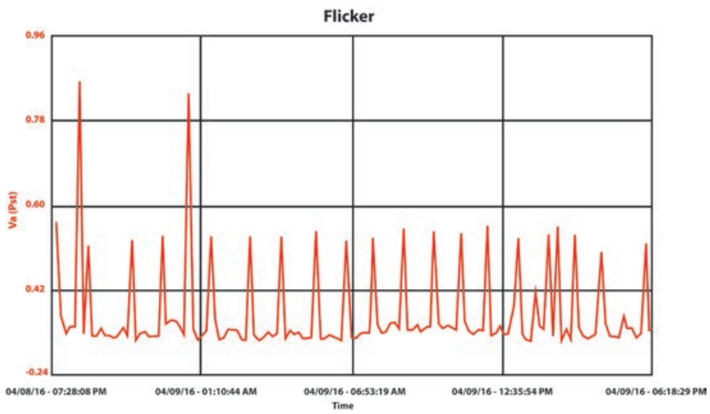
The European EN50160 standards limit the voltages 3rd harmonic content to 5.0% and the 9th harmonic content to 1.5% and the 15th order harmonics to 0.5%.

IEEE519 recommended practices limits all individual voltage harmonics to 5%.

Analysis of Flicker

When troubleshooting lighting issues, flicker is an important phenomenon to evaluate. Flicker makes light bulbs repeatedly flash or pulsate. The level of flicker is a measurement of human perception to the changing light output of an incandescent light bulb. A weighted curve is used based on the visual response to an incandescent lamp at 115V 60Hz or 230V 50Hz.

When examining flicker values we want to review both the short term flicker (Pst) and the long term flicker (Plt).



Reaction to flicker is subjective. Different individuals may perceive flicker severity differently. For some people a long term flicker value (Plt) of 1.0 may cause annoyance, whereas in other cases higher levels of Plt may be noticed without annoyance.

The European standard EN50160 requires that the long term flicker should be less than or equal to 1.0 for 95 % of the time, under normal operating conditions.

In the US the IEEE limits as defined in IEEE1453 recommend the following for low voltage systems.

Short term flicker (Pst) should be less than or equal to 1.0 for 95% of the time.

Long term flicker (Plt) should be less than or equal to 0.8 for 95% of the time.

Sources of flicker

Flicker is caused by voltage variations. These variations can be caused by many different sources. These sources include, but are not limited to, the operation of ovens, welders, cranes, mills, arc furnaces, inrush currents from loads turning on as well as poor wiring and bad connections.

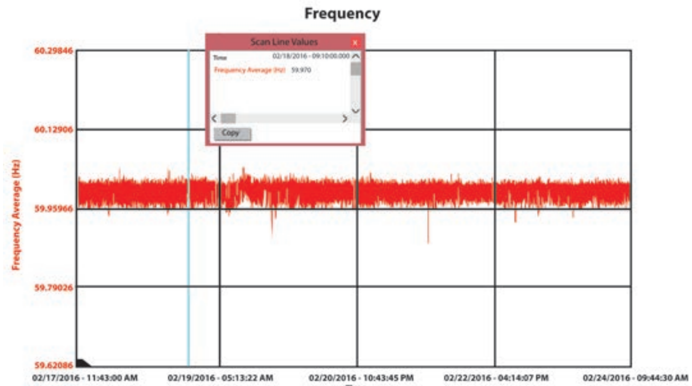
Disturbance source

Disturbance sources causing flicker are welders, arc furnaces, heat pumps, induction cooktops, car scrap plants, rolling mills, heat pumps…etc. The frequent turning on and off of loads can cause flicker. This is often in combination with a weak grid. It is often the operator who has equipment that is causing the disturbances.

In certain cases inter-harmonics, even at low levels, give rise to flicker, or cause interference in ripple control systems. These would be low frequency inter-harmonics equal to or below the 2nd order. If the 0 bin or second order inter-harmonic bin levels from 0.95% to 5% of fundamental, this may be a possible cause of the light flicker.

Analysis of frequency

Frequency disturbances are relatively rare, however, the consequence can be severe. Motors and generators can be disconnected or damaged. Systems that have frequency protection can trip off line due to a frequency change.



The nominal frequency of the supply voltage shall be 50 Hz.

The European EN50160 standard requires the power frequency for systems with synchronous connection to an interconnected system to be as follows:

50 Hz ± 1 % during 99.5% of a year

50 Hz + 4 % - 6 % during 100% of the time

For systems with no synchronous connection, such as islanded systems, the requirements are as follows:

50 Hz ±2% 95% of a week

50 Hz ±15% 100% of the time

IEEE states that a typical power frequency should be within ±0.10Hz of the nominal value (IEEE1159).

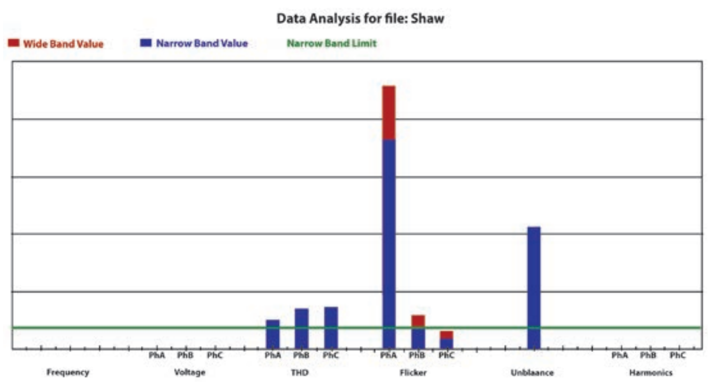
Disturbance sources

Frequency disturbances occur with abrupt connection or disconnection of major power generation systems, when islanding occurs on distributed generation systems such as solar or wind.

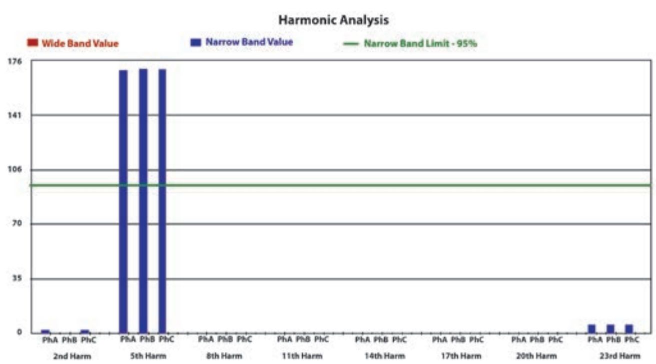
Data analysis software

When analyzing power quality data, data analysis software can be helpful.

Data analysis software will go through the data file and show what parameters are outside expected norms. This can allow you to quickly identify potential power quality phenomenon that are causing issues.



Data analysis software can also be helpful in performing harmonic analysis. Quickly identifying problem harmonics.



Appendix D

Performing an energy audit

The steps to performing an energy audit are as follows:

- Benchmark
- Audit
- Recommend changes
- Re-test
- Benchmark
- Collect 1-3 years of historical energy bills
- Review historical energy consumption
- Review the yearly energy trend
- Is the trend seasonal

Seasonal increases are expected, but large changes could point to issues in heating, AC, insulation or process control.

- What are the utility rate schedules
- List the primary energy consumption equipment
- Note the hours of operation of this equipment
- Note the type of lighting
- Is the present lighting in the building adequate

Changing lighting technologies is a common step taken to achieve energy savings. This is an ideal time to determine if modifications are needed to improve the lighting.

Inspect

Inspecting the system will not only allow you to determine where safety hazards may be, but may help you determine if the problem is due to poor connections or poor grounding.

- Check for safety hazards
- Check everything is to code
- Check for bad connections

NOTE: Thermal imaging can help find bad connections.

Audit

When performing the audit, connect the analyzer to the PCC (Point of Common Coupling). This is the point where the utility's input power meets the customer's building. This will allow you to record the entire facility's energy usage.

Before starting the recording, first select the proper current transducer.

Determine the proper range

If the selected CT range is too low then you run the risk of saturating the CT when large loads turn on.

If the select CT range is too high then it may give you a poor resolution. This will introduce false noise into your recording.

Do you want to use a flexible or split core CT?

A flexible CT (Rogowski coil) can fit into tight locations better. They can also have multiple ranges. Flexible CTs work very well on high voltages. However, since they have an air core, they have a low permeability. This means at low levels they may have poorer resolution and poorer phase response.

You can increase the sensitivity of a flexible Rogowski coil by wrapping around the cable two times. This will double its output level. If this is done, set a ratio of 0.5 in the analyzer's configuration. This will tell the analyzer to multiply the measured input from the Rogowski coil by 0.5. (In essence, dividing the value by 2.) Since the double wrapped Rogowski coil is outputting double the value by having the analyzer divide that value by two you end up recording the actual real value, but get more sensitivity out of the flexible Rogowski coil.

Flexible current clamps (Rogowski coils) develop a voltage across them when placed on a line. This value needs to be integrated. Therefore, flexible current clamps require circuitry to perform this integration. This circuitry needs power. Therefore, some flexible current clamps require batteries and others may be powered by the analyzer to which they are connected. If the flexible current clamp requires batteries, be sure to place fresh batteries in the current clamps before starting the recording.

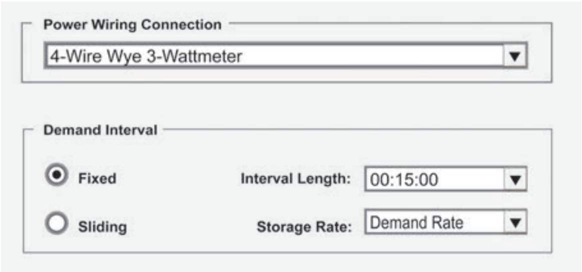
Are you performing a test on a medium voltage system where you are connecting to current transformer secondaries? If the secondary current being measured is just a few amps, it is recommended to use a split core CT. Split core current clamps have iron cores. These have high permeability, which means they transfer a magnetic field more efficiently. At these low levels, you will not only get more accurate current measurements, but more accurate phase measurements as well.

NOTE: If you are recording off a secondary of a current transformer, you may have limited frequency response. This is because the current transformers used in these step down applications typically have low bandwidths. This means that higher frequency harmonics may be attenuated. Typically when recording off the secondary of a current transformer harmonic accuracy will start falling off after approximately the 11th order.

Are you recording DC? If yes, then you must use Hall effect CT. Both split core current clamps and flexible current clamps require an alternating magnetic field in order to develop a changing field within them. They cannot measure direct current. In fact if an iron core CT is placed on a DC line the core will be magnetized and you may not be able to easily remove the CT. On DC lines, you need current clamps that utilize Hall effect sensors. Named after the physicist Edwin Herbert Hall, a Hall effect sensor is a transducer that varies its output voltage in response to a magnetic field. The Hall effect sensor works on either AC or DC currents. In order for the Hall effect sensor to operate it also requires power. So always be sure to change the batteries before performing an extended recording.

Verify the PQ analyzer is configured properly

Verify the proper power configuration is selected, whether it be a 4 wire 3 wattmeter wye, a red leg delta, a 3 wire delta, a three wire split phase or a single phase configuration. If the proper configuration is not selected, then the recorded power and energy measurements will be incorrect.

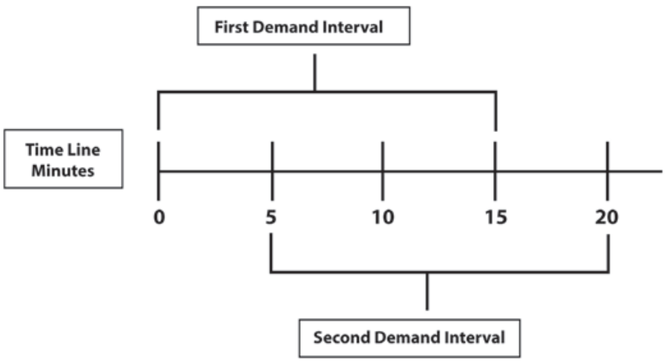


Set the demand rate in the analyzer setup file to the same rate as the revenue meter.

Fixed or Sliding: A fixed demand rate will aggregate the power and energy once every time interval. For example, a common fixed demand interval would be 15 minutes. This means every 15 minutes the power and energy values will be aggregated and saved.

A sliding demand rate will use the interval length to aggregate the first demand interval. After that the power and energy values will be aggregated based on the storage rate.

For example using the sliding demand interval shown below the first aggregated and stored interval would occur 15 minutes after the start of the recording. Every following interval would consist of a 15 minute window that "slides" every 5 minutes. So you would get a power and energy measurement every 5 minutes.



Be sure to enable harmonic recording. As discussed in the energy section of this document, the power triangle does not hold true in the presence of harmonics.

Verify the CT range in the analyzer configuration is set to match the current clamps to be used. If the value in the setup file does not match the value of the CT being used then the analyzer will use the wrong slope and record the wrong values.

Connect the PQ analyzer

Use PPE (Personal Protection Equipment)

- Verify voltage leads are connected per power configuration diagrams. If these are not connected properly, then the recorded voltages, as well as power and energy values will be incorrect.

- Verify CT ranges are set correctly and they are in the proper direction. Power flows from the source to the load. When the KW are positive then the power is flowing in the proper direction. If the KW is negative this is an indication of either a reverse power flow (from the load to the source) or a backwards current clamp.

An analyzer with auto CT detection and configuration verification helps ensure that both the current clamps range is correct and the power analyzer connections are correct.

- Verify unit power setting is correct. Some power quality analyzers have multiple methods of powering themselves. An analyzer can either be powered off of battery in the case of chart recording of just a few hours. Others require an AC source. This may be in the form of an AC power cord or an AC to DC power adapter. Either way these need to be plugged in to an electrical outlet. Other power quality analyzers can be powered off of their Phase A input. This means they do not need to be plugged into an AC outlet. They will get power directly from the lines they are measuring.

Whichever method is chosen, verify any switch settings on the instrument are set appropriately (Phase A or AUX power).

Ground the unit: Whenever performing a PQ analysis the instrument should always be grounded for safety reasons. This will prevent any part of the instrument from becoming live should an internal fault occur.

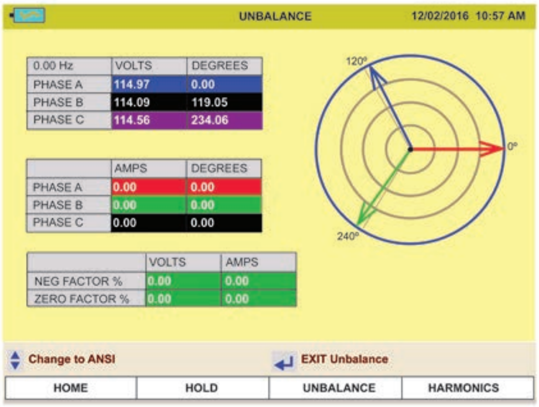
Lock up the unit: If leaving an instrument in a location where it can be seen, it is wise to lock up the analyzer. Some analyzers come with Kensington locks, similar to those on laptop computers. Some have lids that can be closed and locked using a padlock. They can then be secured in place as well.

Review the data before starting the recording.

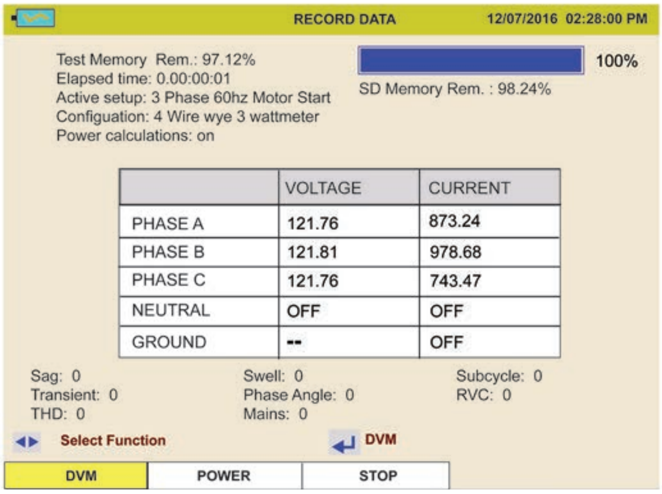
- Verify the RMS voltage and current values are reading properly.

- Verify the KW is positive. If it is negative, this is a sign a current clamp is backwards.

- Verify phase angles are correct per the connection diagrams. Reference manuals for proper configurations. An instrument with configuration verification helps ensure the connections are correct.



Verify the unit is recording before leaving the site.



Allow the analyzer to record for at least 1 full week.

Audit - Analyze data.

Review power consumption.

Examine the projections and compare them to the historic data from your past billing.

			Energy Consumption for Whole Test		
Channel	KWattHr	KVARHr	KVAHr		
Va	35.09	-0.60	35.29		
Vb	45.65	-9.97	47.05		
Vc	46.05	7.77	47.05		
Total	126.79	-2.80	129.39		
			Energy Projections		
Va	Hour	Day	Week	Month	Year
KWattHr	20.89	501.28	3508.98	15038.48	182968.16
KVARHr	-0.36	-8.54	-59.81	-256.34	-3118.78
KVAHr	21.01	504.13	3528.92	15123.92	184007.75
Vb	Hour	Day	Week	Month	Year
KWattHr	27.18	652.24	4565.66	19567.11	238066.53
KVARHr	-5.93	-142.41	-996.87	-4272.29	-51979.59
KVAHr	28.01	672.17	4705.22	20165.23	245343.66
Vc	Hour	Day	Week	Month	Year
KWattHr	27.41	657.93	4605.53	19738.00	240145.70
KVARHr	4.63	111.08	777.56	3332.39	40544.08
KVAHr	28.01	672.17	4705.22	20165.23	245343.66
Total	Hour	Day	Week	Month	Year
KWattHr	75.48	1811.45	12680.17	54343.59	661180.38
KVARHr	-1.66	-39.87	-279.12	-1196.24	-14554.28
KVAHr	77.02	1848.48	12939.36	55454.39	674695.13

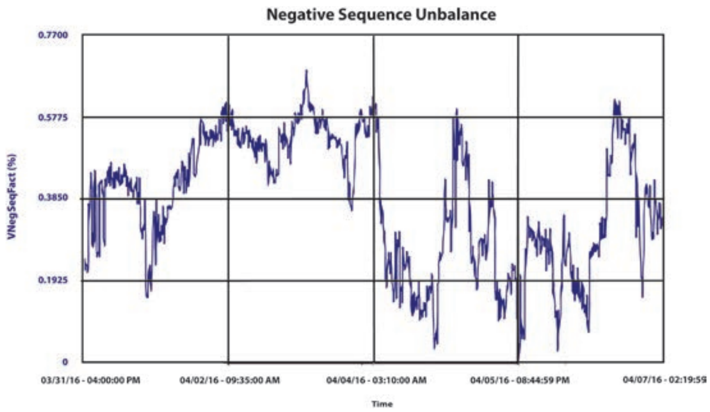
Review weekly energy. At what times are the peak loads? During peak loads, a premium can be charged.

Energy Parameter	Total KWH (in Kilo Notation)							
Start Date	03/31/16							
	THU	FRI	SAT	SUN	MON	TUE	WED	AVG
Time	3/31	4/1	4/2	4/3	4/4	4/5	4/6	
01:00		4.282	4.275	4.282	4.233	4.437	4.322	4.305
02:00		4.282	4.275	4.278	4.229	4.435	4.321	4.303
03:00		4.282	4.275	4.282	4.229	4.435	4.319	4.304
04:00		4.282	4.275	4.278	4.229	4.443	4.313	4.303
05:00		14.231	4.275	4.275	13.868	14.155	14.990	10.965
06:00		23.994	4.275	4.277	23.883	24.262	25.028	17.620
07:00		25.111	25.420	4.282	25.300	25.759	25.373	21.874
08:00		25.491	24.933	4.282	26.206	25.937	25.743	22.099
09:00		26.436	25.304	4.282	26.860	26.548	26.609	22.673
10:00		26.684	25.298	4.282	26.852	26.927	26.730	22.796
11:00		27.120	25.275	4.275	27.175	27.005	27.095	22.991
12:00		25.742	25.158	4.277	27.168	25.311	26.529	22.364
13:00		25.344	22.738	4.282	26.101	25.554	25.417	21.573
14:00		26.464	4.565	4.275	27.321	26.558	26.711	19.316
15:00		26.401	4.512	4.275	26.441	26.747	26.587	19.160
16:00		26.078	4.516	4.267	26.514	26.430	26.195	19.000
17:00	27.131	25.763	4.516	4.261	26.405	26.625	26.850	20.222
18:00	25.363	25.958	4.521	4.269	24.786	26.099	26.269	19.609
19:00	24.510	25.810	4.517	4.284	23.824	25.956	25.214	19.159
20:00	24.365	25.277	4.512	4.290	23.803	25.734	24.776	18.965
21:00	23.675	24.891	4.273	4.284	23.040	25.021	24.141	18.475
22:00	4.533	4.313	4.273	4.271	4.537	4.355	24.220	7.214
23:00	4.519	4.269	4.275	4.261	4.451	4.234	20.977	6.712
24:00	4.309	4.275	4.277	4.244	4.449	10.358	13.963	6.553
Total	138.406	456.779	248.530	102.616	455.902	467.324	506.693	
AVG	17.301	19.032	10.355	4.276	18.996	19.472	21.112	

Load scheduling: Electric utilities charge large commercial and industrial customers a peak demand penalty. This is in addition to the total electric usage over the billing period. The maximum amount of electricity used at any point in time is referred to as the Maximum Demand. These peak demand intervals are typically caused by inrush currents as multiple loads come on simultaneously.

Identify large loads that operate at the same time. By staggering the turn on of these loads or moving certain processes to off peak hours, you may be able to avoid these peak demand penalties.

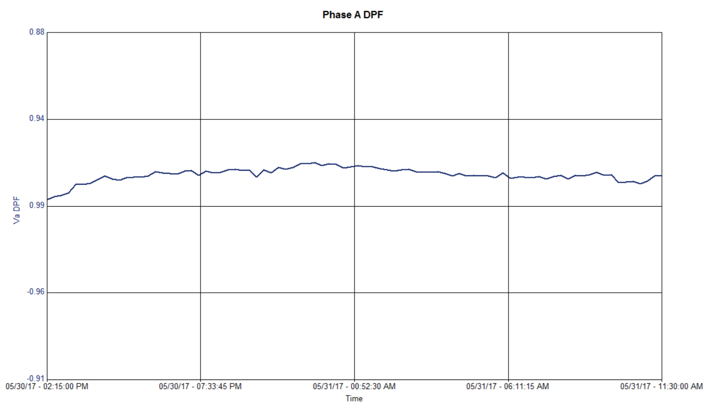
Unbalance: Examine the unbalance of the system. Unbalance is a cause of neutral currents. Neutral currents create heat which does contribute to energy loss.



Negative sequence unbalance creates losses in rotating equipment. The European EN50160 standards limit voltage unbalance to 2%. North America also recommends a 2% limit on voltage unbalance.

Note: In a 3-phase motor, just a 1% unbalance in voltage can lead to a 6 to 10% unbalance in a current. So, high voltage unbalances can lead to 3-phase motors overheating.

Displacement power factor: Examine the displacement power factor. If it gets too low, you can get penalties from the utility.

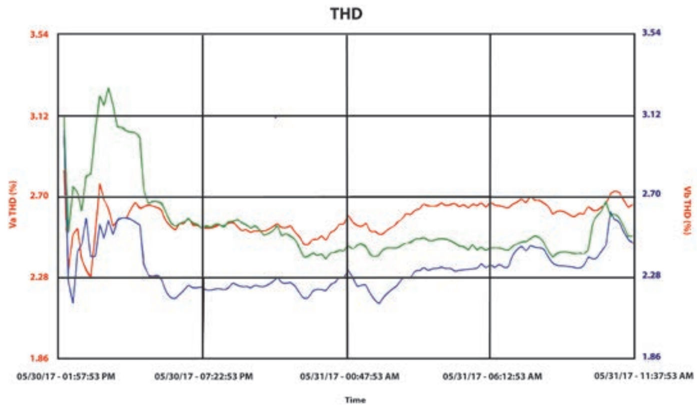


The greater the amount of inductive loads, such as motors, the greater the current lag between the voltage and current. This increases reactive power and decreases active power. Capacitor banks are used to compensate for this.

True power factor: Examine the true power factor. Is it significantly lower than the displacement power factor? If yes, then this is a sign of harmonics on the system. The greater the harmonic content, the greater the energy loss.

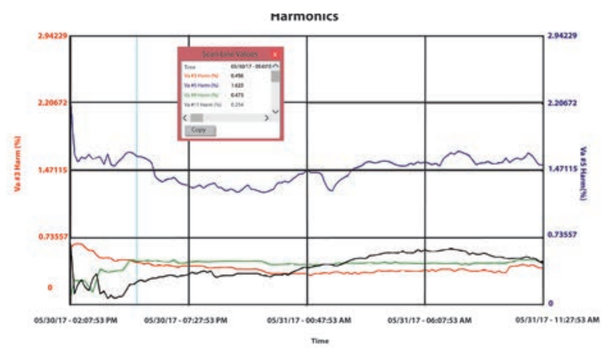
Date / Time	Volt	Amp	KW	KVAR	KVA	KWH	KVARH	KVAH	TPF	DPF
05/30/17 02:15:00.012 PM										
PH A	282.476	83.294	20.44	3.70	23.50	5.11	0.926	5.87	+0.870	+0.981
PH B	280.941	74.865	17.30	0.071	21.01	4.33	0.018	5.25	+0.824	+1.000
PH C	282.380	69.880	15.10	4.77	19.65	3.77	1.19	4.91	+0.768	+0.947
Total			52.83	8.54	64.16	13.21	2.14	16.04	+0.824	
05/30/17 02:30:00.009 PM										
PH A	282.092	83.838	20.86	4.27	23.64	5.22	1.07	5.91	+0.883	+0.980
PH B	280.558	74.049	17.30	-0.142	20.72	4.33	-0.036	5.18	+0.835	-0.999
PH C	281.996	68.248	14.60	5.20	19.23	3.65	1.30	4.81	+0.759	+0.935
Total			52.76	9.33	63.59	13.19	2.33	15.90	+0.830	
05/30/17 02:45:00.000 PM										
PH A	281.613	85.650	21.29	4.34	24.07	5.32	1.09	6.02	+0.885	+0.979
PH B	280.030	73.687	17.09	-0.570	20.58	4.27	-0.142	5.14	+0.830	-0.999
PH C	281.469	68.702	14.31	5.70	19.30	3.58	1.42	4.82	+0.742	+0.931
Total			52.69	9.47	63.94	13.17	2.37	15.99	+0.824	
05/30/17 03:00:00.005 PM										
PH A	282.380	85.650	21.15	4.41	24.14	5.29	1.10	6.03	+0.876	+0.978
PH B	280.798	74.412	17.45	-0.712	20.86	4.36	-0.178	5.22	+0.836	-0.999
PH C	282.092	68.248	14.24	5.20	19.23	3.56	1.30	4.81	+0.741	+0.942
Total			52.83	8.90	64.23	13.21	2.23	16.06	+0.823	
05/30/17 03:15:00.005 PM										
PH A	282.572	84.925	20.79	4.70	23.92	5.20	1.17	5.98	+0.869	+0.973
PH B	280.846	75.318	17.94	-0.641	21.15	4.49	-0.160	5.29	+0.848	-0.999
PH C	282.092	66.617	14.03	4.77	18.73	3.51	1.19	4.68	+0.749	+0.952
Total			52.76	8.83	63.80	13.19	2.21	15.95	+0.827	

What is the total harmonic distortion? Harmonics cause energy losses. Harmonics cause heating effects in cables, motors as well as transformers and can also interfere with sensitive electronics.



The European EN50160 standards and IEEE519 recommended practice both limits voltage THD to 8% on low voltage systems (<1kV). On medium voltage systems (1kV to 69kV), the European EN50160 standards limit the THD to 8% while the IEEE519 recommended practice limits the voltage THD to 5%.

Harmonics: If you see harmonics, what order harmonics are you seeing?



Zero sequence harmonics produce high neutral currents. This creates losses through heat. A common zero sequence harmonic is the 3rd order harmonic and 9th order harmonic.

The 3rd order harmonic is very common and typically caused by commercial power supplies found in computer systems and everyday consumer electronics.

The European EN50160 standards limit the voltages 3rd harmonic content to 5.0% and the 9th harmonic content to 1.5%. The IEEE519 recommended practice limits the voltages 3rd and 9th harmonic to 5% on low voltage systems (<1kV). On medium voltage systems (1kV to 69kV), the European EN50160 standard limits the 3rd harmonic to 5.0% and the 9th harmonic to 1.5%, while the IEEE519 recommended practice limits both the 3rd and 9th harmonic to 3%.

Negative sequence harmonics can setup counter rotational magnetic fields in motors. This not only leads to energy loss but can also lead to vibrations within the motor. A common negative sequence harmonic is the 5th order harmonic and 11th order harmonic. The 5th order harmonic is commonly caused by 6 pulse converters, such as those in 3-phase power supplies, while the 11th order harmonic is commonly caused by 12 pulse converters.

The European EN50160 standards limit the voltages 5th harmonic content to 6.0% and the 11th harmonic content to 3.5%. The IEEE519 recommended practice limits the voltage 5th and 11th harmonic to 5% on low voltage systems (<1kV). On medium voltage systems (1kV to 69kV), the European EN50160 standard limits the 5th harmonic to 6.0% and the 11th harmonic to 3.5%, while the IEEE519 recommended practice limits both the 5th and 11th harmonic to 3%.

Some changes that can be made to help save energy include the following:

- Reduce the load by turning off systems
- Shift load to off-peak hours. Move some operations to off peak times
- Change to more efficient lighting

NOTE: Always perform a power quality load study when making electrical changes. The power system is dynamic, it changes with the load. For example changing over to LED lighting will save energy. However these lights are non-linear loads. They operate off of DC. Which means they use AC to DC converters which create harmonics. Since they draw low current the harmonic impact will be low for a single light. However when changing an entire floor the load will add up.

- Reduce heating and cooling requirements
- Add Insulation
- Get more efficient windows
- Check with the local utility for any energy saving rebates that may be available.

Power Quality Analyzers Available from Megger

Megger power quality analyzers are highly intuitive instruments, simple to use and have the ability to measure all power quality problems from high-speed transients to RVC, high-frequency harmonics, signaling and much more. They are smart enough to recognize the CT connected as well as the CT range and let you know they are connected properly. The on-board data analysis on the large color display makes analysis easy for anyone to use. Both units are IEC61000-4-30 Class A compliant.

MPQ1000

Handheld Power Quality Analyzer

The MPQ1000 is Class A compliant and rated CATIV at 600 V. It can be used for a wide variety of applications including substation monitoring, equipment and breaker tripping, load studies and balancing, as well as switchgear and component failure.

Some of its features include:

- Automatic CT recognition
- Automatic connection verification
- On-board data analysis
- SD card and USB stick support
- 1000 V AC and DC range
- Scope and DMM modes

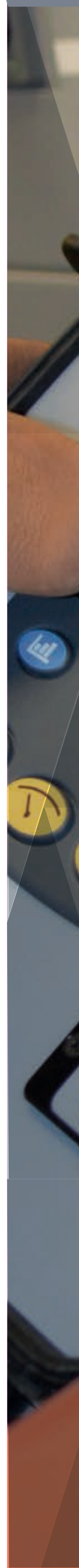
MPQ2000

Portable Power Quality Analyzer

The MPQ2000 is housed in a NEMA4 IP54 weatherproof enclosure for outdoor use. The unit is robust enough to remain recording outdoors. It can record for extended periods of time because of its large memory.

Some of the MPQ2000 features include:

- Powered off of Phase A voltage ac/dc
- 1000 V ac and 1000 V dc range
- Real time scope and DVM
- Connection verification
- On-board data analysis



Guide to power quality testing_en_V01

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