Tennessee Metering School
Power Quality

Andrew Sagl

Megger
Power on

Power Quality

- What is Power Quality?

- The concept of powering and grounding sensitive equipment in a manner that is suitable to the operation of that equipment.

Megger

Power on

Introduction

- The modern power grid is changing.
- The addition of green energy sources
  - Solar
  - Wind energy
- The reduction of coal bulk generation plants
- As loads increase coupled with the intermittent nature of solar and wind energy the voltage stability will suffer.
- New technologies such as, electric vehicles are adding new loads to the grid which, can lead to altered peak hours.
- The implementation of the smart grid technology which is designed to makes the grid more efficient.

Agenda

- Under-Voltage
- Over-Voltage
- Dips (Sags) and Swells
- Transients
- Unbalance
- Harmonics
- Power and Energy
- Power Factor
- ARC Flash
- Conducting a PQ Investigation

Under-Voltage

- An under-voltage is a decrease in rms voltage less than 0.9 pu for a duration longer than 1 min.
  - Typical values are between 0.8 pu and 0.9 pu.

- Effects of under-voltage events
  - Motors can overheat
    - Current increases - Heat increases in the coils.
  - Lighting systems
    - Incandescent lights dim.
    - Fluorescent lighting flash or may not turn on
  - Manufacturing equipment Drop off line.
    - High Cost in lost production

Under-Voltage Causes

- Typically not due to system faults
- Generally due to variations on the system load and / or system switching
  - Large load switching on
  - Capacitor bank switching off
  - Overloaded circuits
- Utility feeders attempt to maintain ± 5% voltage regulation
- Under voltages can occur due to:
  - Overloaded feeders
  - Incorrect tap settings
  - Malfunctioning regulators
  - Blown fuses on capacitor banks
  - Capacitor banks in service during light load conditions

Megger. Power on

Over-Voltage

- Defined as an rms increase in AC voltage greater than 1.1 percentile units (pu) for a duration longer than 1 min.
- For example if nominal voltage were 100V then an over voltage event occurs when the voltage rises above 110V for over a 1 minute interval.
  - Typical values are 1.1 to 1.2 pu or 110% to 120% of nominal.

Over-Voltage

- Effects of Over Voltage
- Stress and damage electrical equipment insulation.
- Breakdown of Cable
- Transformer and Motor Damage
- Flash over
- Tripping breakers
- Equipment controllers dropping off line.
- Increased current inrush / increased energy usage.

Over-Voltage

- Causes
- Commonly caused by load variations and switching operations
- Large loads turning off
- Capacitor
- Solar panels
- Other causes include
- Incorrect tap settings on transformers
- Resonance
- Ungrounded delta system
- Long cable runs with light loads

Megger
Power on

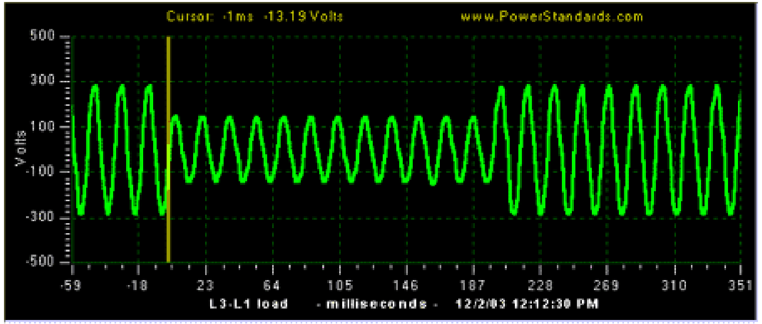
Voltage Dips (Sags)

- IEEE uses the term sag
- IEC uses the term dip
- They are the same thing
- IEEE classifies sags into different categories.

- Sag: A short duration event
  - 0.5 cycle to 1 minute where the
- RMS voltage decreases
  - Between 0.1 and 0.9 (pu) of nominal

Voltage Dips (Sags)

- A sag is described in terms of the remaining voltage.
- 90% Sag = 90% of nominal voltage remaining.
  - For example:
  - Nominal voltage = 230V
  - 80% Sag =184V
- Three categories of sags
  - Instantaneous
  - Momentary
  - Temporary

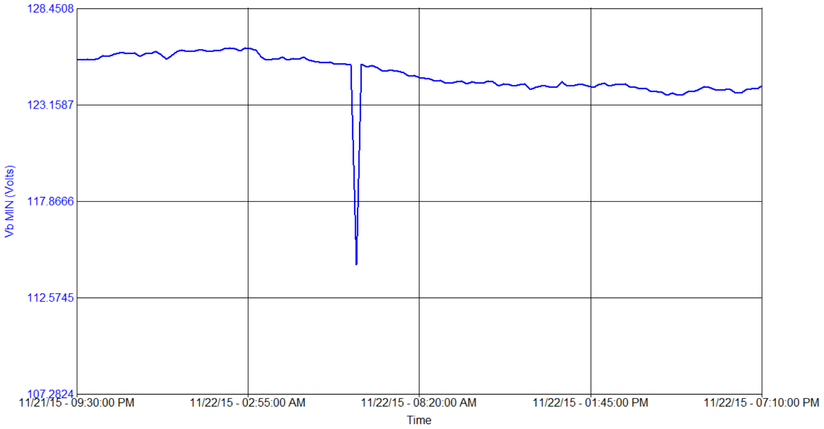


Megger.
Power on

Voltage Dips (Sags)

- Instantaneous Sag
  - Voltage = 10% - 90% nominal
  - Duration = 0.5 cycles to 30 cycles.
- Momentary Sag
  - Voltage 10% to 90% of nominal
  - Duration = 30 cycles to 3 seconds.
- Temporary Sag
  - Voltage = 10% to 90% of nominal
  - Duration = 3 seconds to 1 minute.

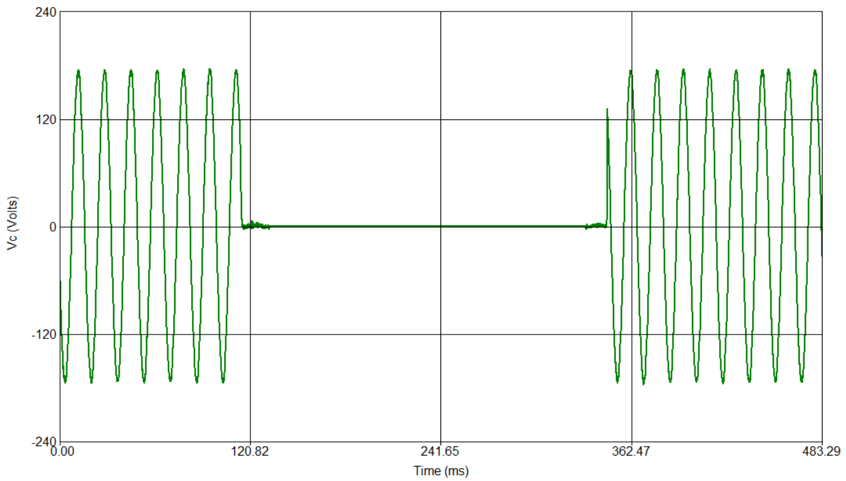
Instantaneous Sag



Voltage Dips (Sags)

- Interruption - short duration event
  - 0.5 cycle to 1 minute
  - RMS voltage < 0.1 (pu) of nominal
- Two categories of interruptions
  - Momentary
  - Temporary.
- Momentary Interruption
  - Voltage < 10% of nominal
  - Duration = 0.5 cycles to 3 seconds
- Temporary Interruption
  - Voltage < 10% of nominal
  - Duration = 3 seconds to 1 minute

Momentary Interruption



Voltage Dips (Sags)

- Effects
- Equipment shutting down
  - Costly
    - Lost Time
    - Lost Material
- Switching power supplies operating incorrectly
- Speed change of induction machinery
- Capacitor bank output reduction
- Dimming of lighting devices

Voltage Dips (Sags)

- Causes
  - Large loads turning on
  - Intermittent connections
  - Source side faults
- Large loads draw large inrush current
  - Inrush current causes voltage drop
    - Induction motor
      - 6 to 10 times full load at start up
- Intermittent connections
  - Change system impedance
  - Changing the voltage
- Source side fault
  - Single line to ground faults (SLG)
  - Line to Line faults (LL)

Megger. Power on

Voltage Swells

- A voltage swell = increase in rms voltage above 1.1 percentile units (pu) that last from 0.5 cycle to 1 min.
- Swell described by remaining voltage
  - For example a 120% Swell on 120V line = max voltage of 144V.
- Sags are also categorized as instantaneous, momentary, or temporary.

Voltage Swells

- Instantaneous swell
  - Voltage = 110% to 180% of nominal
  - Duration = 0.5 cycles to 30 cycles.
- Momentary swell
  - Voltage = 110% to 140% of nominal
  - Duration = 30 cycles to 3 seconds.
- Temporary swell
  - Voltage = 110% to 120% of nominal
  - Duration = 3 seconds to 1 minute.

Voltage Swells

- Effects
- Equipment shutdown
- Critical process shutdowns can require hours to restart = lost $
- Tripping breakers
- Relay switching
- Component failure; such as,
- Adjustable Speed Drive (ASD)
- Computer equipment
- Electronic controllers
- Surge protectors

Voltage Swells

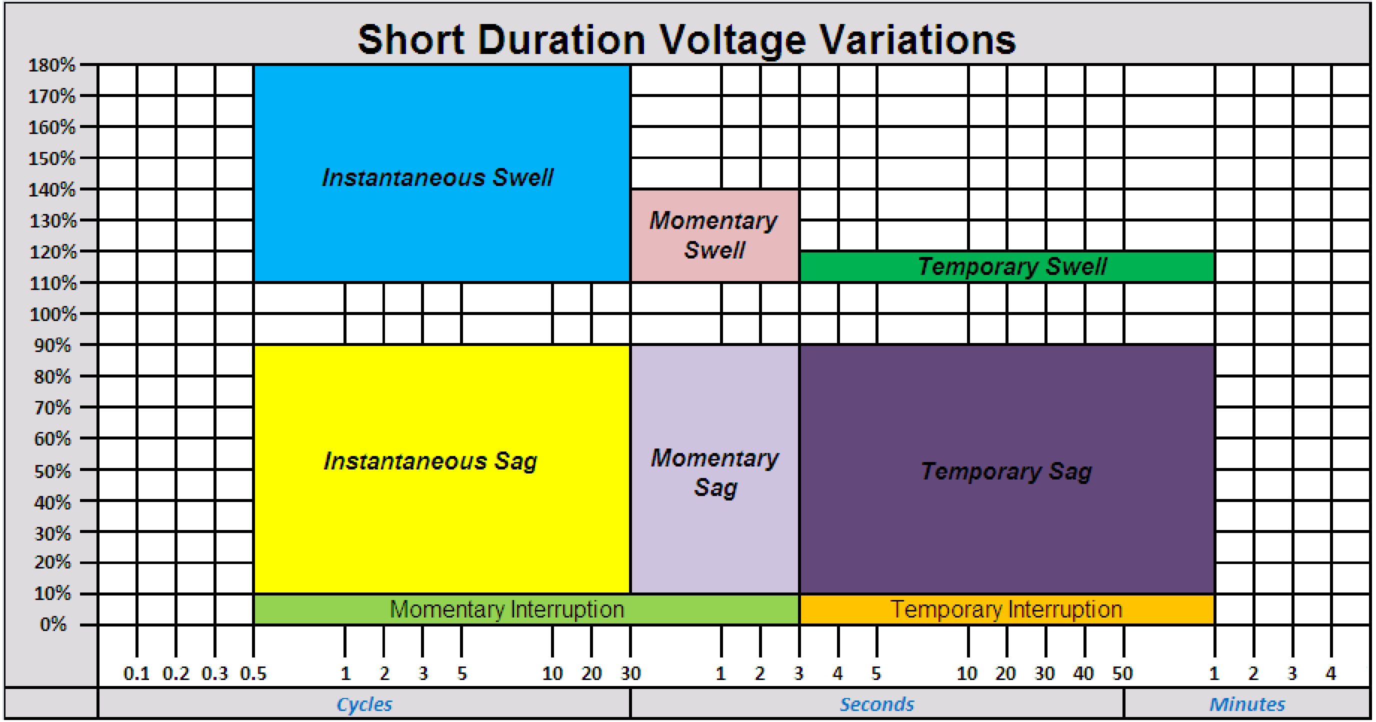
- Repeated Swells can effect:
- Transformers
- Cables
- Busses
- Switchgear
- CTs, PTs
- Rotating machinery
- Capacitor bank
- Lighting

Voltage Swells

- Causes
- Load changes
  - Switching off large loads
  - Switching on capacitor banks

- Source side faults
  - Less common than sags
- Single line to ground fault (SLG)
  - Rise on the un-faulted phases
  - Delta configuration

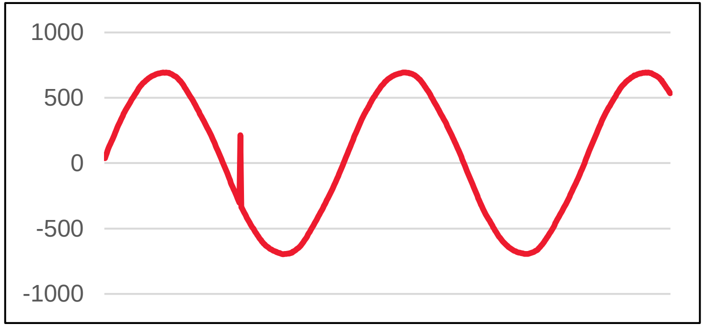
Voltage Dips (Sags) and Swells

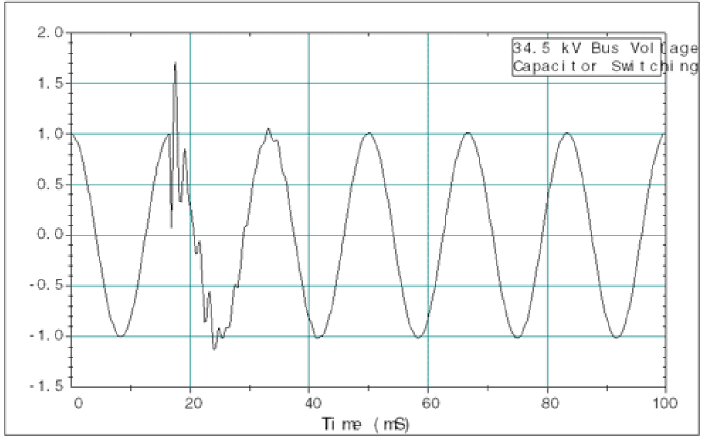


Megger. Power on

Transients

- Generally there are two different types of transient over voltages: low frequency transients with frequency components in the few-hundred-hertz region typically caused by capacitor switching, (Oscillatory transients) and high-frequency transients with frequency components in the few-hundred-kilohertz region typically caused by lighting and inductive loads. (Impulsive Transients)



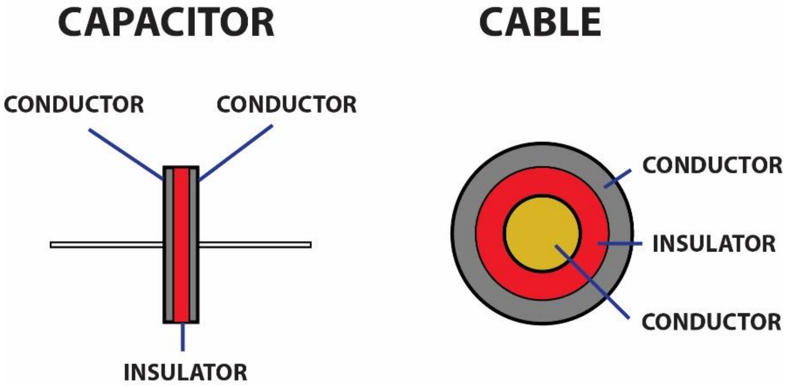


Transients

- Transient voltages can result in degradation or immediate dielectric failure in all classes of equipment.
- High magnitude and fast rise time contribute to insulation breakdown in electrical equipment like switchgear, transformers and motors.
- Repeated lower magnitude application of transients to equipment can cause slow degradation and eventual insulation failure, decreasing equipment mean time between failures.

Transients

- Transients can damage insulation because insulation, like that in wires has capacitive properties.
- Both capacitors and wires have two conductors separated by an insulator.
- The capacitance provides a path for a transient pulse.
- If the transient pulse has enough energy it will damage that section of insulation.



Transients

- This can be understood by examining the basic formula for Capacitive Reactance.
- It can now be seen that as the value of the frequency increases, the lower the reactive capacitance and therefore the lower the impedance path.

$$X_c = \frac{1}{2\pi f C}$$

Xc = Capacitive Reactance
f = Frequency
C = Capacitance

Transients

- A transient acting on a coil of a motor or a transformer will dissipate the majority of its energy in the first few coils.
  - Each successive coil presents more resistance and capacitance to the transient.
  - This will reduce its magnitude and increase its period, reducing the energy.
- Since the majority of the energy is transferred to the first few coils, this is where the damaged insulation will typically appear.

Megger.
Power on

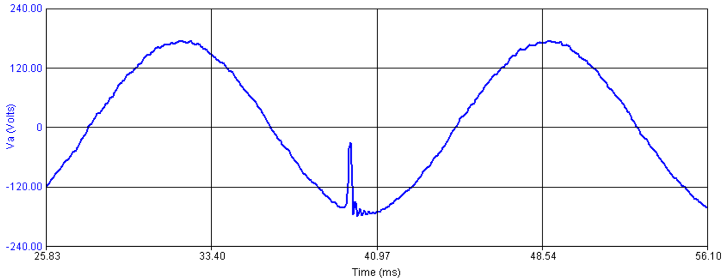
Transients

- Transients can also affect fluorescent lighting.
  - A fluorescent light illuminates because the gas inside of the light is ionized when voltage is applied across the electrodes.
- Transients can produce excessive energy that can displace the material within the electrodes.
- This will eventually reduce the amount of light given off by the fluorescent light, as well as reducing its lifespan.

Megger. Power on

Transients

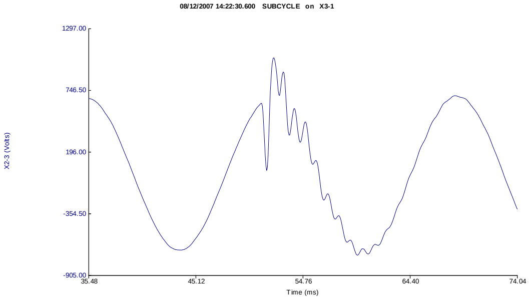
- Lightning is a major cause of transients.
  - A bolt of lightning can be over 5 miles long, reach temperatures in excess of 20,000 degrees Celsius.
- Lightning strikes or high electromagnetic fields produced by lighting can induce voltage & current transients in power lines & signal carrying lines.
- These are typically seen as unidirectional transients.



Megger. Power on

Transients

- When capacitor banks are switched on there is an initial inrush of current.
- This will lead to a low-frequency transient that will have a characteristic ringing.
- These types of transients are referred to as oscillatory transients.
- Oscillatory transients can cause equipment to trip out and cause UPS systems to turn on and off erroneously.



Megger. Power on

Transients

- (Extremely fast transients, or **EFT**'s, have rise and fall times in the nanosecond region. They are caused by arcing faults, such as bad brushes in motors, and are rapidly damped out by even a few meters of distribution wiring. Standard line filters, included on almost all electronic equipment, remove EFT's.)
- These typically will cause issues in areas with short cable runs, such as off shore platforms

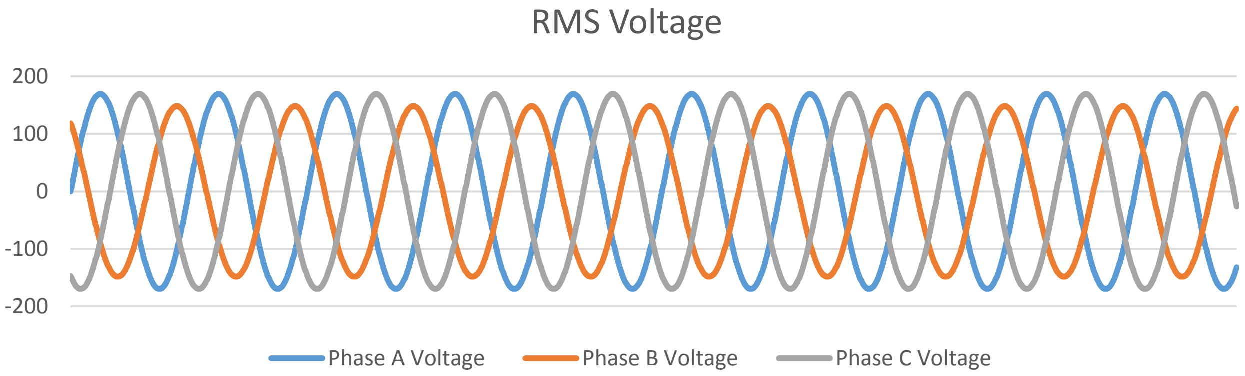
Megger. Power on

Transients

- The effect of **EFT**'s, are limited because they are typically low energy due to their short duration.
- 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 microseconds that drives a current of10A this will deliver an energy of 0.005 joules.
  - .005 joules = (500 * 10) * (1 *10^{-6})

Unbalance

- Unbalance is a condition in a poly-phase system in which the RMS values of the line voltages (fundamental component), or the phase angles between consecutive line voltages, are not all equal per IEEE 1159 and IEC 61000-4-27.



Megger
Power on

Unbalance

- Unbalanced voltages cause problems, to inductive devices
  - Transformers
  - Motors
  - Generators.
- Unbalance not exceed 1% on 3 phase motors
- Unbalanced current 6 to 10 times higher
- Motor overheat

Megger
Power on

Unbalance

- ANSI measurement
- Ratio of the maximum deviation of a the voltage to the average voltage of all phases, expressed in percent. This is done using phase-to-phase voltage measurements.

$$U_{unb} = 100 * (\frac{\max(\text{Urms phase X} - \text{Vavg})}{\text{Vavg}}$$

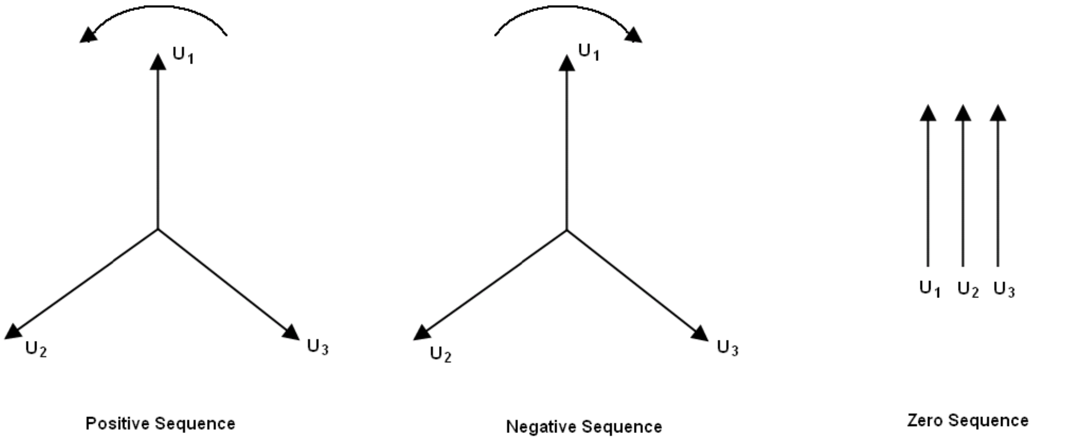
$$U_{unb} = \frac{\text{Vrms1} + \text{Vrms2} + \text{Vrms3}}{3}$$

Line-to-line voltages are typically used for this calculations If phase to neutral voltages are used then the phase angle unbalance is not reflected in the % Unbalance, therefore this method is seldom used

Megger. Power on

Unbalance

- Symmetrical Components allows voltage unbalance to be mathematically broken down into three balanced systems, the positive sequence, the negative sequence and the zero sequence.



Unbalance

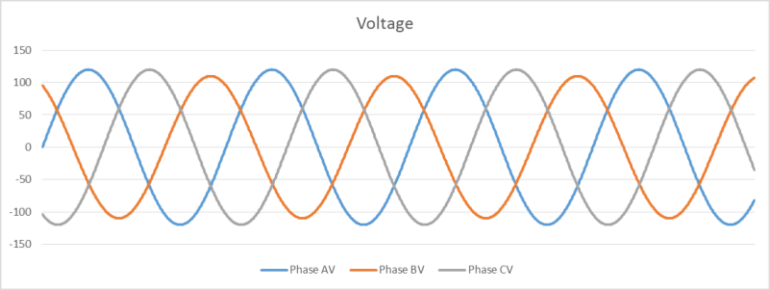
- The level of voltage unbalance can described in terms of negative sequence factor and the zero sequence factor.
- The negative sequence factor is a ratio of the negative sequence component to the positive sequence component.
- The zero sequence factor is the ratio of the zero sequence component to the positive sequence.

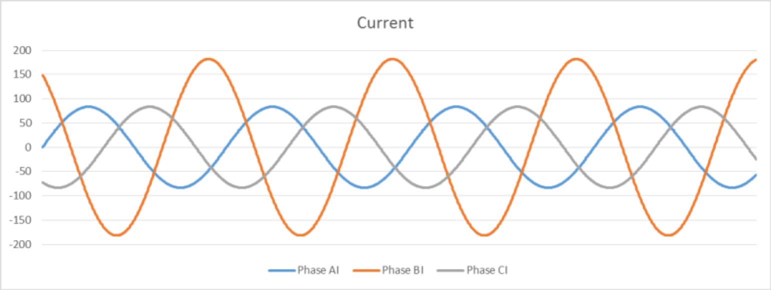
$$U_2 = \frac{\text{negative sequence}}{\text{positive sequence}} * 100\%$$

$$U_0 = \frac{\text{zero sequence}}{\text{positive sequence}} * 100\%$$

Unbalance

- Minor voltage unbalance (< 2%) typically due to unbalanced loads.
- Some causes can include:
  - Large single phase loads
  - Blown fuse on capacitor bank
  - Single-phase line regulator
  - Residential solar panels
- Larger unbalance (> 5%) due to single-phasing conditions:
  - Open protective device
  - Wrong tap settings
  - Open phase on transformer

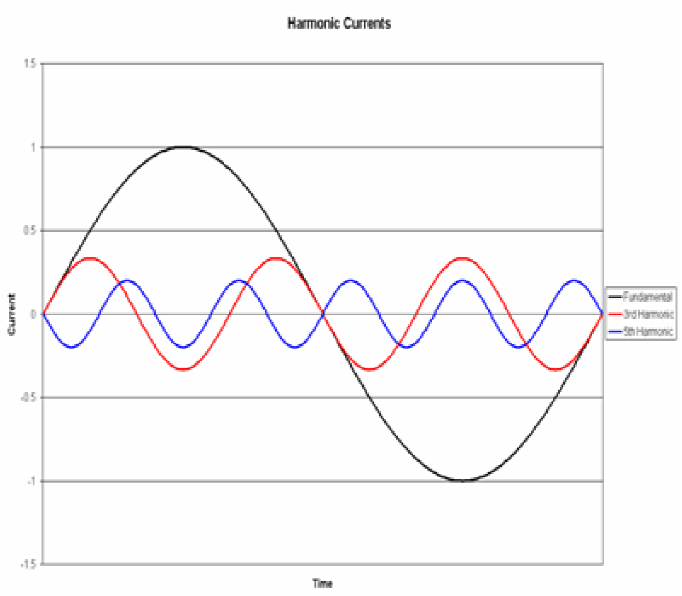




Megger. Power on

Harmonics

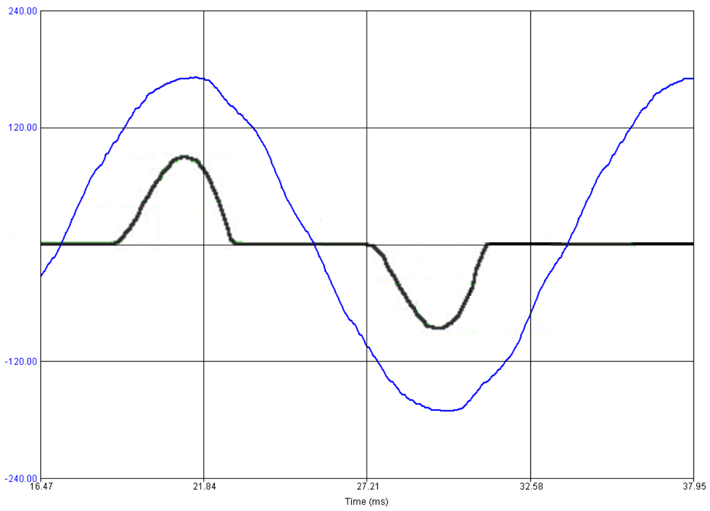
- Harmonics are a sinusoidal component of periodic waves that have frequencies that are multiples of the fundamental frequency
- Harmonics can cause many problems, such as:
  - Neutral wires to over heat
  - Motors to overheat
  - Transformers to overheat
  - Electronic Failures



Megger.
Power on

Harmonics

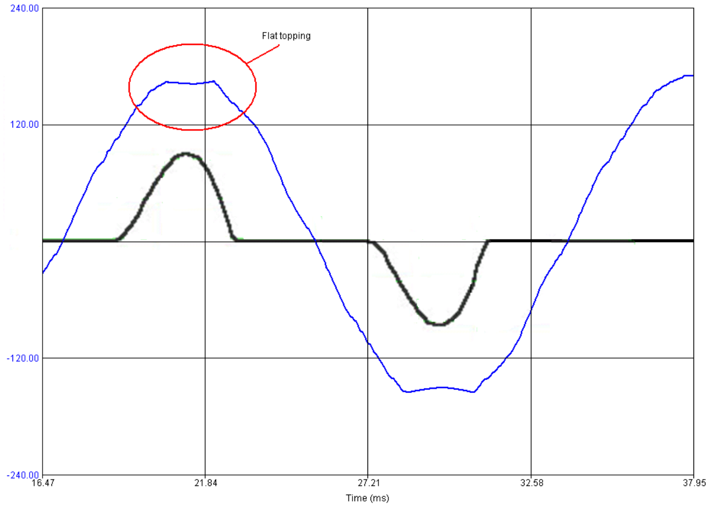
- Linear Loads such as incandescent light and motors draw current equally throughout the waveform.
- Non-Linear loads such as switching power supplies draw current only at the peaks of the wave.
- It is these non linear loads that cause harmonics.



Megger. Power on

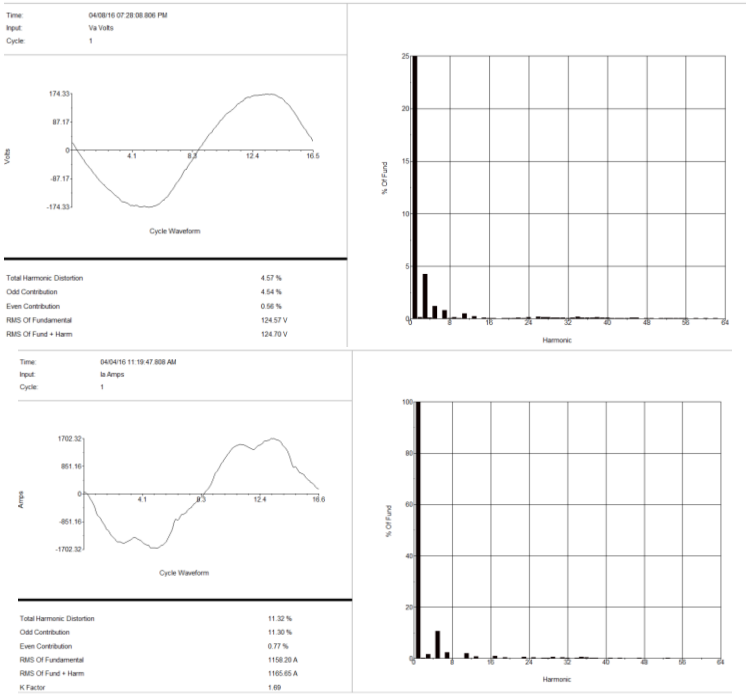
Harmonics

- Typically current harmonics will not propagate through a system.
- Voltage harmonics will propagate through a system, as they will pass through transformers.
- When non-linear loads get high enough they can cause harmonics in the voltage.



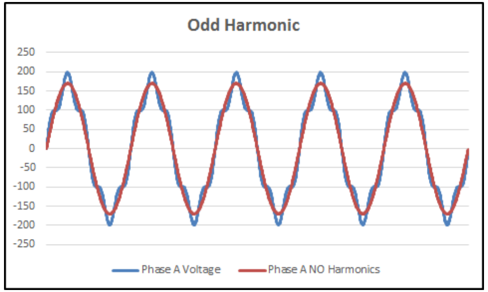
Harmonics

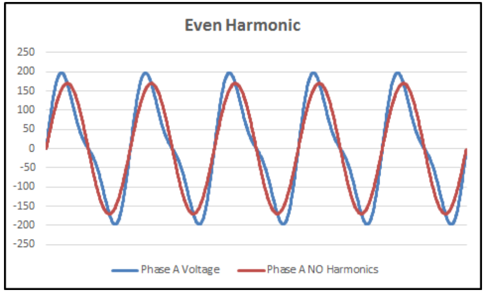
- Rectifiers convert AC to DC.
- Different configurations
- Different harmonic signatures
- Computer = 4 pulse converter
  - Predominate harmonic = # of pulses minus 1.
- 4 Pulse converter = 3rd
- 6 pulse converter = 5th
- 12 pulse converter = 11th

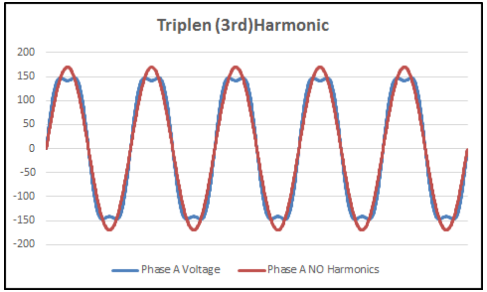


Harmonics

- Harmonics can be characterized based on their order.
- Odd Harmonics are harmonics with odd order numbers.
- Even Harmonics are harmonics with even order numbers.
  - Non-symmetrical due to faulty rectifiers.
- Triplens are odd harmonics that are multiples of 3.
  - These will not cancel out and will add and cause high neutral currents.



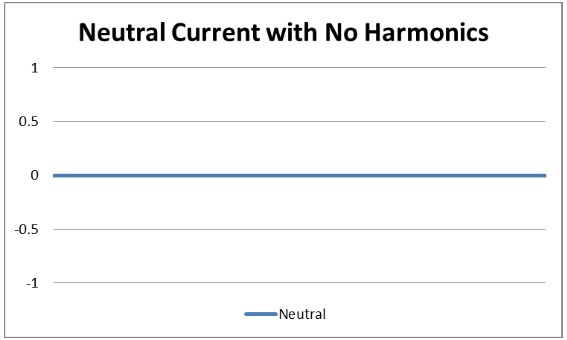


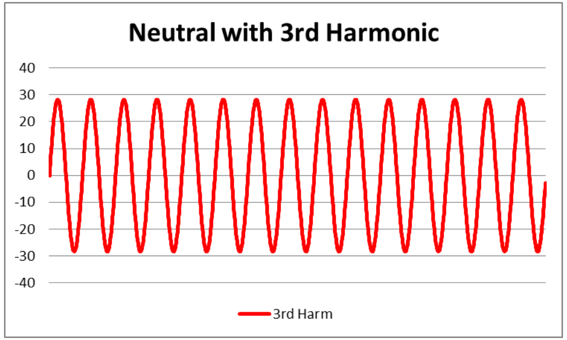


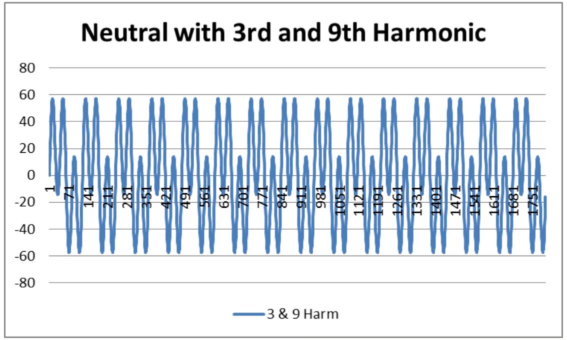
Megger. Power on

Harmonics

- When all the phases are balanced and there are no harmonics the neutral lead will not have current present.
- Add third harmonic and neutral current flows.
- Add 9^{th} harmonic to that and the neutral current increases.
- As the current increases the heat in the neutral increases. $P = I^2R$







Harmonics

- Harmonics can characterized in different sequences, based on the rotation of their magnetic field. Positive sequence harmonics creates 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.

- 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 and generate heat.

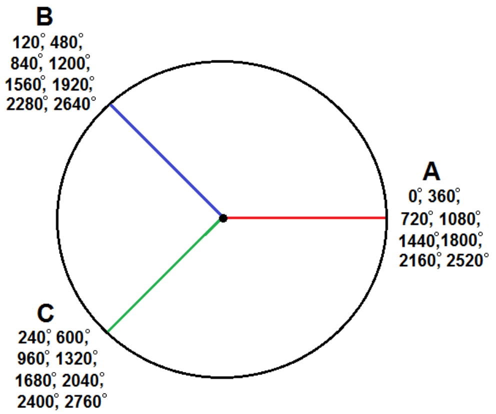
Harmonics

- The positive, negative, and zero sequence harmonics run in sequential order (positive, negative, and then zero).Since the fundamental frequency is positive, this means that the second order harmonic is a negative sequence harmonic. The third harmonic is a zero sequence harmonic.

60Hz Harmonics Frequencies				50Hz Harmonics Frequencies		
Harmonic	Frequency	Note		Harmonic	Frequency	Note
0	0	DC		0	0	DC
1	60	Fundamental		1	50	Fundamental
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 sequence				*The fundamental has a positive sequence*		

Harmonics

- Sequence Rotation
  - Phase A = 0°, 360°, 720°
  - Phase B = 120°, 480°, 840°
  - Phase C = 240°, 600°, 960°
- 1st Order = ABC rotation
  - Positive Sequence
- 5th Order = ACB rotation
  - Negative Sequence
- 3rd Order = No rotation
  - Zero Sequence

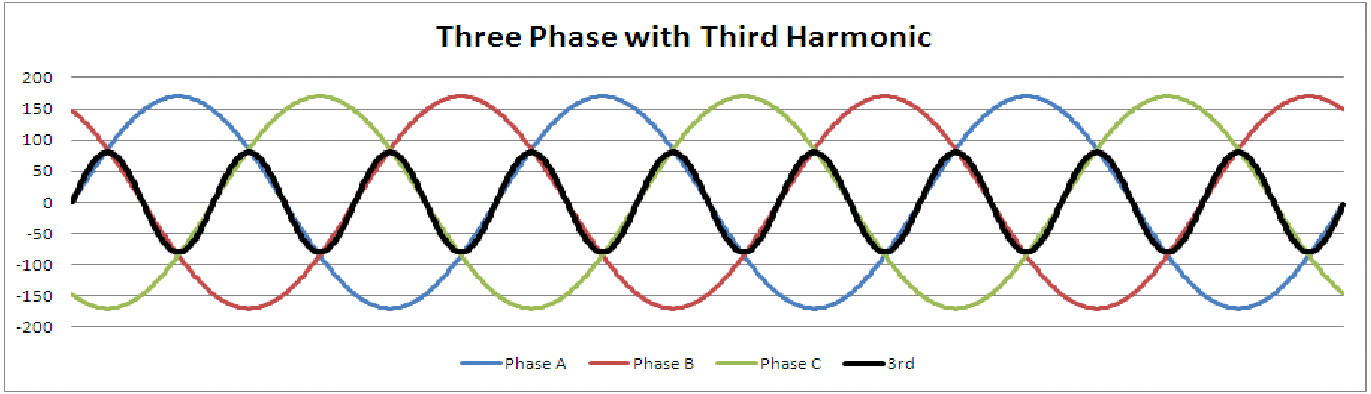


Harmonic	Phase A	Phase B	Phase C	Rotation	Sequence
1	0	120	240	ABC	Positive Seq.
3	0x3=0	120x3=360	240x3=720	No Rotation	Zero Seq.
5	5x0=0	5x120=600	5x240=1200	ACB	Negative Seq.
7	7x0=0	7x120=840	7x240=1680	ABC	Positive Seq.
9	9x0=0	9x120=1080	9x240=2160	No Rotation	Zero Seq.
11	11x0=0	11x120=1320	11x240=2640	ACB	Negative Seq.

Megger.
Power on

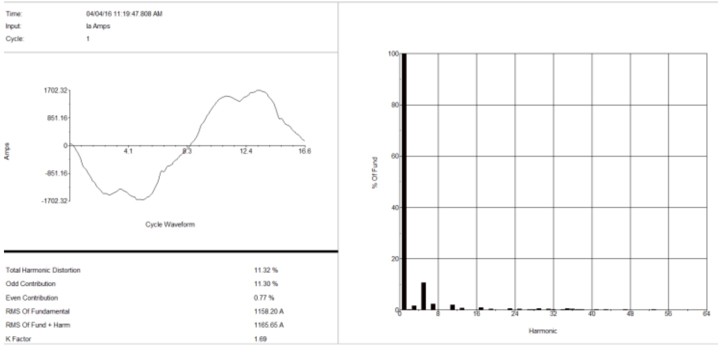
Harmonics

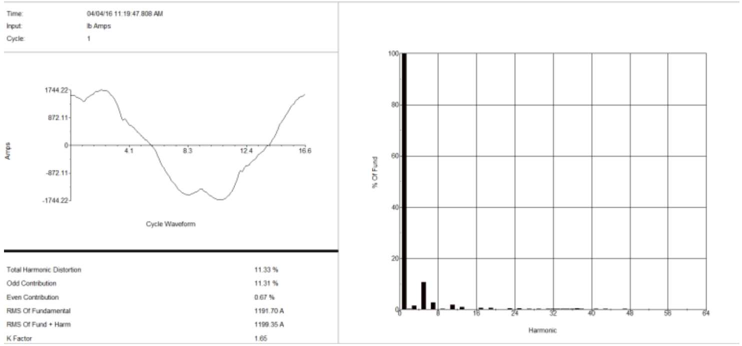
- In three-phase systems, the fundamental currents will cancel each other out, add up to zero amps in the neutral line.
- Zero sequence harmonic (*such as the third harmonic)* will be in phase with the other currents of the three-phase system.
- Since they are in phase they will sum together and can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

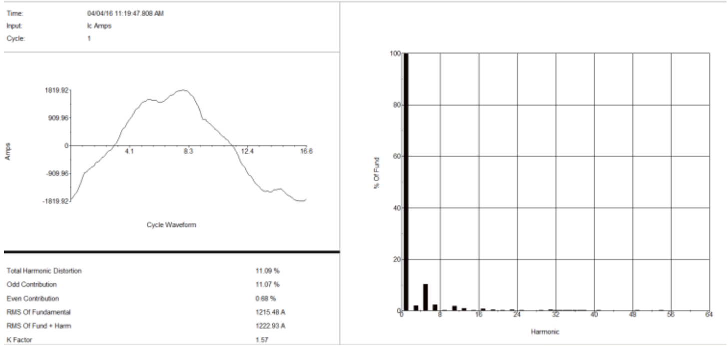


Harmonics

- Example I have a
- 3 phase load
- 6 pulse converter
- 5th harmonic
- Dominate

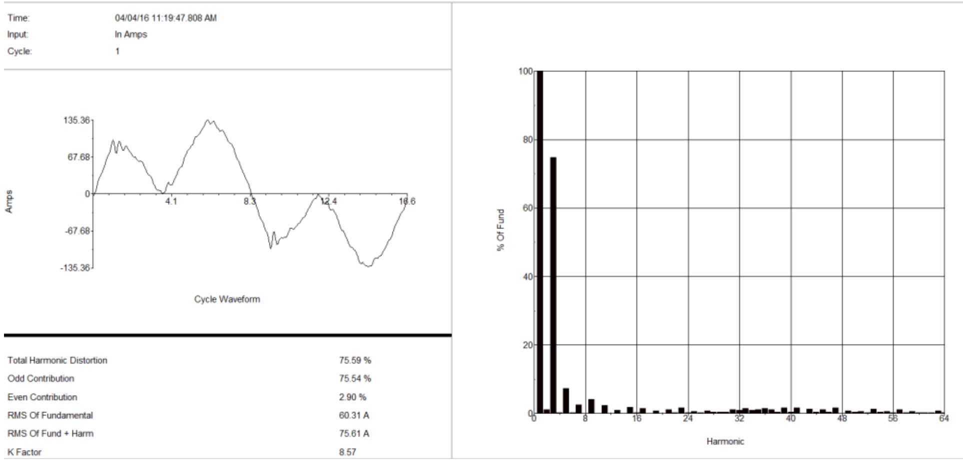






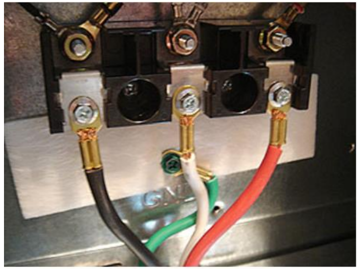
Harmonics

- Neutral current
- 3rd harmonic dominate
- Positive and negative sequence tend to cancel on the neutral.
- Zero sequence add together



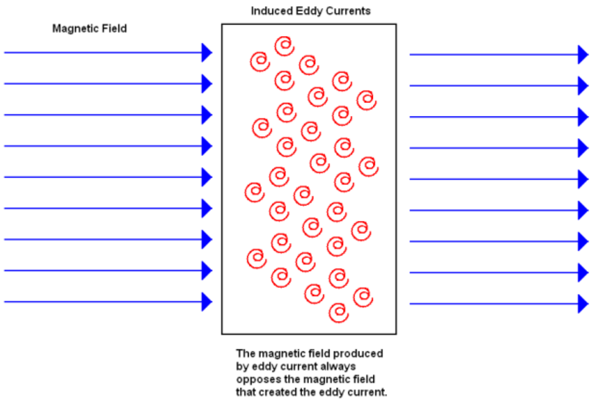
Harmonic Effects

- Excessive harmonic distortion can cause many power quality problems due to the heat generated by harmonics. These power quality problems can include neutral wires, transformers as well as motors overheating.



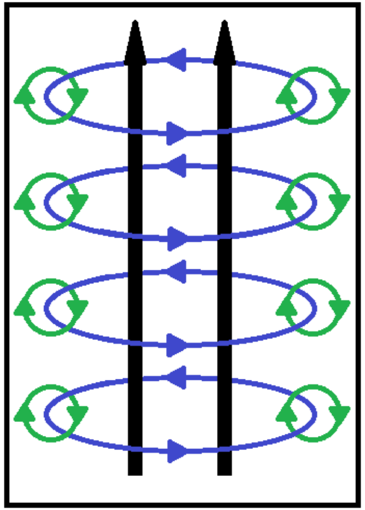
Eddy Currents

- Alternating current through a wire creates eddy currents.
- Eddy Currents are circular currents that are induced in the conductors of the windings by alternating magnetic fields.
- Eddy currents induce magnetic fields that are opposite from the magnetic fields that created them. The repulsion of the magnetic fields increases the resistance in the winding. This in turn creates heat and loss of power. Higher frequency harmonics will increase the energy of the eddy current.



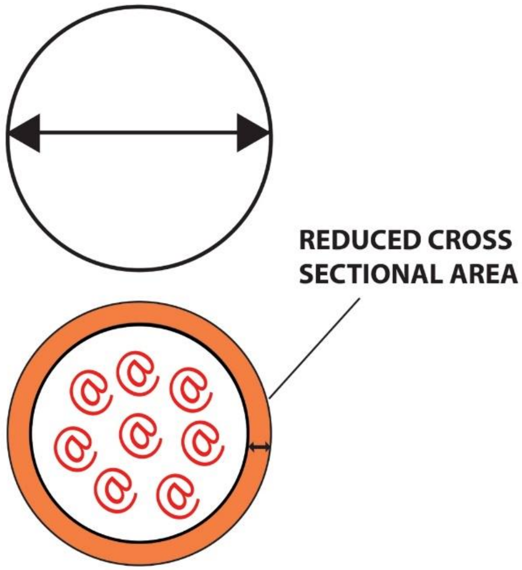
Skin Effect

- Skin Effect
  - Eddy currents cause the phenomenon called “skin effect” in transformer windings.
  - Skin effect refers to the tendency of AC current to be distributed in a conductor such that the density is greatest near the surface of the conductor.
  - Eddy currents induced in the wire create magnetic field that oppose the magnetic fields that generated them.



Skin Effect

- Skin Effect
  - This opposition increases the resistance in the center of the conductor. This causes the current density to be greater near the surface of the conductor, which reduced the effective cross sectional area of the wire, causing a higher resistance and therefore a greater winding loss.
  - At low frequencies skin effect is minimal.



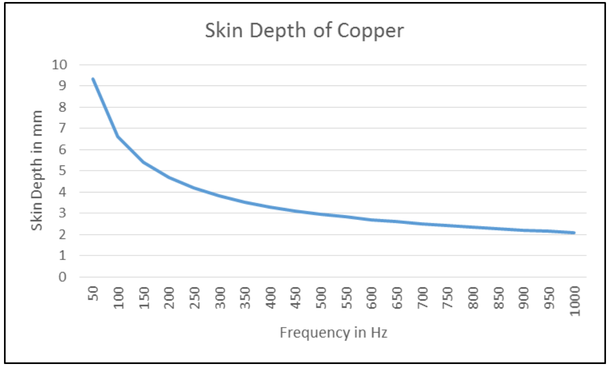
Megger.
Power on

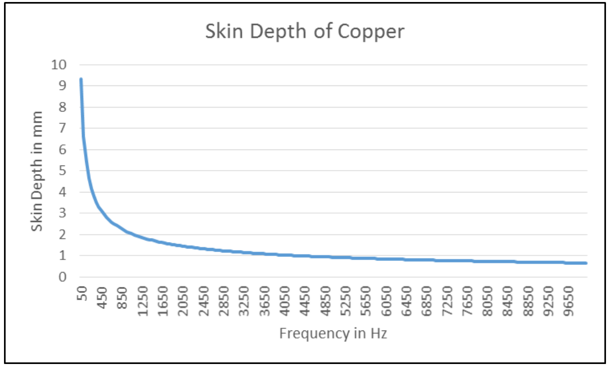
Skin Effect

- At higher harmonic frequencies the skin depth becomes smaller which, further increases the conductor resistance and winding loss.

$$\delta = \sqrt{\frac{2P}{2\pi f \mu_r \mu_0}}$$

δ = Skin depth
ρ= Resistivity of the conductor
μ_r= Relative magnetic permeability of the conductor
μ_0= The permeability of free space

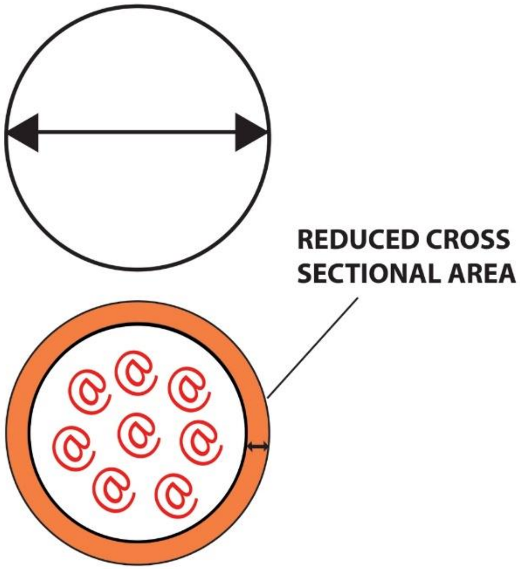




As the frequency goes up the skin depth goes down.

Harmonic Effects on Cables

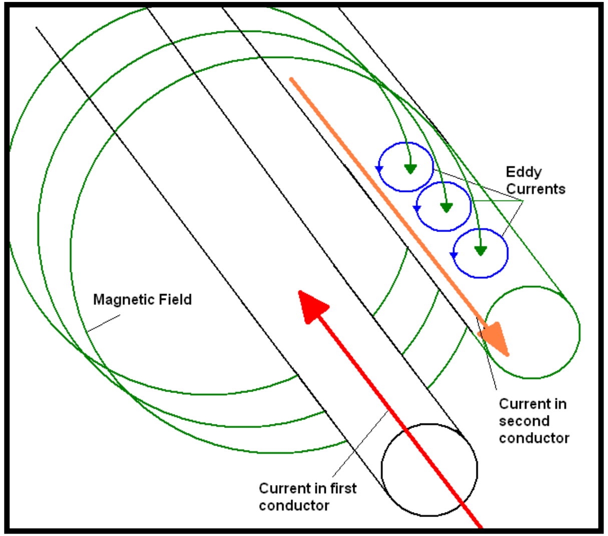
- 60Hz current in a cable produces IR^2 losses
- Current distortion introduces additional losses.
- Cable impedances increases with frequency due to skin effect caused by eddy currents.
- Reduced cross sectional area increases the impedance.
- Higher the frequency of the AC current, the greater this tendency.



Megger
Power on

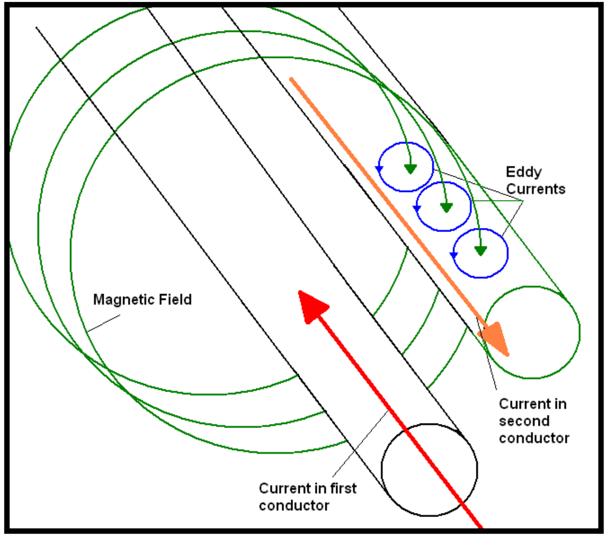
Proximity Effect

- Proximity Effect
  - The proximity effect phenomenon occurs when an AC current flows through a conductor which is in close proximity to another conductor, such as within a coil.
  - Due to induced eddy currents in the adjacent wire the current density will be constrained to smaller region on the side of the wire.
  - As the AC current flows through the first coil it generates a magnetic field which in turn induces longitudinal eddy currents in the adjacent coil.



Proximity Effect

- Proximity Effect
  - The eddy currents create a magnetic field which opposes the magnetic field that created it.
  - This increases the resistance of the conductor.
  - This causes the current density in the adjacent coil to be greater.
  - This reduces the effective cross sectional area of the conductor which in turn increases the effective resistance of the conductor.



Harmonic Effects

- Higher harmonic orders mean higher frequencies.
- The higher frequencies increase the inductive reactance, which increases the impedance.
- As the impedance increases so does the winding loss.
- As frequency increases so does the inductive reactance, which increases the impedance which increases the winding loss.

Winding Loss = I^2 x Z

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

$$X_L = 2\pi\ f\ L$$

Harmonic Effects on Transformers

- Harmonics increase the losses in the core of the transformer in much the same way as in a motor.
- Harmonics increase the copper losses in the windings due to eddy currents.
- The eddy current losses increase with the square of the current in the conductor and the square of the frequency.
- Copper losses due to harmonics have a significant effect on the operating temperature of the transformer.

Harmonic Effects on Transformers

- Using larger-size or multiple winding conductors, K factor rated transformers are capable withstanding additional winding eddy current losses.

- Also, due to the additive nature of zero sequence harmonics flowing in the neutral conductor, k rated transformers are provided with a neutral terminal that is sized at least twice as large as the phase terminals.

Megger. Power on

K-Factor

- Transformer De-rating
  - Transformers need to be de-rated based on the harmonic content to avoid overheating and failure. The measurement used to determine the transformer de-rating is called 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, not the core.
  - The basis for K-factor is *ANSI C57.110*
    - *T*he term does not appear in the standard. ANSI C57.110 is an accepted means of de-rating transformers for non-linear loads.

K-Factor

- K-factor
  - The heating effect of harmonics is proportional to the square of the current and the square of the harmonic.
  - 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.

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

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.

Harmonic Effects on Motors

- Increased use of variable frequency drives (VFDs)
- VFD produce high harmonic components.
- Eddy currents and hysteresis add to the core losses in the magnetic frame.
- Higher frequency harmonics produce additional losses in the core, which increases operating temperature.

Harmonic Effects on Motors

- Positive sequence harmonics create magnetic fields rotating in same direction as fundamental.
- Negative sequence harmonics develop magnetic fields and currents that rotate opposite to the fundamental.
- Zero sequence harmonics do not rotate & do not develop usable torque, but produce additional losses.

Harmonic Effects on Motors

- Interaction between positive and negative sequence magnetic fields produces oscillations of the shaft.
- Oscillations = shaft vibrations.
- If oscillations coincides with the natural frequency of the shaft, then severe damage to shaft may occur.

Megger. Power on

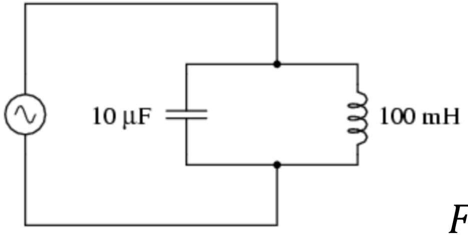
Harmonic Effects on Capacitors

- Cap banks are installed to offset the effect of low power factor.
- Large voltage or current harmonics can exceed the limits of the cap bank.
- Capacitive reactance is inversely proportional to frequency.
- High frequency harmonic currents get into capacitor banks & overloaded them.
- Blow Fuses
- Harmonic resonance can lead to substantial damage.

Megger. Power on

Harmonic Resonance

- Resonant conditions occur when inductive reactance = capacitive reactance.
- Resonance can be series or parallel.
- Parallel resonance = high currents through the caps.
- Calculate resonance frequency = 159Hz.
- $X_L = X_C = 100\Omega$
- Z approaches ∞



$$F_R = \frac{1}{2\pi\sqrt{LC}}$$

$$F_R = 159.154 Hz$$

$$X_L = 2\pi f L \qquad X_L = 100\Omega$$

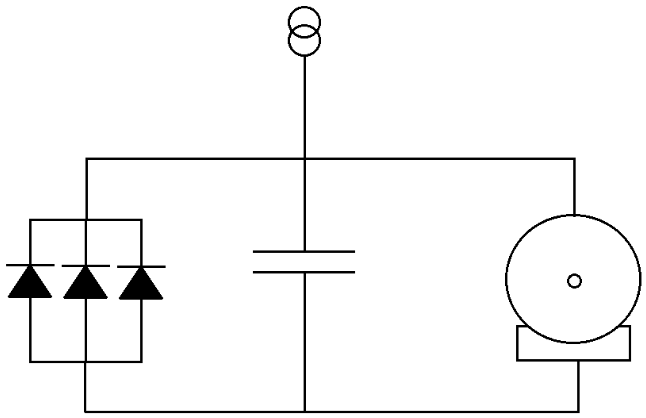
$$X_C = \frac{1}{2\pi f C} \qquad X_C = 100\Omega$$

$$Z = \frac{1}{\sqrt{\left(\frac{1}{R}\right)^2 + \left(\frac{1}{X_L} - \frac{1}{X_C}\right)^2}}$$

Megger. Power on

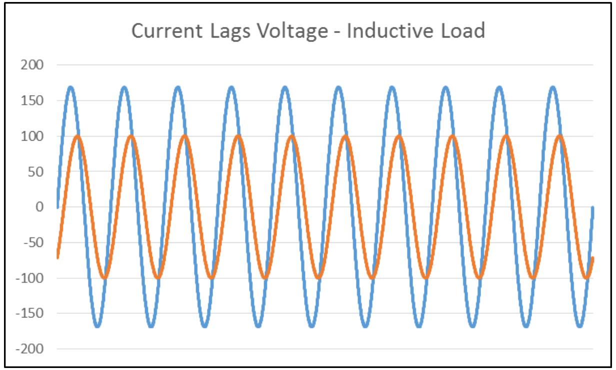
Harmonic Resonance

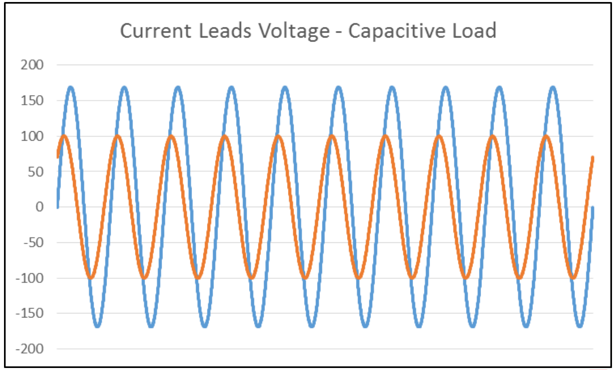
- Resonant conditions occur when inductive reactance = capacitive reactance.
- Resonance can be series or parallel.
- Parallel resonance = high currents through the caps.
- Calculate resonance frequency = 159Hz.
- $X_L = X_C = 100\Omega$
- Z approaches ∞



Phase Angles

- Inductive Loads
  - Current Lags Voltage
- Capacitive Load
  - Current Leads Voltage
- ELI the ICE man

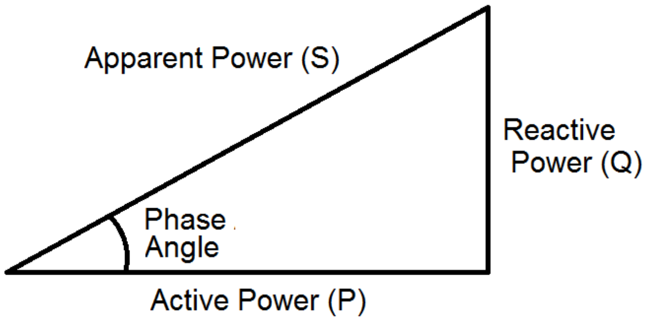




Power and Energy

- KVA = Apparent Power
  - V * I
- KW = Active Power
  - V * I * cos(phase angle)
- KVAR = Reactive power
  - V * I * sin(phase angle)
- Power triangle
  - Harmonics

$$P = \frac{1}{kT}\int_{\tau}^{\tau+kT} p\,dt$$



$$Q = \frac{1}{kT}\int_{\tau}^{\tau+kT} v\frac{di}{dt}dt$$

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

Power Factor

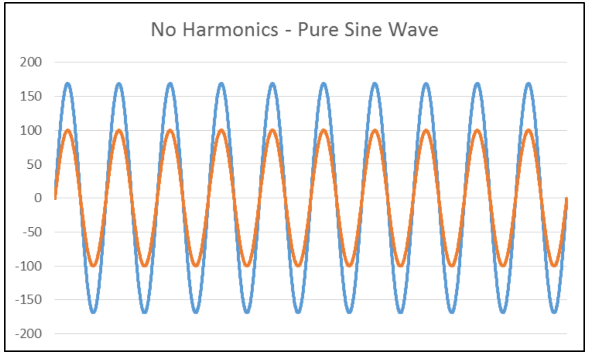
- Power Triangle
- Displacement Power Factor (DPF)
- Cosine of the angle between the voltage and current.
- Power Factor of the fundamental values
- As reactance is added the DPF drops as the phase angle increases.
  - Purely resistive load the DPF = 1.00
  - Angle θ = 8° the DPF = 0.992
  - Angle θ = 26° the DPF = 0.898

$$DPF = cos\theta \measuredangle$$

Power Factor

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

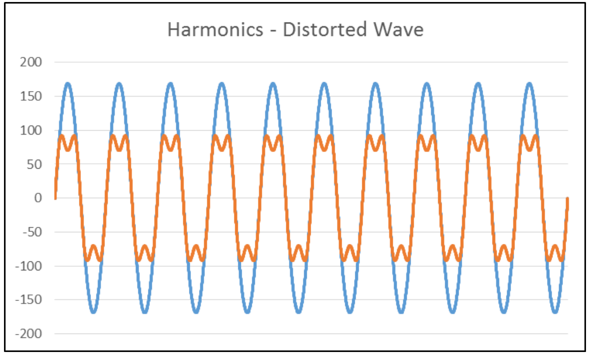
- Harmonic Distortion
- DPF = Displacement PF
  - Phase Shift
- TPF = True Power Factor
  - Distortion
- TPF = P/S = KW / KVA
  - TPF < DPF then harmonic exist.
- Distortion Power Factor
  - (dPF) = TPF / DPF



KW	8.45
KVA	8.45
KVAR	0.00
DPF	1.0000
TPF	1.0000
dPF	1.0000

$$8.45 = \sqrt{8.45^2 + 0^2}$$

✓



KW	8.45
KVA	8.82
KVAR	0.00
DPF	1.0000
TPF	0.9578
dPF	0.9578

$$8.82 \neq \sqrt{8.45^2 + 0^2}$$

X

Megger. Power on

Power

- Low power factors can cause systems to run at increased capacity.
- Can lead to low voltage
- Increasing the Power Factor can allow a system to run at lower capacity.
  - Lower cost
  - Improving reliability

i.e. System at 95% capacity

DPF = 0.829
S = 7030 KVA
P = 5828 KW
Q = 3931 KVAR

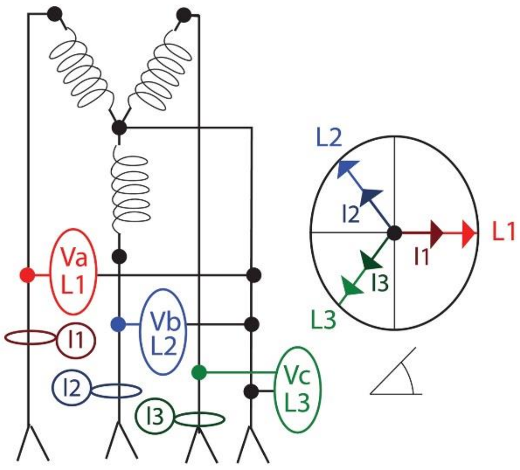
Increasing the DPF to 0.990 and the VA can be lowered while maintaining KW (Capacity = 80.5%)

DPF = 0.990
S = 5960 KVA
P = 5900 KW
Q = 0.829 KVAR

Megger
Power on

Power

- Three Phase Power
- 4 Wire Wye 3 Wattmeter
  - Line to Neutral Voltage
  - Line Current (In phase with the voltage)
  - A-N = 0 : B-N = -120° : C-N = 120°



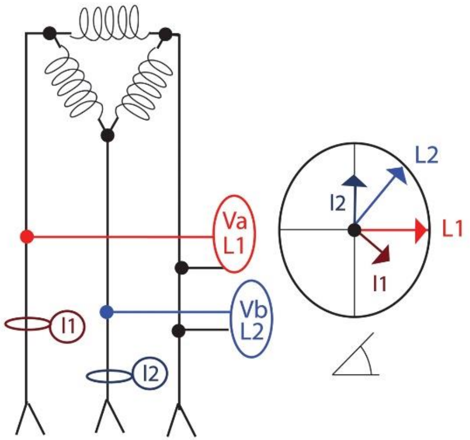
- Total Power $P_T = P_a + P_b + P_c$
- Total Reactive Power $Q_T = Q_a + Q_b + Q_c$
- Total Apparent Power $S_T = S_a + S_b + S_c$
- Total Power Factor $\text{TPF} = P_t / S_t$
  - No Total DPF (DPF only applies to phases)

Power

- Three Phase Power
- 3 Wire Delta 2 Wattmeter
  - Line to Line Voltage
  - Line Current (30° phase shift to voltage)
  - V-V = 60° : V-I = 30°
- Total Power $P_T = P_{ab} + P_{ac}$
- Total Reactive Power $Q_T = Q_{ab} + Q_{ac}$
- Total Apparent Power $S_T = S_{ab} + S_{ac}$

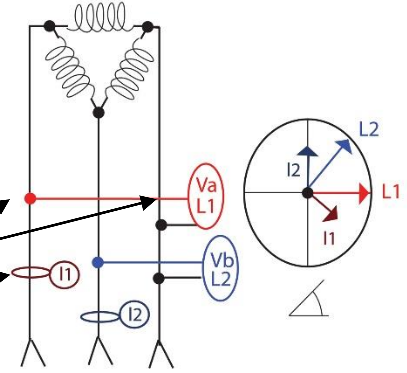
$$[S_{ab} = V_{ab} \cdot I_{ab} \cos 30°]\ [S_{ac} = V_{ac} \cdot I_{ac} \cos(90° - \theta V_{ac}°]$$

- Total Power Factor $\text{TPF} = P_t / S_t$
  - Due to mismatch of phase V and line current only totals values.



Power

- Blondel's Theorem
- The total power in a system of (N) conductors can be properly measured by using (N) wattmeters or watt-measuring elements.
  - One potential coil connected between the conductors and a common point.
  - One current coil on the conductors
- If the common point is chosen to be one of the (N) conductors, there will be zero voltage across one of the measuring element potential coils. This element will register zero power.



Therefore, the total power is correctly measured by the remaining (N – 1) elements

Arc Flash

- What to use?
  - NESC, NFPA, IEEE
- National Electric Safety Code (NESC)
  - Voluntary standard
  - Used by Utilities for Medium Voltage Systems
- NESC is not intended as a design specification or an instruction manual
- NESC is globally accepted as good engineering practices
- IEEE1584 addresses voltages up to 15KV
- An alternate method is to use the NFPA 70E Table 130.7(C)(15)(A).

Arc Flash

- Hazards must be quantified and workers protected before entering proximity of exposed energized conductors.
- NFPA 70E provides guidelines for the selection of arc flash protective equipment.
- To select proper protective gear one must have knowledge of the potential thermal energy.
- IEEE 1584 is the standard for calculating the incident energy of an arc flash.

www.voltimum.co.uk

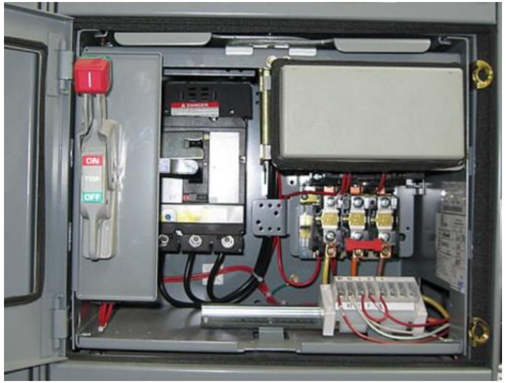
Megger. Power on

Arc Flash

- NFPA 70E states that facilities must provide:
  - A safety program with defined responsibilities
  - Calculations for the degree of arc flash hazard
  - PPE for workers
  - Training for workers
  - Tools for safe work practices
- De-energizing equipment does not free the facility from performing the arc flash analysis or providing the required PPE.

Arc Flash

- IEEE 1584 analysis begins with complete data collection from the power system.
- Characteristics of the power source
  - Power system components
    - Transformers, cables, tripping characteristics of OCPD
    - Entered into a digital computer program.
- Calculates bolted 3-phase short circuit current & arc fault current.
- Next clearing time of protective device
  - (under arc flash conditions)



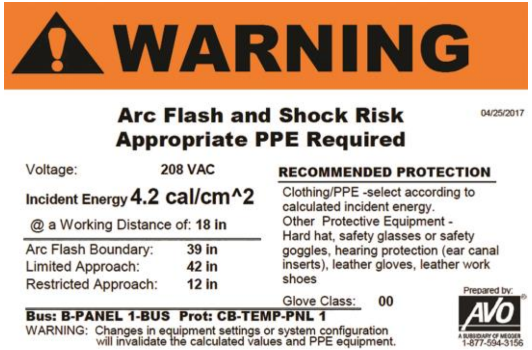
Megger
Power on

Arc Flash

- After clearing time is determined, the working distance at each bus is given and the incident energies are calculated.
- Incident energy = energy impressed on the face and body of the electrical worker.
  - In calories/cm2.
- Flash protection boundary based on incident energy of 1.2 calories/cm2 is calculated.
  - Energy level that causes second-degree burn.

Arc Flash

- Adequate PPE may be required during:
  - Load interruption
  - Visual inspection
  - Lockout / tag-out.
- Where required arc flash labels need to be provided.
  - Labels based on the arc flash calculation software output.
- The labels must have the following characteristics.
  - UL 969 standard compliance for durability and adhesion
  - Include shock protection data per NFPA 70E in addition to arc flash hazard data



Arc Flash

- PPE Category 1 & 2 Examples

(This listing is a summary only. For a complete list of see the NFPA 70E standard.)

PPE Category 1	PPE Category 2
Arc-rated clothing (minimum of 4 cal/cm2) • Arc-rated long sleeve shirt and pants or coverall • Arc-rated face shield or arc flash suit hood • Arc rated jacket, parka, rainwear or hard hat liner Protective equipment • Hard hat • Safety glasses or goggles • Hearing protection (ear canal inserts) • Heavy duty leather gloves • Leather footwear • No metal-framed eyeglasses, cell phones, or radios, jewelry, rings, keys or watches • Insulated hand tools	Arc-rated clothing (minimum of 8 cal/ cm2), including: • Arc-rated long sleeve shirt and pants or arc-rated coverall • Arc-rated face shield or arc flash suit hood and arc-rated balaclava • Arc rated jacket, parka, rainwear or hard hat liner Protective equipment • Hard hat • Safety glasses or goggles • Hearing protection (ear canal inserts) • Heavy duty leather gloves • Leather footwear • No metal-framed eyeglasses, cell phones, or radios, jewelry, rings, keys or watches • Insulated hand tools

Arc Flash

- PPE Category 3 & 4 Examples

(This listing is a summary only. For a complete list of see the NFPA 70E standard.)

PPE Category 3	PPE Category 4
Arc-rated clothing (minimum of 25 cal/ cm2), including: • Arc-rated long sleeve shirt • Arc-rated pants • Arc-rated coverall • Arc-rated arc flash suit jacket • Arc-rated arc flash suit pants • Arc-rated arc flash suit hood • Arc-rated arc flash gloves • Arc-rated jacket, parka. rainwear or hard hat liner Protective equipment • Hard hat • Safety glasses or goggles • Hearing protection (ear canal inserts) • Heavy duty leather gloves • Leather footwear • No metal-framed eyeglasses, cell phones, or radios, jewelry, rings, keys or watches • Insulated hand tools	Arc-rated clothing (minimum of 40 cal/ cm2) • Arc-rated long sleeve shirt • Arc-rated pants • Arc-rated coverall • Arc-rated arc flash suit jacket • Arc-rated arc flash suit pants • Arc-rated arc flash suit hood • Arc-rated arc flash gloves • Arc-rated jacket, parka. rainwear or hard hat liner Protective equipment • Hard hat • Safety glasses or goggles • Hearing protection (ear canal inserts) • Heavy duty leather gloves • Leather footwear • No metal-framed eyeglasses, cell phones, or radios, jewelry, rings, keys or watches • Insulated hand tools

Arc Flash

- As an alternative you can use the NFPA 70E 130.7(C)(15)(A) Table to determine the PPE requirements.

Table 130.7(C)(15)(A)(b)

Table 130.7(C)(15)(A)(b) Arc-Flash Hazard PPE Categories for Alternating Current (ac) Systems		
Equipment	**Arc Flash PPE Category**	**Arc Flash Boundary**
Panelboards or other equipment rated 240V and below Parameters: Maximum of 25 kA short-circuit current available; maximum of 0.03 sec (2 cycles) fault clearing time; working distance 455 mm (18 in.)	1	485 mm (19 in.)
Panelboards or other equipment rated >240V and up to 600V Parameters: Maximum of 25 kA short-circuit current available; maximum 0.03 sec (2 cycles) fault clearing time; working distance 455 mm (18 in.)	2	900 mm (3ft.)
600-V class motor control centers (MCCs) Parameters: Maximum of 65 kA short-circuit current available; maximum of 0.03 sec (2 cycles) fault clearing time; working distance 455 (18 in.)	2	1.5m (5 ft)
600-V class motor control centers (MCCs) Parameters: Maximum of 42 kA short-circuit current available; maximum of 0.33 sec (20 cycles) fault clearing time; working distance 455 mm (18 in.)	4	4.3 m (14 ft)

Conducting a PQ Investigation

- Plan and Prepare
  - What are the reported symptoms?
  - How often does the symptom occur?
  - Can any patterns be recognized? Can any correlations be made?
  - Has there been any changes to the equipment or the power system?
  - Receive input from all those involved.

Megger. Power on

Conducting a PQ Investigation

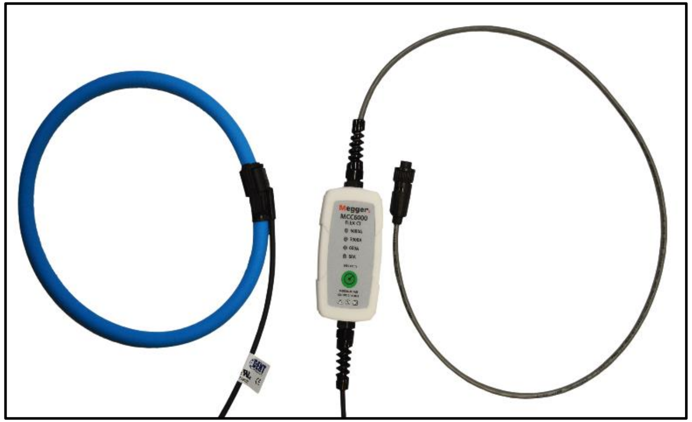
- Inspect
  - Check for safety hazards.
  - Check everything is to code.
  - Check for bad connections.
    - Thermal imaging may find bad connections.

Conducting a PQ Investigation

- Monitor
- Select the proper location
  - Connect as close to failing equipment as possible.
  - Long motor leads can amplify transients. Connect on the motor.
- Take the environment into account.
  - Verify your instrument is rated for the temperature, moisture and humidity levels.

Conducting a PQ Investigation

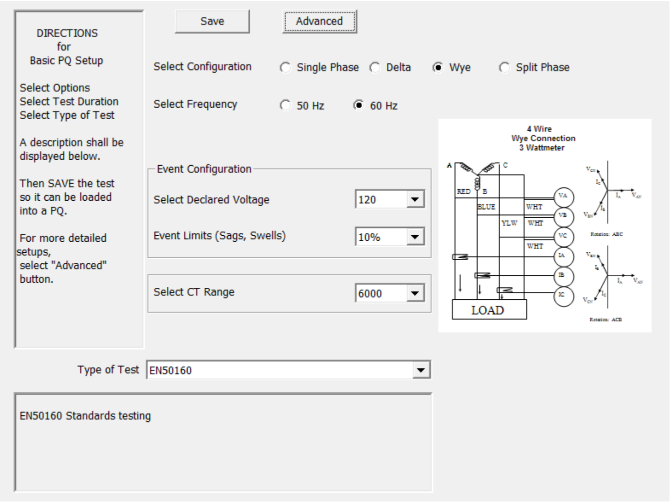
- Monitor
- Select the proper Current Transducer.
  - Determine the proper range.
    - Too low and it may saturate
    - Too high may give poor resolution.
- Flexible or Split core?
  - Does it fit in location?
  - Does it require batteries?
- Does the area have high EMF?
  - If yes, then use split core CT.
- Are you recording DC?
  - If yes, then you must use hall effect CT.



Megger. Power on

Conducting a PQ Investigation

- Monitor
- Verify the proper power configuration is selected.
- Verify the proper event triggers.
  - 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.
- Verify CT Range
- Consult application notes
- Use software wizards.



Megger
Power on

Conducting a PQ Investigation

- Monitor
- Connecting the PQ Analyzer
  - **Use PPE**
  - Verify voltage leads are connected per power configuration diagrams
  - Verify CT ranges are set correctly
  - Verify CT are in the proper direction
- Verify unit power setting is correct.
  - Phase A or AUX power?
- Ground the unit
- Lock up the unit

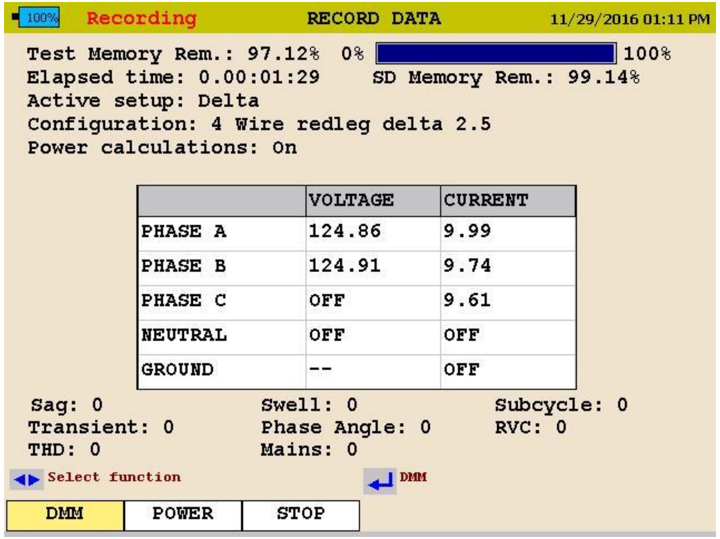
Megger.
Power on

Conducting a PQ Investigation

- Monitor
- Review the data before starting the recording.
  - Verify the RMS Voltage and Current values are reading properly.
  - Verify the KW is positive.
  - Verify phase angles are correct per the connection diagrams.

Conducting a PQ Investigation

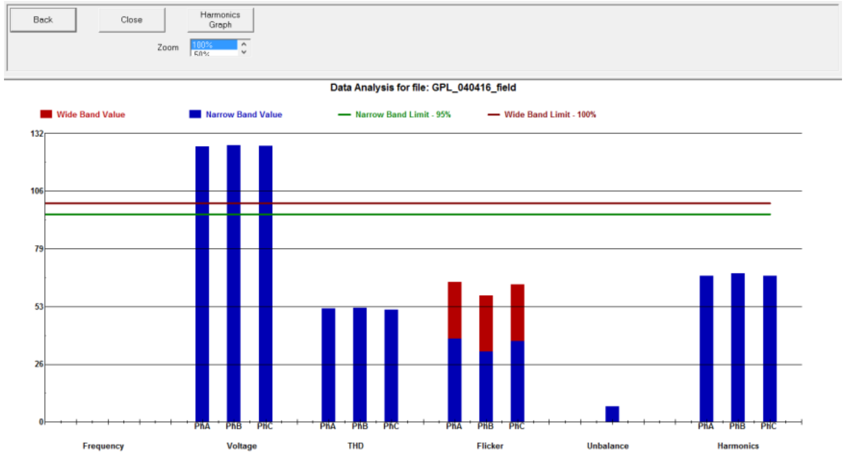
- Record Data
- Verify the unit is recording.
- Record for at least 1 complete problem cycle.
  - If the problem happen every couple of days then record for at least 2 days.
  - If the problem happen only once a week then record for at least a full week.



Megger. Power on

Conducting a PQ Investigation

- 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.
  - Dips (Sags) / Swells / Transients / Unbalance / Harmonics / RVC..etc.
- Data Analysis Software can be helpful.
- Determine appropriate solution.



Megger
Power on

Questions?

Power on

At Megger, we understand that keeping the power on is essential for the success of your business. That is why we are dedicated to creating, designing and manufacturing safe, reliable, easy-to-use portable test equipment backed by world-leading support and expertise.

We can assist your acceptance, commissioning and maintenance testing for predictive, diagnostic or routine purposes. By working closely with electrical utilities, standards bodies and technical institutions, we contribute to the dependability and advancement of the electrical supply industry.

Megger®

Power on