Power Quality

AGENDA

- Introduction to Power Quality
- Parameters of Power Quality and PQ Events
- Standards Governing Power Quality
- Power Quality Measurement and Evaluation
- Waveform Analysis
- Solutions to Improve Power Quality
- Software for Utility Power Quality Issues

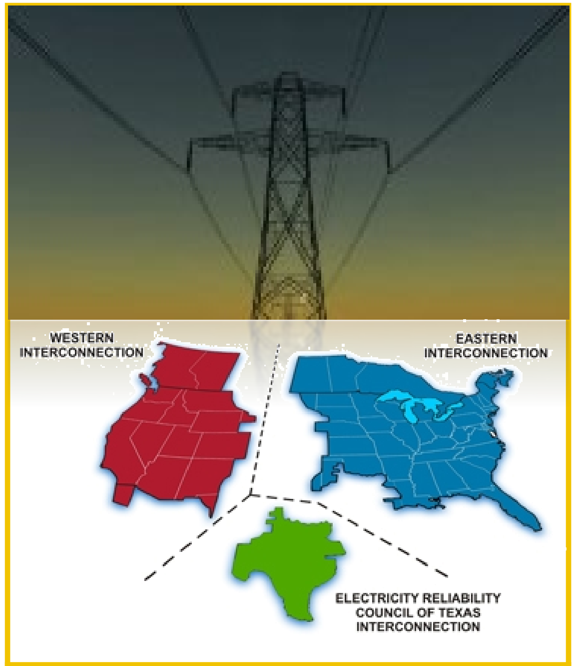
GENERAL INFORMATION

- The main elements of an electrical power system are generators, transformers, TX lines, distribution lines, loads, and protection and control equipment.
- These elements are interconnected, so that the generated electricity can be conveyed to the customer to satisfy their demand requirements.
- Delivered electricity must be supplied at good quality and at competitive pricing.

- The quality of the power supply is measured in terms of:
  - Constant voltage magnitude.
  - Constant frequency.
  - Constant power factor.
  - No harmonics superimposed.
  - Reliable power supply without any interruptions.
  - Rigid power supply to withstand faults and recover quickly.

POWER GRID

create



transport

consume

7,000 POWER PLANTS

55,000 SUBSTATIONS

450,000 MILES OF TRANSMISSION LINES

5.5 MILLION MILES OF DISTRIBUTION LINES

There are five major reasons for the increased concern about Power Quality:

- Newer-generation load equipment, with microprocessor-based controls and power electronic devices, is more sensitive to power quality variations than equipment used in the past.
- Increasing emphasis on overall power system efficiency has resulted in continued growth in the application of devices such as high-efficiency, adjustable-speed motor drives and shunt capacitors for power factor correction, to reduce losses. The result of this has been an increase in harmonic levels of power systems; many people have concerns about the future impact on system capabilities.
- End users have an increased awareness of power quality issues. Utility customers are becoming better informed about issues such as interruptions, sags, and switching transients, and are challenging the utilities to improve the quality of power delivered.
- Many things are now interconnected in a network. Integrated processes mean that the failure of any one component has much more important consequences.
- Introduction of DERs and DGs, which have an impact on power quality.

POWER QUALITY (PQ)

Power Quality is a major concern to utility customers and the utility.

For the energy consumer, the **economic impact** of power disturbances can range from hundreds of dollars in equipment repair to millions of dollars in production losses and downtime.

For utilities, disturbances lead to **customer dissatisfaction** and **losses in load and revenue**.

This session clarifies the unique relationship between electrical utilities and their customers in relation to power quality. It introduces power quality terminology, tools to determine compatibility, and the PQ data that is available for analysis.

DEFINING POWER QUALITY

The definition can change based on the reference:

The utility may define power quality as reliability and show statistics demonstrating that its system is 99.98 percent reliable.

A manufacturer will define PQ as characteristics of the power supply that enable their equipment to work properly. Good PQ will mean no interruption either to the operation of the equipment or to the quality of the output.

PQ is a consumer driven issue because the consumer determines and faces the issues.

A power quality problem is “Any power problem manifested in voltage, current, or frequency deviations that results in failure or mis-operation of customer equipment.” (ref 1)

This is a generalized book definition.

POWER QUALITY PARAMETERS AND EVENTS

Power Quality Events

These are the power quality events found in the Distribution System

- Electrical Transients
- Notch and Noise
- Voltage Sag and Swell
- Voltage Interruption
- Voltage fluctuation
- Harmonics
- Voltage unbalance

Power System Unacceptable Behaviors

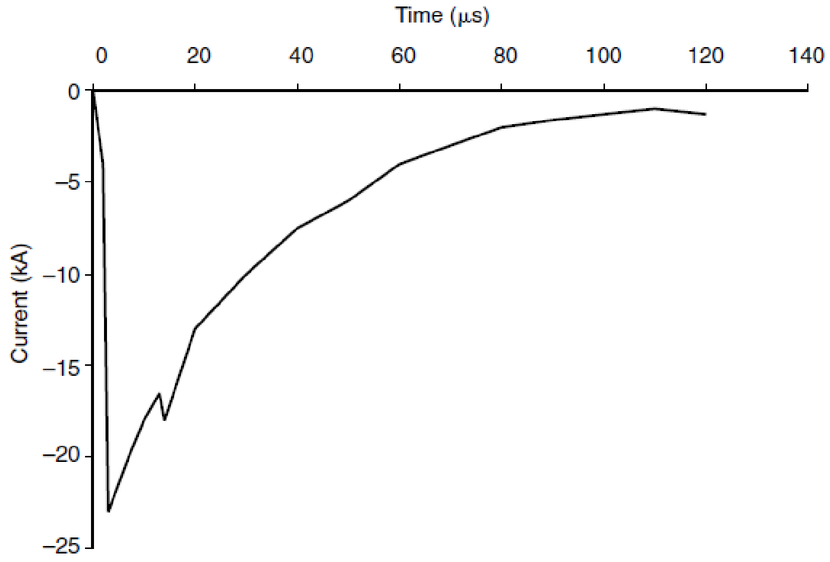
The most classic issue affecting the power supply system, which compromises the PQ, is Transients.

A transient is a sudden change of variable from one steady state to another, which is caused by some external influence.

There are two types of transients:

- Impulsive
- Oscillatory

An impulsive transient is a sudden, non–power frequency change in the steady-state condition of voltage, current, or both. It is non-directional. This kind of transient can be due to a lightning strike.

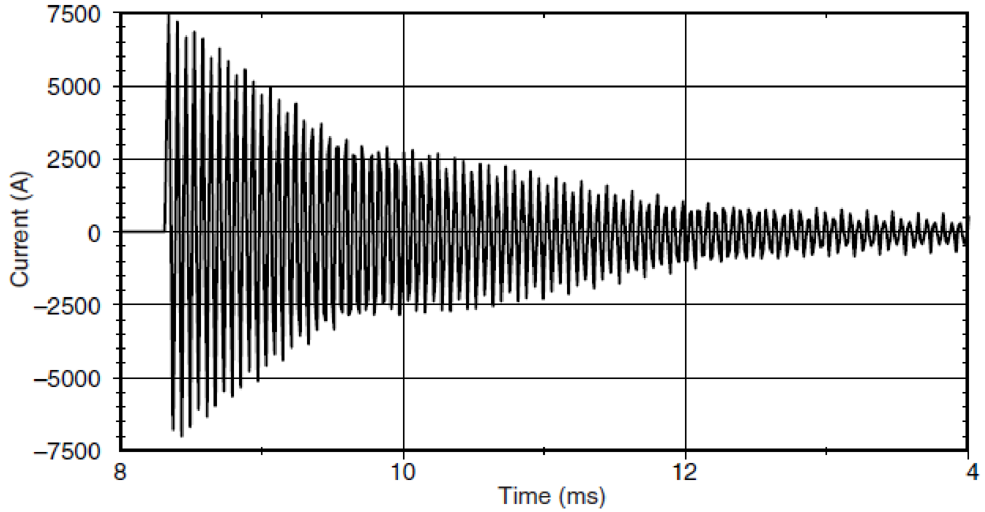


Power System Unacceptable Behaviors

Oscillatory Transient:

An oscillatory transient is a sudden, non–power frequency change in the steady-state condition of voltage, current, or both, that includes both positive and negative polarity values. The polarity can change rapidly as a ringer type. These can be low, medium and high frequency transients based on the frequency.

Ex.: Capacitor switching transients.

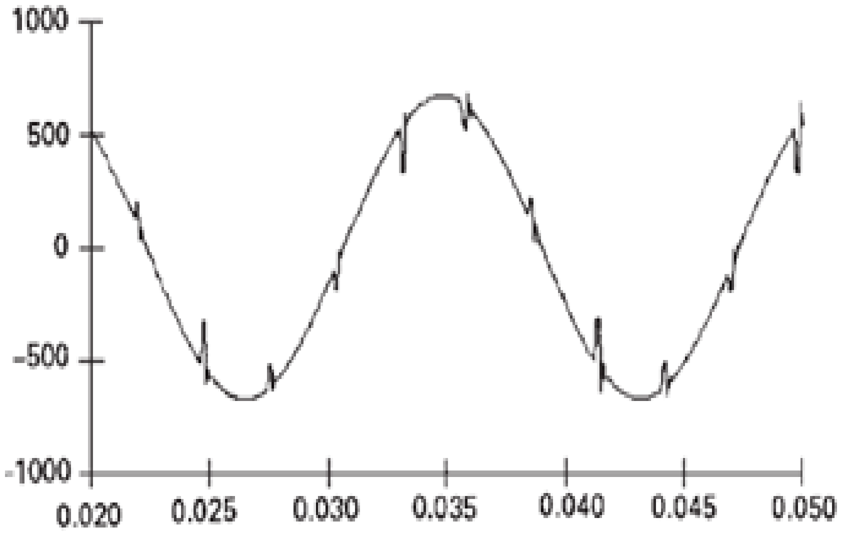


Power System Unacceptable Behaviors

Notch and Noise are two PQ disturbances.

Notching is a periodic disturbance in the voltage created by the operation of power electronic devices. Typically, notches can be a continuous, periodically occurring phenomenon, which can be characterized by the harmonic spectrum of the affected voltage signal.

Noise is a high frequency unwanted signal superimposed on the electrical signal, generated by different sources. This can cause interference, damage to components, and mis-operation.



Notching in voltage signal iproduced by a 3 phase converter

Power System Unacceptable Behaviors

Voltage Sag

This is a decrease of the normal voltage levels, of between 10% and 30% of the nominal rms voltage at the power frequency, for durations of 0.5 cycles to 1 minute. (ref 5)

Causes:

Faults on the transmission or distribution network, or the customer installation.

Connecting heavy loads to the system and starting large motors.

Consequences:

- Tripping of relays and contactors, causing the computer and electric devices to shutdown and restart.
- Tripping of motors and drives, etc.

Power System Unacceptable Behaviors

Very Short Interruptions

This is a total interruption of electrical supply for a duration of a few milliseconds to one or two seconds. (ref 5)

Causes:

Mainly due to the opening and automatic reclosing of protective devices to decommission a faulty section of the network. Ex.: lightning, flashover etc.

Consequences:

- Tripping of relays, contactors, and switchgear, causing the motors and drives to shutdown, etc.
- Causes transfer scheme to operate.

Power System Unacceptable Behaviors

Long Interruptions

This is a total interruption of electrical supply for a duration greater than one or two seconds.

Causes:

Equipment failures in the power system network, nature and storm destruction, human error, and poor relay coordination, etc.

Consequences:

Tripping of relays, contactors, and switchgear, causing the systems and equipment to shut down.

Power System Unacceptable Behaviors

Voltage Spike

This is a very fast variation of the voltage value for durations from several ms to a few ms. These spikes may reach thousands of volts. (ref 5)

Causes:

Lighting, switching of lines or power factor correction capacitors, disconnection of heavy loads.

Consequences:

Destruction of components, equipment, interference, mis-operations, device failures, etc.

Power System Unacceptable Behaviors

Voltage Swell

This is a momentary increase of the voltage at the power frequency, outside the normal tolerances, with a duration of more than one cycle and typically less than a few seconds. (ref 5)

Causes:

Switching on of capacitor banks, heavy load drop, poor regulators, etc.

Consequences:

Data loss, flickering of lights, damage to sensitive equipment if the voltage level is beyond its tolerance level.

Power System Unacceptable Behaviors

Harmonic Distortion

This is when the voltage and current waveforms are not a sinusoidal shape. This can be characterized as the sum of different sine-waves with different magnitudes and phases, having frequency integers in multiples of the power system frequency. (ref 5)

Causes:

- Electrical machines working above the knee point of the magnetization curve can cause distorted current and voltage waveforms.
- All nonlinear loads and power electronic drives can cause this.

Consequences:

Overheating of cables and electrical machines; metering errors; interference with communication system frequency, causing resonance effects; etc.

Waveform Distortion

- Waveform distortion is defined as a steady-state deviation from an ideal sine wave of power frequency.
- The distortion could be caused by super imposing of harmonics, interharmonics, DC offsets, notching, and noise.
- Harmonics are sinusoidal signals which have the frequency of multiples of the fundamental frequency components.
- Interharmonics are sinusoidal signals which have the frequency higher or lower than the fundamental but not multiples of fundamental.
- Harmonics are defined using THD (harmonics % in respect to fundamental) and TDD (harmonics % in respect to rated value):

$$I_{THD} = \frac{\sqrt{\sum_{h=2}^{\infty} I_h^2}}{I_1}$$

$$TDD = \sqrt{\sum_{h=2}^{\infty}\left[\frac{I_h^2}{I_L^2}\right]}$$

Power System Unacceptable Behaviors

Voltage Fluctuation

This is the oscillation of voltage value and amplitude in a repeated, periodic routine. This can be produced by devices or machinery connected to the same power system. (ref 5)

Causes:

Arc furnaces, frequent starting and stopping of motors or cyclic loads, etc.

Consequences:

Tripping of relays and contactors, flickering of lighting loads, mis-operations, etc.

Power System Unacceptable Behaviors

Voltage Unbalance

This is when, in a three-phase system, the magnitude of voltages, currents and phase angles between phasors are not balanced. This creates negative sequence components in the three-phase system. (ref 5)

Causes:

Operation of arc furnaces, uneven distribution of loads, single phase faults.

Consequences:

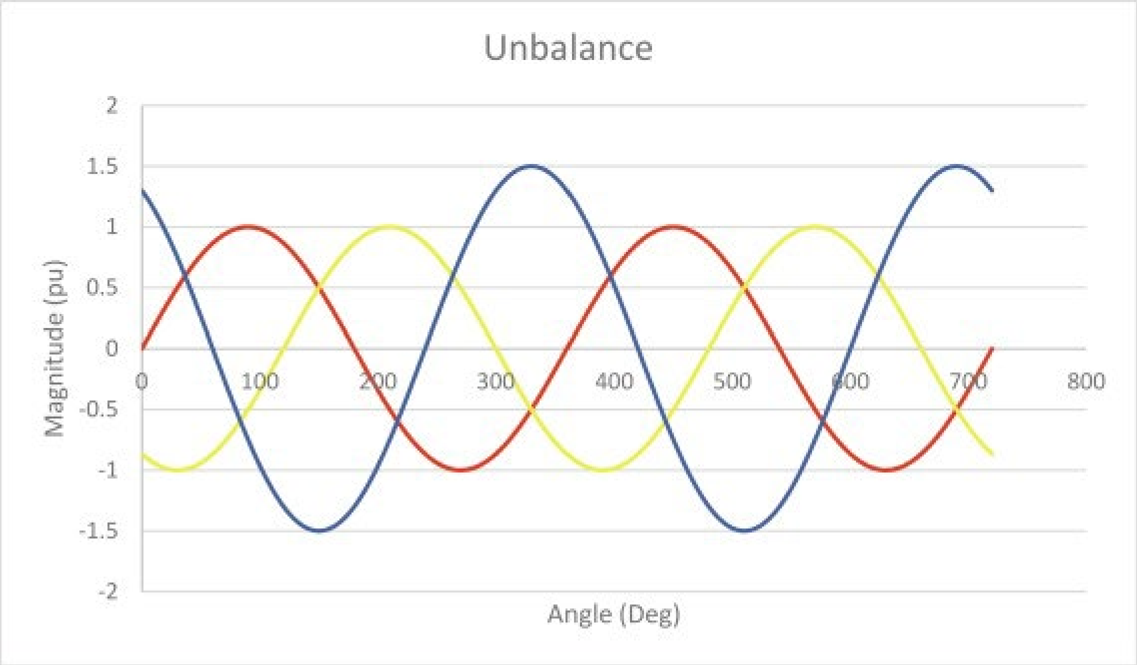
An unbalance load will create negative sequence current, which is harmful to motors. Presence of a negative sequence current can cause motor heating and insulation failures.

Voltage Unbalance

In a balanced condition in a three phase system, the magnitude of all three phases are the same and they are 120 degrees apart to each other.

However, improper balancing of the phases and the influence of nonlinear loads can cause phase imbalance, characterized as follows:

1. Maximum deviation from the average of the three-phase voltages, divided by the average of the three-phase voltages.
2. Ratio between the negative sequence component of the voltage over the positive sequence component (industrial applications) or zero sequence over positive sequence (commercial applications).



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CHALLENGES OF POOR POWER QUALITY

Power Quality Issues Can Result in Downtime, Equipment Failures, and Increased Energy Costs

10% of PQ Issues are Voltage Swells

POTENTIAL IMPACTS:
Hardware failures and plant-wide shutdowns

46% of PQ Issues are Voltage Sags

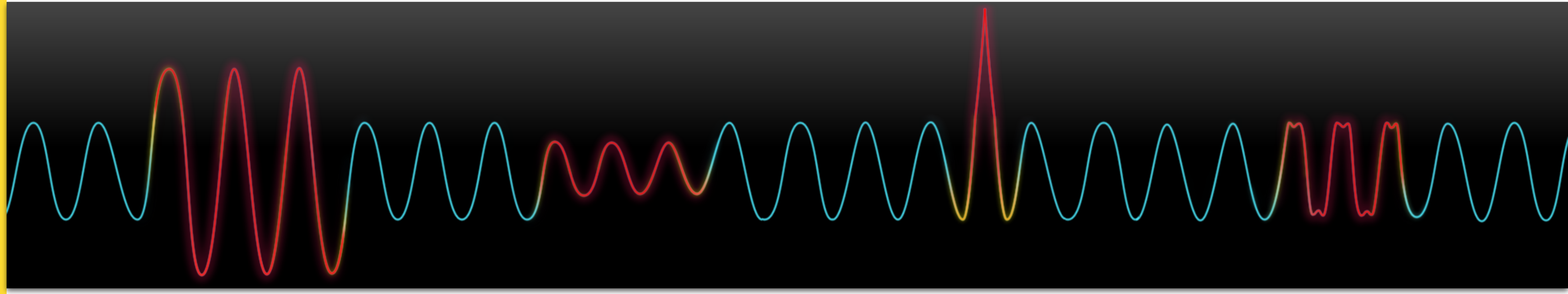
POTENTIAL IMPACTS:
Process disruptions, product damage & wastage

10% of PQ Issues are Surges and Transients

POTENTIAL IMPACTS:
Equipment degradation, damage & downtime

5% of PQ Issues are Harmonics

POTENTIAL IMPACTS:
Nuisance tripping and equipment malfunctions



Mitigate risk by determining the most needed infrastructure upgrades.

OEB report on power quality

- This document guide to addressing the Electricity Power quality issue.
- Applicable to the distribution system up to 50kV.
- Describes the overview of the PQ issues.
  - Identification,
  - Investigation
  - Mitigation :By Collaborating with Customer and distributor to manage PQs.
- Address the PQ issues according to Distribution standard code with facilitation of CSA, IEEE, IEC , industrial acceptable practice etc.

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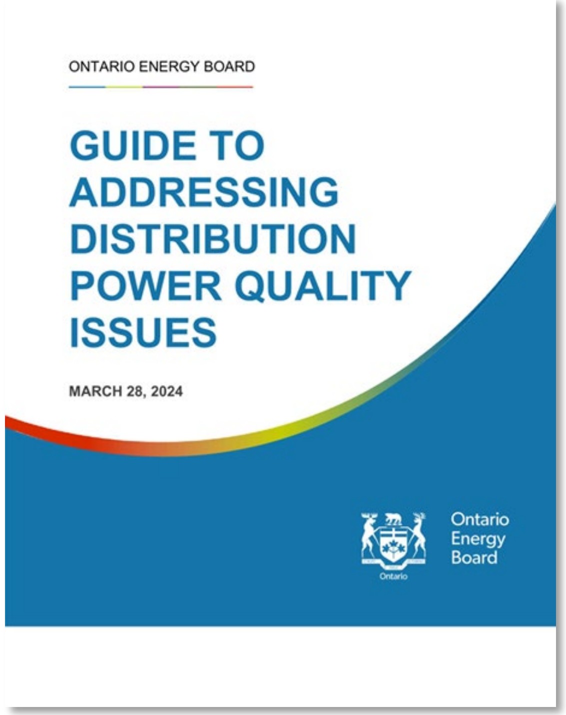

ONTARIO ENERGY BOARD

GUIDE TO ADDRESSING DISTRIBUTION POWER QUALITY ISSUES

MARCH 28, 2024

Ontario Energy Board

https://grandbridgeenergy.com/wp-content/uploads/2024/07/Distribution-Power-Quality-Guidance_20240328.pdf

Power quality resolution

The Resolution process can be categorized based on origin of the issue:

From Customer site:

- PQ only affect the customer
- Section 4.1.4 of DSC details used for resolutions
- Distributor can help for resolution and charge

From Distributor site:

- Voltage fluctuation apply section 4.1.2 of DSC and comply with CAN-C235.
- Harmonic: Section 4.1.5 of DSC. If it is required major shutdown and correction, normal industrial standards can be applied.
- If not addressable need to provide the details explanation.

Other Neighbor Customer:

- Section 4.1.6&7. Distributor advice the customer address the issue.
- Further action if customer fails as per DSC.

This report carry Appendix with the following information which can be used as a guidance:

- **Appendix 1: Power Quality Disturbance Types**
- **Appendix 2: Power quality Standards**
- **Appendix 3: List of Power Quality Monitoring and Analysis Tools**

POWER QUALITY STANDARDS

Power Quality Standards

The main institutions producing PQ standards:

- IEEE Standards Coordinating Committee
- IEC
- CIGRE, etc.

Some of the main power quality standards:

- IEEE 519
- IEC 62586-2 & and 1
- IEC 61000-4-30
- EN 50160
- In addition, CBEMA and ITIC curves

IEEE 519 Provides Guidance

- Guidance is required at the time of design of nonlinear loads. The standard provides limits to apply at different levels in the power system. Utilities have to meet regulations.
- The limits in this recommended practice are intended for application at a point of common coupling (PCC) between the system owner – Utilities or operator and a user.
- Mostly, for service to industrial users via a dedicated service transformer, the PCC is at the HV side of the transformer.
- Limits in this recommended practice represent a shared responsibility for harmonic control between system owners or operators and users.
- All users limit their harmonic current emissions to reasonable values determined in an equitable manner based on the essential ownership stake each user has in the supply system.
- System owner or operator takes action to decrease voltage distortion levels by modifying the supply system impedance characteristics, as necessary.

Key Terminology Used

Harmonics: Any frequency components which are integer multiples of fundamental frequency are called harmonics. Hamonic signals are superimposed on the fundamental frequency component.

Interharmonics: The definition is similar to harmonics, but the frequency of the signals is not an integer multiple of the fundamental frequency.

$$THD = \sqrt{\sum_{h=2}^{40} (u_h)^2}$$

Point of Common Coupling (PCC): Point on a public power supply system, electrically nearest to a particular load, at which other loads are connected.

THD: By knowing the magnitudes of the harmonics, THD can be calculated using the equation shown on the right.

Maximum demand load current: This current value is established at the point of common coupling and should be taken as the sum of the currents corresponding to the maximum demand during each f the twelve previous months divided by 12.

How to measure harmonics?

Any instruments designed to measure harmonics and that comply with the standards IEC 61000-4-7 and IEC 61000-4-30 can be used to measure the harmonic levels.

Measurement window width:

The width of the measurement window used by digital instruments employing Discrete Fourier Transform techniques should be 12 cycles (approximately 200 ms) for 60 Hz power systems (10 cycles for 50 Hz power systems).

The value displayed for a harmonic as a spectrum of the magnitude is computed using the three rms values of the signals with the frequency of 5 Hz before and after in addition to the rms value of the frequency of the harmonic.

Ex: 120 Hz components will be computed using the 115 Hz, 125 Hz and 120 Hz components and the combined value will be displayed at 120 Hz.

Very short time harmonic measurements:

Very short time harmonic values are assessed over a 3-second interval based on an aggregation of 15 consecutive 12 (10) cycle windows for 60 (50) Hz power systems.

$$F_{n,vs} = \sqrt[2]{\frac{1}{15}\sum_{i=1}^{15} F_{n,i}^{2}}$$

F = Parameter (V or I)

n = Harmonic Order

Short time harmonic measurements:

Short time harmonic values are assessed over a 10-minute interval based on an aggregation of 200 consecutive very short time values for a specific frequency component.

$$F_{n,sh} = \sqrt[2]{\frac{1}{200}\sum_{i=1}^{200} F_{(n,vs),i}^{2}}$$

Fvs = Parameter (V or I)

n = Harmonic Order

Statistical Evaluation:

Very short and short time harmonic values should be accumulated over time periods of one day and one week, respectively. Computation is done as per the standards.

Recommended Harmonics Voltage Limits

The recommended level will be applied at the PCC, not at the individual equipment level:

Bus voltage V at PCC	Individual harmonic (%)	Total harmonic distortion THD (%)
$V \leq 1.0$ kV	5.0	8.0
1 kV $< V \leq$ 69 kV	3.0	5.0
69 kV $< V \leq$ 161 kV	1.5	2.5
161 kV $< V$	1.0	1.5[a]

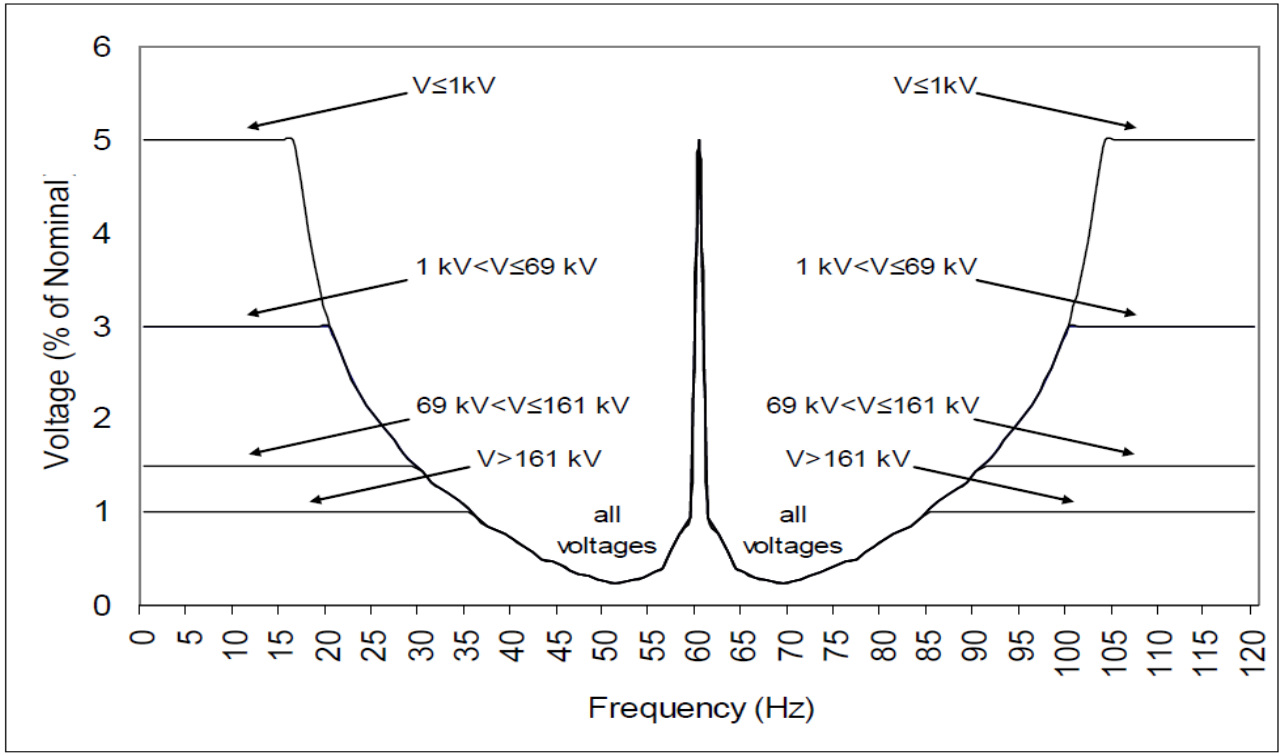
At the PCC, system owners or operators should limit line-to-neutral voltage harmonics as follows:

1. Daily 99th percentile very short time (3 s) values should be less than 1.5 times the values shown in the table.
2. Weekly 95th percentile short time (10 min) values should be less than the values given in the table.

NOTE: HV systems can have up to 2% THD, depending on the HVDC system.

Recommended Voltage Interharmonics Limits

The following table gives the limits as per IEEE Std 1453 and IEC 61000-4-15. The chart below shows the limit for the weekly 95th percentile short time harmonic voltages:



Interharmonic voltage limits are based on flicker for frequencies up to 120 Hz for 60 Hz systems.

Recommendation for Current Distortion Limits:

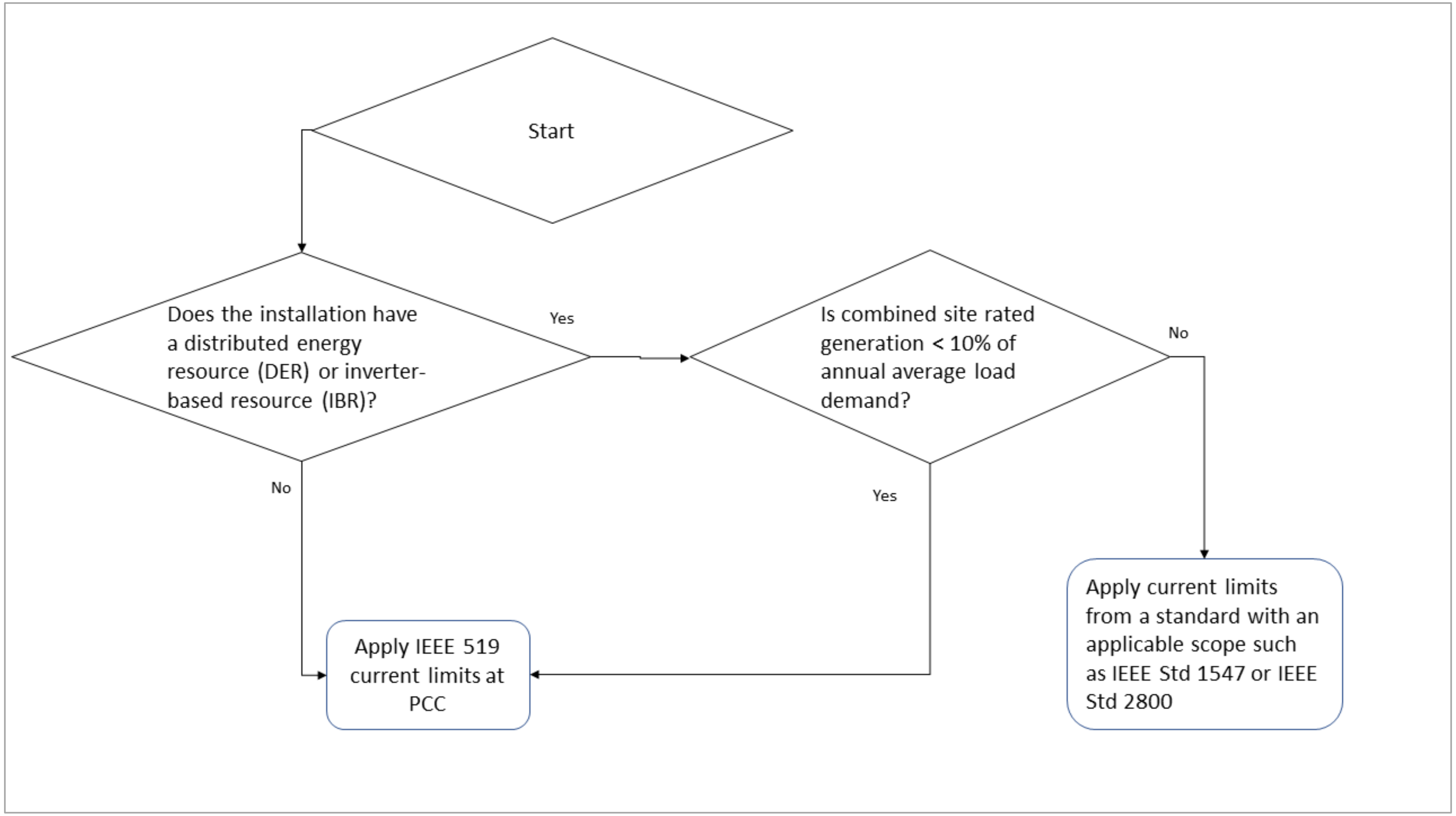
The tables on the next few slides provide the different criteria based on the rated nominal value.

The limits are applied at the PCC and the user should limit the harmonic currents as per the following three items:

1. Daily 99th percentile very short time (3 s) harmonic currents should be less than 2.0 times the values given in the table.
2. Weekly 99th percentile short time (10 min) harmonic currents should be less than 1.5 times the values given in the table.
3. Weekly 95th percentile short time (10 min) harmonic currents should be less than the values given in the table.

Recommendation for Current Distortion Limits:

This is the added portion in the 2022 standards: ref IEEE 519-2022.



Limits for the 120 V to 69 kV System

- Even harmonics limited to 25% of the odd harmonic above: ex: 2 Hz use the 25% of the 3 Hz value.
- Harmonics caused by DC offset are not considered.
- All the power generation equipment is limited to the values shown in the 1 row regardless of actual I_{sc}/I_L

I_{sc} = Maximum short-circuit current at PCC
I_L = Maximum demand current of fundamental component at PCC

Maximum harmonic current distortion in percent of I_L						
Individual harmonic order (odd harmonics)[a, b]						
I_{SC}/I_L	$3 \le h < 11$	$11 \le h < 17$	$17 \le h < 23$	$23 \le h < 35$	$35 \le h \le 50$	TDD
< 20[c]	4.0	2.0	1.5	0.6	0.3	5.0
$20 < 50$	7.0	3.5	2.5	1.0	0.5	8.0
$50 < 100$	10.0	4.5	4.0	1.5	0.7	12.0
$100 < 1000$	12.0	5.5	5.0	2.0	1.0	15.0
> 1000	15.0	7.0	6.0	2.5	1.4	20.0

EN 50160 (by CENELEC)

- This is a European standard which talks about the voltage characteristics of electricity supplied by public electricity networks.
- This standard defines, describes and specifies the main characteristics of the voltage at PCC in public Low, Medium, and High voltage AC networks under normal operating conditions.
- This standard describes the limits or values within which the voltage value characteristics can be expected to remain in public networks.
- This standard defines the characteristics of the voltage supply concerning or based on, frequency, magnitude, waveform, and voltage balance. These characteristics can change based on load, supply source, faults, weather etc.
- The limiting specification for power quality is formed considering the above four parameters.

Key Terminology Used in EN 50160 (ref 3)

There are two terms used to measure Flicker:

- Short Term Severity: Short term severity (*Pst*) is a statistical process, measured over a period of ten minutes.
- Long Term Severity: Long term severity (*Plt*) is calculated from a sequence of twelve *Pst* values over a period of two hours, as shown in the equation below.

$$P_{lt} = \sqrt[3]{\sum_{i=1}^{12} \frac{P_{sti}^{\;3}}{12}}$$

Harmonic Voltage: This is the sinusoidal voltage signal with the frequency of integer multiples of the fundamental superimposed on the fundamental voltage signal. There can be multiple harmonic signals superimposed on the signal. Knowing the magnitude of them, the THD value of the signal can be calculated using the equation shown below.

$$THD = \sqrt{\sum_{h=2}^{40} (u_h)^2}$$

Interharmonic signals are the same as harmonics; the difference is that their frequencies are not integer multiples of the fundamental.

Low Voltage Supply Characteristics (ref 3)

This clause describes the requirements for the supplied electricity.

Power frequency: Mean value of the frequency measured for a period of 10 s.

For systems with synchronous connection to an interconnected system:

- 60 Hz ± 1% (i.e., 59.4 Hz... 60.6 Hz) during 99.5% of a year.
- 60 Hz + 4% / - 6 % (i.e., 56.4 Hz... 62.4 Hz) during 100% of the time.

For systems with no synchronous connection to an interconnected system (e.g., supply systems on certain islands):

- 60 Hz ± 2% during 95% of a week.
- 60 Hz ± 15% during 100% of the time.

Low Voltage Supply Characteristics (ref 3)

Supply Voltage:

- Under normal conditions, supply voltage should be ±10% of the nominal value.
- If this is not an interconnected supply, the voltage variations should not exceed + 10% / - 15% of *Un*.
- Equipment manufactured should be able to work with 10% tolerance.
- Flicker severity: Under normal operating conditions, during each period of one week the long-term flicker severity *Plt* caused by voltage fluctuations should be less than or equal to 1 for 95% of the time.

Voltage unbalance: During normal operation, during each period of one week, 95% of the 10 min mean rms value of the negative sequence component of the supply voltage should be within the range of 0% to 2% of the positive sequence component.

Low Voltage Supply Characteristics (ref 3)

- Harmonic Voltage: Under normal operating conditions, for each period of one week, 95% of the 10 min mean rms values of each individual harmonic voltage shall be less than or equal to the values shown in the table below:

Odd harmonics				Even harmonics	
Not multiples of 3		Multiples of 3			
Order h	Relative amplitude u_h	Order h	Relative amplitude u_h	Order h	Relative amplitude u_h
5	6,0 %	3	5,0 %	2	2,0 %
7	5,0 %	9	1,5 %	4	1,0 %
11	3,5 %	15	0,5 %	6 ... 24	0,5 %
13	3,0 %	21	0,5 %		
17	2,0 %				
19	1,5 %				
23	1,5 %				
25	1,5 %				

NOTE No values are given for harmonics of order higher than 25, as they are usually small, but largely unpredictable due to resonance effects.

- THD: The THD of the supply voltage (including all harmonics up to the 40^{th} order) shall be less than or equal to 8%.

- In addition, the limits on voltage dip and swell are defined based on the voltage level vs. the amount of time the event lasted. These limits are based on the statistical data from the IEC 61000-4-30 standard.

Medium Voltage Supply Characteristics (ref 3)

This clause describes the requirements for the supplied electricity.

Power frequency: Mean value of the frequency measured for a period over 10 s shall be within the specified range.

For systems with synchronous connection to an interconnected system:

- 60 Hz ± 1% (i.e., 59.4 Hz... 60.6 Hz) during 99.5% of a year.
- 60 Hz + 4% / - 6 % (i.e., 56.4 Hz... 62.4 Hz) during 100% of the time.

For systems with no synchronous connection to an interconnected system (e.g., supply systems on certain islands):

- 60 Hz ± 2% during 95% of a week.
- 60 Hz ± 15% during 100% of the time.

Medium Voltage Supply Characteristics (ref 3)

Supply Voltage:

- Under normal conditions, supply voltage should be ±10% of the nominal value.
- At least 99% of the 10 min mean rms values of the supply voltage shall be below the upper limits of +10%.
- At least 99% of the 10 min mean rms values of the supply voltage shall be above the lower limits of -10%.
- If it is not an interconnected supply, the voltage variations should not exceed + 10% / - 15% of *Un*.
- Equipment manufactured should be able to work with 10% tolerance.
- Flicker severity: Under normal operating conditions, during each period of one week, the long-term flicker severity *Plt* caused by voltage fluctuations should be less than or equal to 1 for 95% of the time. 1 was selected assuming that the transfer coefficient between LV and MV is equal to 1. However, in reality it is less than 1.
- Voltage unbalance: During normal operation, during each period of one week, 95% of the 10 min mean rms value of the negative sequence component of the supply voltage should be within the range of 0% to 2% of the positive sequence component.

Medium Voltage Supply Characteristics (ref 3)

- **Harmonic Voltage:** Under normal operating conditions, for each period of one week, 95% of the 10 min mean rms values of each individual harmonic voltage shall be less than or equal to the values shown in the below table:

Odd harmonics				Even harmonics	
Not multiples of 3		Multiples of 3			
Order h	Relative amplitude u_h	Order h	Relative amplitude u_h	Order h	Relative amplitude u_h
5	6,0 %	3	5,0 %	2	2,0 %
7	5,0 %	9	1,5 %	4	1,0 %
11	3,5 %	15	0,5 %	6 ... 24	0,5 %
13	3,0 %	21	0,5 %		
17	2,0 %				
19	1,5 %				
23	1,5 %				
25	1,5 %				
NOTE No values are given for harmonics of order higher than 25, as they are usually small, but largely unpredictable due to resonance effects.					

- **THD**: The THD of the supply voltage (including all harmonics up to the 40th order) shall be less than or equal to 8%.

- In addition, the limits on voltage dip and swell are defined based on the voltage level vs. the amount of time the event lasted. These limits are based on the statistical data from the IEC 61000-4-30 standard.

High Voltage Supply Characteristics (ref 3)

Supply Voltage: The standard does not provide any limits to supply voltage variation. This is due to regulations and administrative constraints involved with HV transmission.

Regarding flicker and unbalance , the same limits are applied.

IEC 61000-4-30

IEC 61000-4-30 provides a detailed specification for measurement parameters.

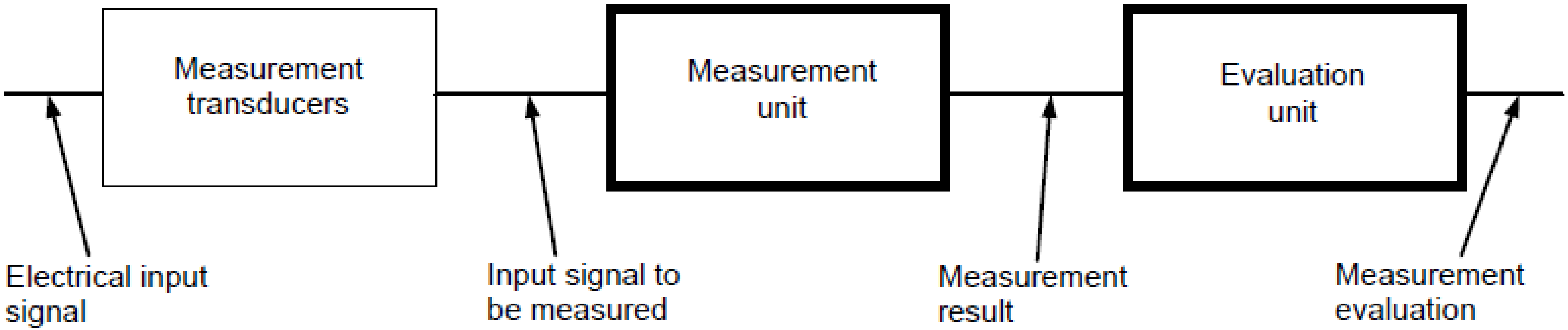
- IEC 61000-4-30 is the international standard instructing how power quality should be measured.
- Instruments certified in compliance with the standard will have reliable and repeatable measurement results regardless of the original manufacturer.
- The items included in this standard are limited to phenomena occurring in the power supply system, such as frequency, supply voltage amplitude (RMS value), flicker, dip/swell/interruption of supply voltage, and harmonics.
- As per the standard, the measurement of parameters is described for two classes, which are Class A and Class S. Each class carries its own parameter measurement criteria.

IEC 61000-4-30

The class of meter used depends on the application requirements.

- Class A: Class A is used when precise measurements are necessary.
  For example, for contractual applications that may require resolving disputes, verifying compliance with standards, etc. The requirement is that if two instruments comply with class A and if both measure the same signal, the measurement result will be the same.

- Class S: Class S is used in statistical applications. Ex: Power quality assessment.
  Although the measuring criteria looks the same as for Class A, Class S accommodates less stringent requirements.



IEC 61000-4-30 Class A Measurement Criteria

- The basic measurement time interval for parameter magnitudes (supply voltage, harmonics, interharmonics and unbalance) shall be a 10-cycle time interval for a 50 Hz power system or a 12-cycle time interval for a 60 Hz power system.

- The 10/12-cycle measurement shall be re-synchronized at every UTC (coordinated universal time) 10-min interval.

- There are three additional intervals used for certain measurements that use the 10/12 – cycle values. They are as follows:
  - 150/180-cycle interval (150 cycles for 50 Hz nominal or 180 cycles for 60 Hz nominal).
  - 10-min interval.
  - 2-hour interval for flicker.

Class S Measurement Criteria are the same but with some lower rigors.

IEC 61000-4-30 Class A Measurement Criteria

IEC 61000-4-30 10 MINUTES AGGREGATION

- The data for the 10-min time interval shall be aggregated from 10/12-cycle time intervals.
- Each 10-minute interval shall begin on a UTC 10-min beat.
- Each value is tagged with a timestamp.
- Class A and Class S have the same calculation. However, Class S does not require time resync: the time does not need to be precise.

IEC 61000-4-30 TWO HOUR AGGREGATION

- The data for the 2-hour interval shall be aggregated from twelve 10-min intervals. The 2-hour interval shall be gapless.
- The aggregation is same for both classes.

Power quality devices must be able to calculate the values as per the standard requirements.

In the occurrence of a power quality event, the flag is triggered, and the data is stored.

IEC 61000-4-30 Magnitude of Supply Voltage and Flicker

- The measurement shall be the rms value of the voltage magnitude over a 10-cycle time interval for a 50 Hz power system or a 12-cycle time interval for a 60 Hz power system.

- Measurement accuracy is defined as 0.1% V_{din} over the range of 10% to 150% of V_{din} for Class A and 0.5% of V_{din} over the range
  of 20% to 120% of V_{din} for Class S.

  V_{din} = Input voltage (raw from source)

Flicker:
Short term Flicker (*Pst*) and long term Flicker (*Plt*) are used in this calculation.
Pst and *Plt* are calculated per IEC 61000-4-15.

IEC 61000-4-30 Supply Voltage Dips and Swells

As per class A, voltage dip is determined using the *Urms* and swell is determined using the *Urms*(1/2).

As per class B, the dip and swell can be the same as class A or use the *Urms* for both.

Users determine the threshold for both pickups. Typically, 110% nominal voltage (*Un*) for swell and 90% of *Un* for dip.

The duration time is calculated from the time when the measured *Urms* falls below the threshold and the time when it goes above the threshold.

A voltage swell is characterized by a pair of data: maximum swell voltage magnitude and duration.

The maximum swell magnitude voltage is the largest *Urms* value measured on any channel during the swell.

The duration of a voltage swell is the time difference between the beginning to the end of the swell.

Accuracy is defined per class A application as 0.2% of *Un* and 1% for Class B application.

Accuracy on measurement duration, ½ cycle for Class A and 1 cycle for Class B application.

Note: *Urms* – This is the rms value of the voltage updated every cycle and *Urms*(1/2) is the rms value of the voltage updated every ½ cycle.

IEC 61000-4-30 Evaluation of the Rest of the Parameters

The standard further expands on definitions with details of the in and out of limits conditions for:

- Evaluation of voltage interruption.
- Evaluation of voltage unbalance.
- Transient voltage.
- Harmonics, etc.

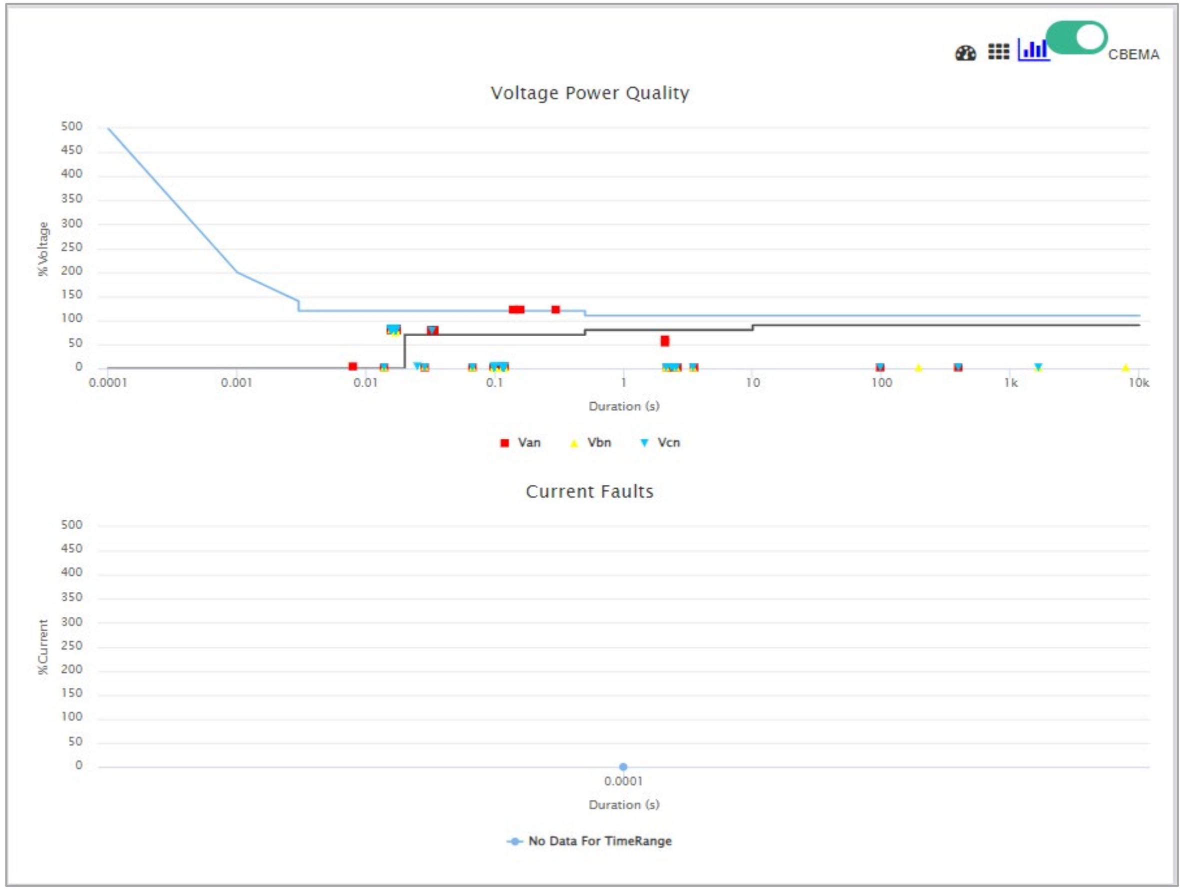
CBEMA Curve and ITI Curve

A set of curves representing the withstand capabilities of computers in terms of the magnitude and duration of the voltage disturbance.

Developed by the Computer Business Equipment Manufacturers Association (CBEMA), it became the de facto standard for measuring the performance of all types of equipment and power systems and is commonly referred to by this name.

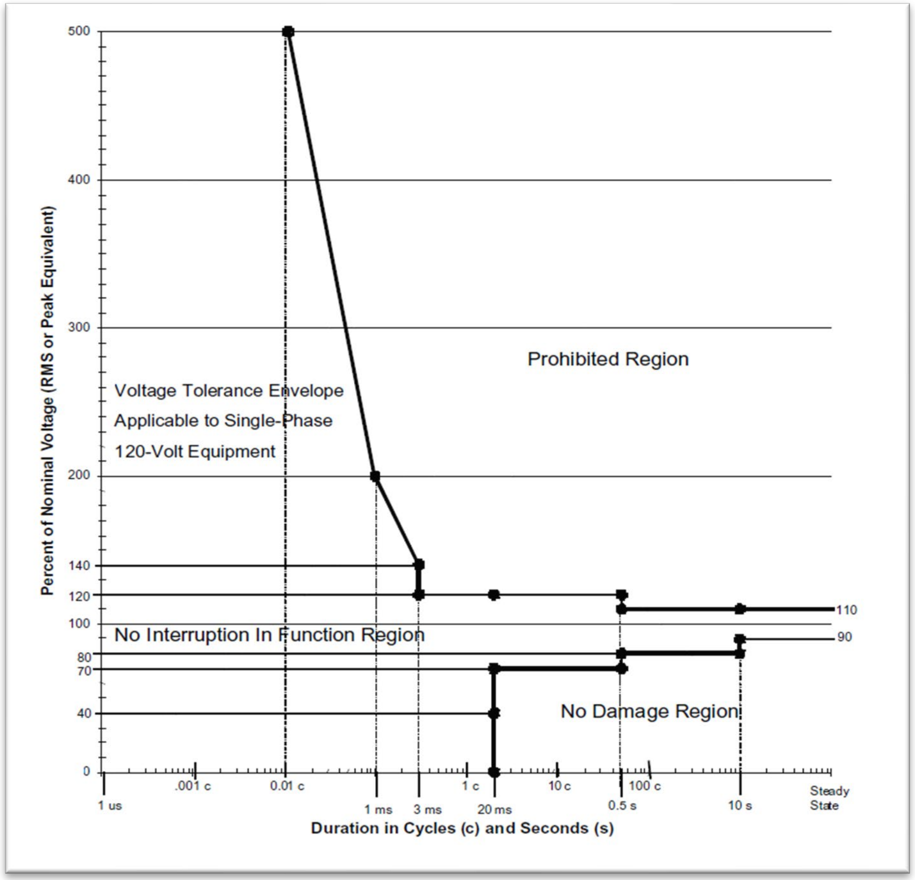
CBEMA has been replaced by the Information Technology Industry Council (ITI), and a new curve has been developed that is commonly referred to as the ITI curve.

ITI curve is the same as CBEMA, but made at 120 V for computer power supplies. This can be mimicked to any other voltage levels, using it as reference.



ITI Curve Compatibility Definition

- The ITI (CBEMA) Curve is published by Technical Committee 3 (TC3) of the Information Technology Industry Council (formerly known as the Computer & Business Equipment Manufacturers Association).
- The ITI Curve describes an AC input voltage envelope which typically can be tolerated (no interruption in function) by most Information Technology Equipment.



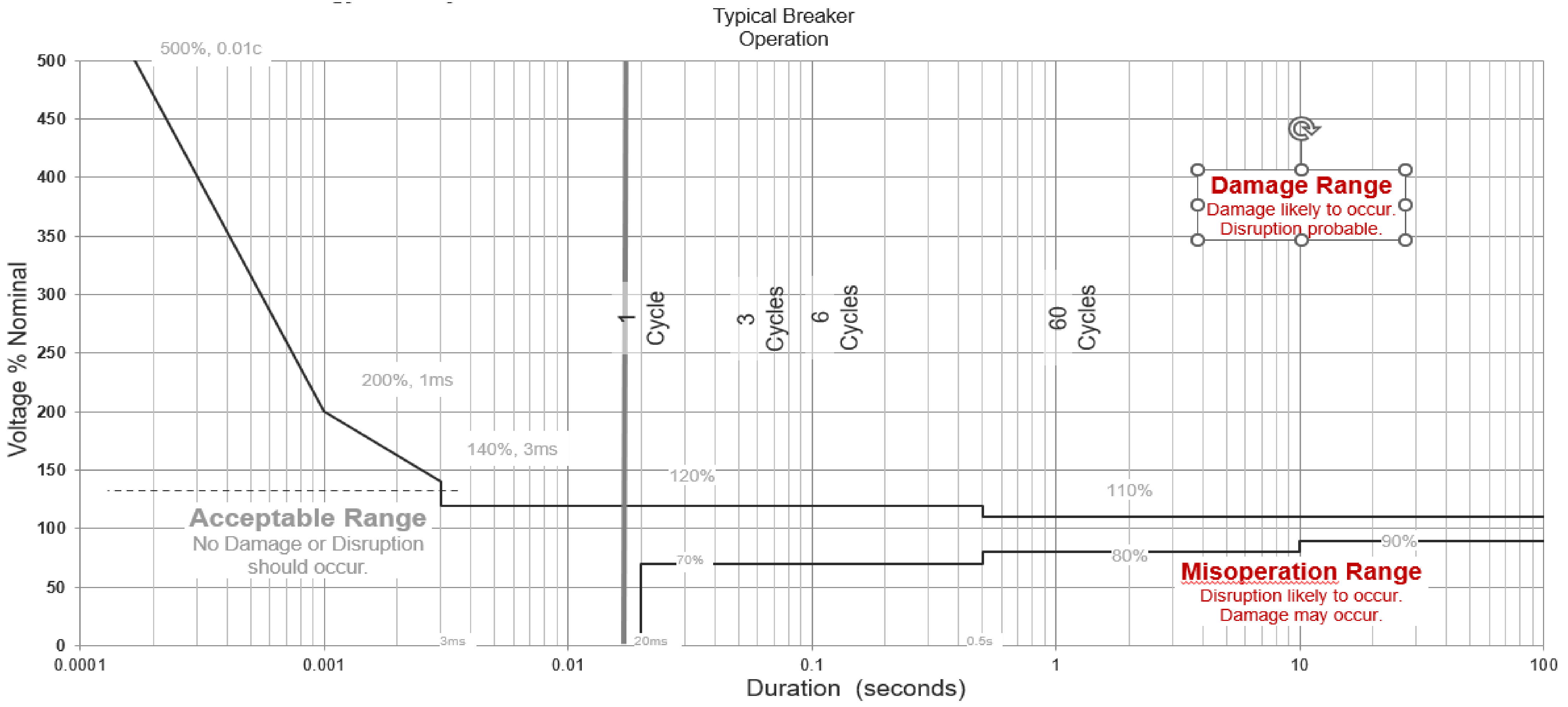
http://.www.itic.org/technical/iticurv.pdf

Range	Above	Below
2 cycles to 30 cycles 0.03 sec to 0.5 sec	120% of Nominal	70% of Nominal
30 cycles to 600 cycles 0.5 sec to 10 sec	110% of Nominal	80% of Nominal
600 cycles and longer… 10 secs and longer…	110% of Nominal	90% of Nominal

SUB-CYCLE

Range	Above
0.1 msec	500% of Nominal
1 msec	200% of Nominal
3 msec	140% of Nominal
after 3 msec	120% of Nominal

ITI Curve


Typical Breaker Operation
500%, 0.01c
200%, 1ms
140%, 3ms
120%
110%
70%
80%
90%
1 Cycle
3 Cycles
6 Cycles
60 Cycles
Damage Range
Damage likely to occur.
Disruption probable.
Acceptable Range
No Damage or Disruption should occur.
Misoperation Range
Disruption likely to occur.
Damage may occur.
3ms
20ms
0.5s
Voltage % Nominal
Duration (seconds)
0
50
100
150
200
250
300
350
400
450
500
0.0001
0.001
0.01
0.1
1
10
100

Additional Power Quality Standards

- IEC 61000-3-2: This standard specifies the limits for harmonic current emissions from electrical and electronic equipment having an input current up to and including 16 A per phase and intended to be connected to public low-voltage distribution systems. (Ref 2)

- IEC 61000-3-4: This standard specifies the limits for harmonic current emissions from electrical and electronic equipment having a rated input current more than 16 A per phase and intended to be connected in public low-voltage AC distribution systems.

- IEEE Standards Related to Voltage Sag and Reliability: IEEE Standard P1564 gives the recommended indices and procedures for characterizing voltage sag performance and comparing performance across different systems. A new IEC Standard 61000-2-8 titled "Environment Voltage Dips and Short Interruptions" has recently been developed to address the same topic.

- IEC 61000-4-15: This standard defines the measurement procedure and monitoring requirements for characterizing flicker. IEEE flicker task force working on Standard P1453 developed the standards.

- IEEE Standard 1250: This standards provides guidelines for service to the equipment sensitive to Momentary Voltage Disturbances (Ex Computers and Electronic devices).

- IEEE Standard P1409: This standard provides guidelines for custom power technologies to provide and maintain power quality on distribution systems. P1547 provides guidelines for interconnecting DG.

- IEEE Standard 141: This standard provides regulations and guidelines for the design, construction, reliability, and operation, concerning power quality, etc., for electrical distribution in Industrial plants.

Power Quality Measurement

- When there is a power quality issue, it is necessary to collect the data and analyze the power quality at the point of investigation.
- IEC 61000-4-7 standard specifies the requirements for PQ measurement devices.
- Power quality analyzers, oscilloscopes, power scopes, and power quality meters can be used. Devices should comply with IEC 61000-4-7 and IEC 62586 Ed 2.
- The main concern with PQ measurement devices is that some don’t have the capacity to monitor for long durations. Ex: oscilloscopes, power scopes, etc.
- High-resolution PQ energy meters are equipped with large memory capacity with high resolution, giving them the ability to capture data for months.
- Modern meters can perform the following tasks: capture electrical parameters, record transients and waveforms, keep event records, record data logs, produce EN 50160 compliance reports, provide CBEMA and ITI curves, detect voltage sags and swells, etc.
- They also provide alarms, fast communication, email capabilities, etc.

Power Quality Measurement – Minimum Parameters Required for Evaluation

- Timestamped Instantaneous voltage and current
- Timestamped Voltage and Current RMS values
- Active, reactive and apparent power and power factor
- Harmonic elements for current and voltage according to quantity and phase.
- Fourier transformation is applied for the computation. Sequential quantities can be computed based on these figures.
- Angle of the harmonic elements relative to the fundamental component.
- Angle between voltage and current of the harmonic components.
- Harmonic active power and harmonic reactive power - total harmonic distortion factor (THD).

In addition, the meter should be able to provide the following:

- Short-term flicker distortion values that are computed from the instantaneous voltage figures utilizing the flicker computation algorithm.
- Long-term flicker values that are computed from the short-term flicker distortion figures.
- Degree of unbalance of voltage and current that are computed from the fundamental components of voltage and current.

Power Quality Measurement – PQ Performance Recording

1. Need to define the problem statement: what is to be accomplished?
2. Select the correct location/site for evaluation or for testing.
3. Based on the site, determine the recording device.
4. Data polling and communication to devices.
5. Data type required.
6. Depending on the recording data type and duration, need to arrange the safe connection of the device.

Power Quality Measurement – PQ Meter (PQM)

- Can handle up to 600/377 V directly. For higher voltages, voltage transformers with higher resolution should be used.
- Operate with conventional current transformers with 1 A and 5 A inputs. Also, work with other current sensing devices ex: Rogowski Coil.
- Capture up to 1024 samples per cycle: Provides high resolution metering.
- Transients can be captured at up to 800,000 samples per cycle.
- Precise metering accuracy up to 0.01% of full-scale value.
- Metering compliance with standards IEEE 519, IEC 61000-4-30, EN 50160, and IEC 62568.
- Cyber security and advanced fast communication capabilities (IEC61850), emailing and alarming etc.

Power Quality Measurement – EN 50160 Report

EN50160 Individual Report Summary

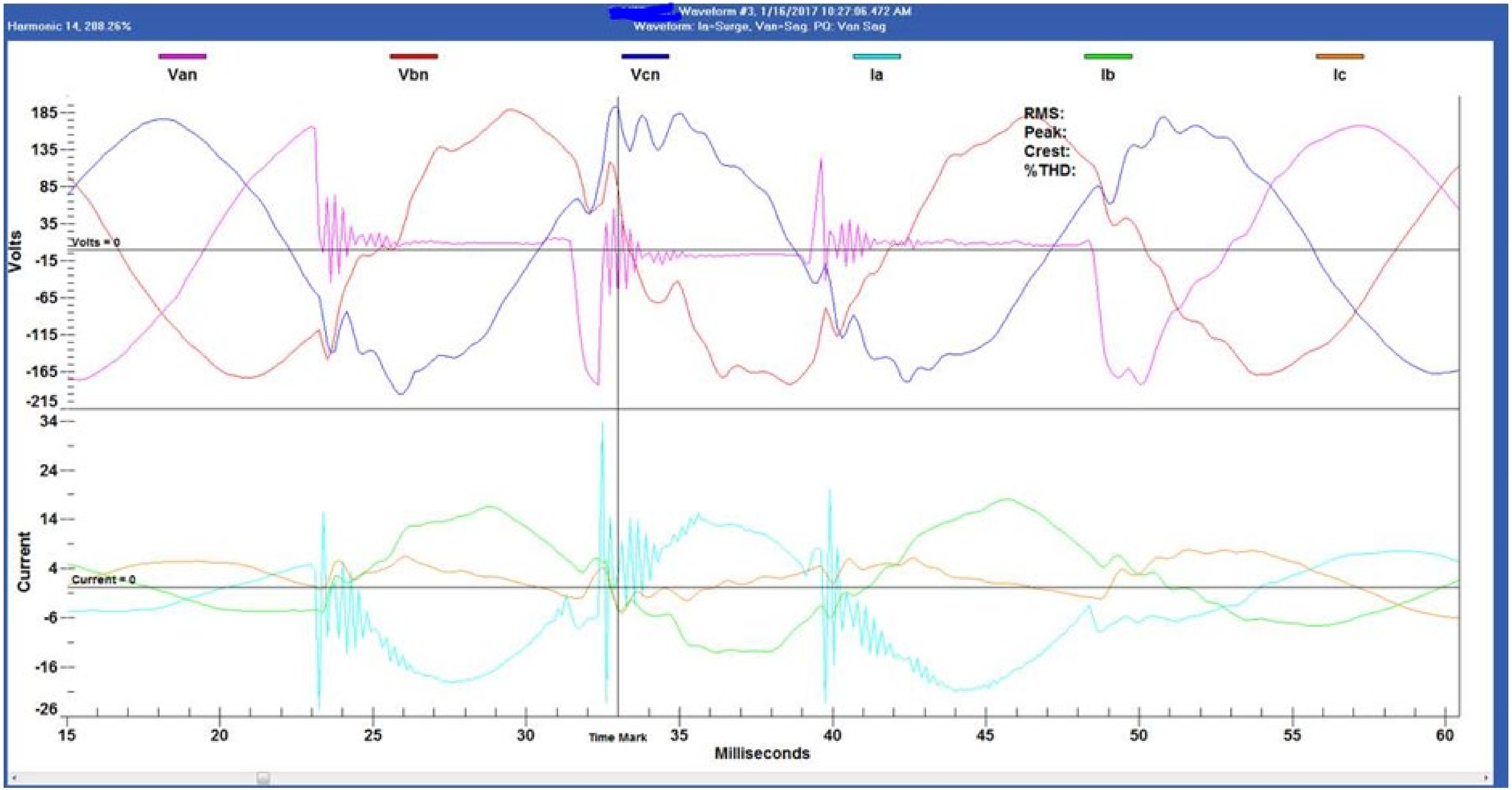
Power Frequency (x.1)	Fail
Supply Voltage Variations (x.3.x)	Fail
Rapid Voltage Changes (x.4.1)	Fail
Flicker PLT (x.4.2)	Fail
Flicker PST	Fail
Supply Voltage Dips (x.5)	Pass
Voltage Swells	Pass
Short Interruption of Supply Voltage (x.6)	Fail
Long Interruption of Supply Voltage (x.7)	Fail
Temporary power frequency overvoltage (x.8)	Pass
Supply Voltage Unbalance (x.10)	Fail
Harmonic Voltage (x.11)	Pass
Mains Signaling Voltage (x.13)	Pass

Power Quality Measurement – Waveforms

- There are various devices available to monitor power quality. Typically, it is always recommended to capture the waveform or oscillography.
- Trigger the waveform on the events.
- Continuously monitor the waveforms.

Let's look at some sample waveforms captured during power system events.

Power Quality Measurement – Waveforms



Cable Fault

Fault initiates at the peak of the voltage waveform.

Indicates that there is insulation breakdown.

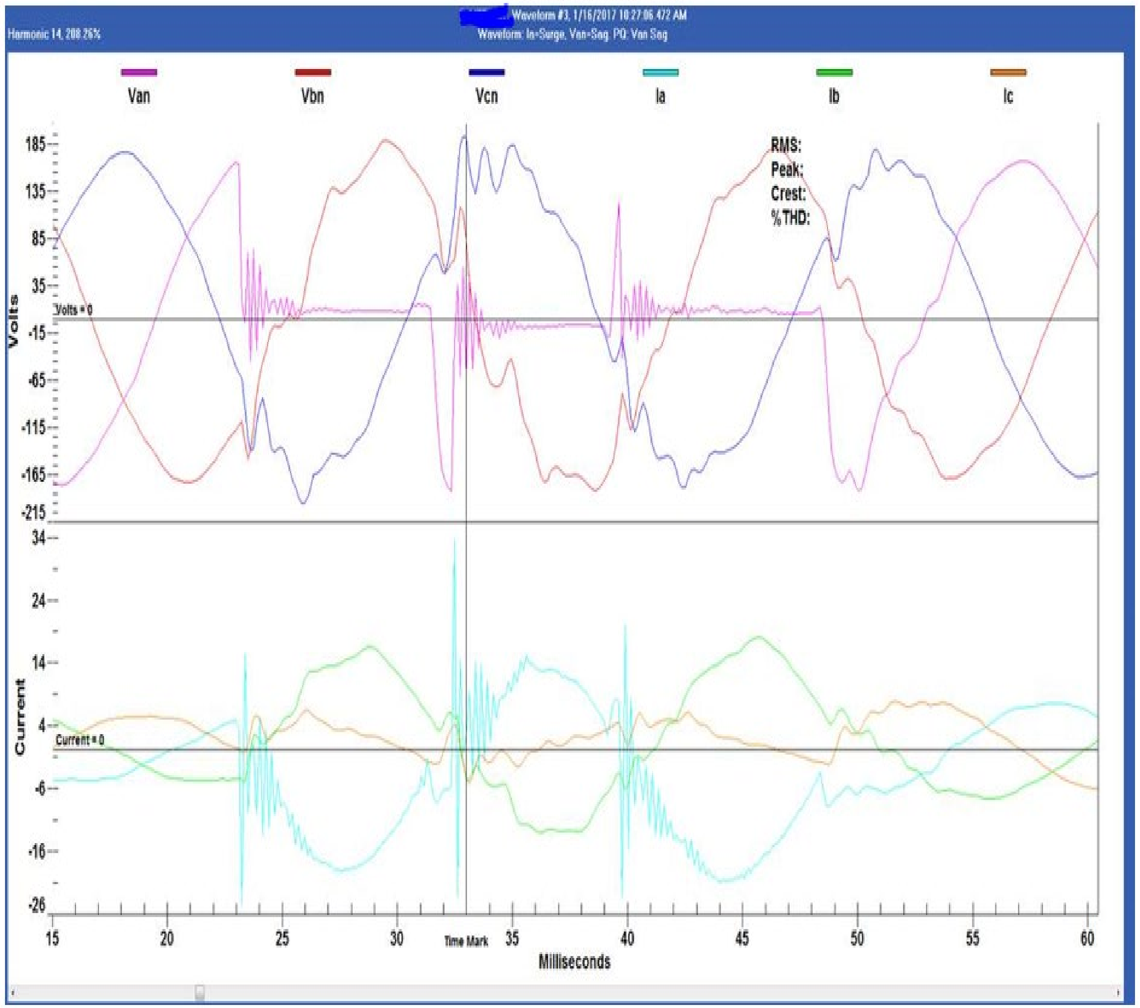
- Doesn't always correlate with cable failure.
- Team tied it back to a cable fault.

High frequency ringing until the next zero crossing.

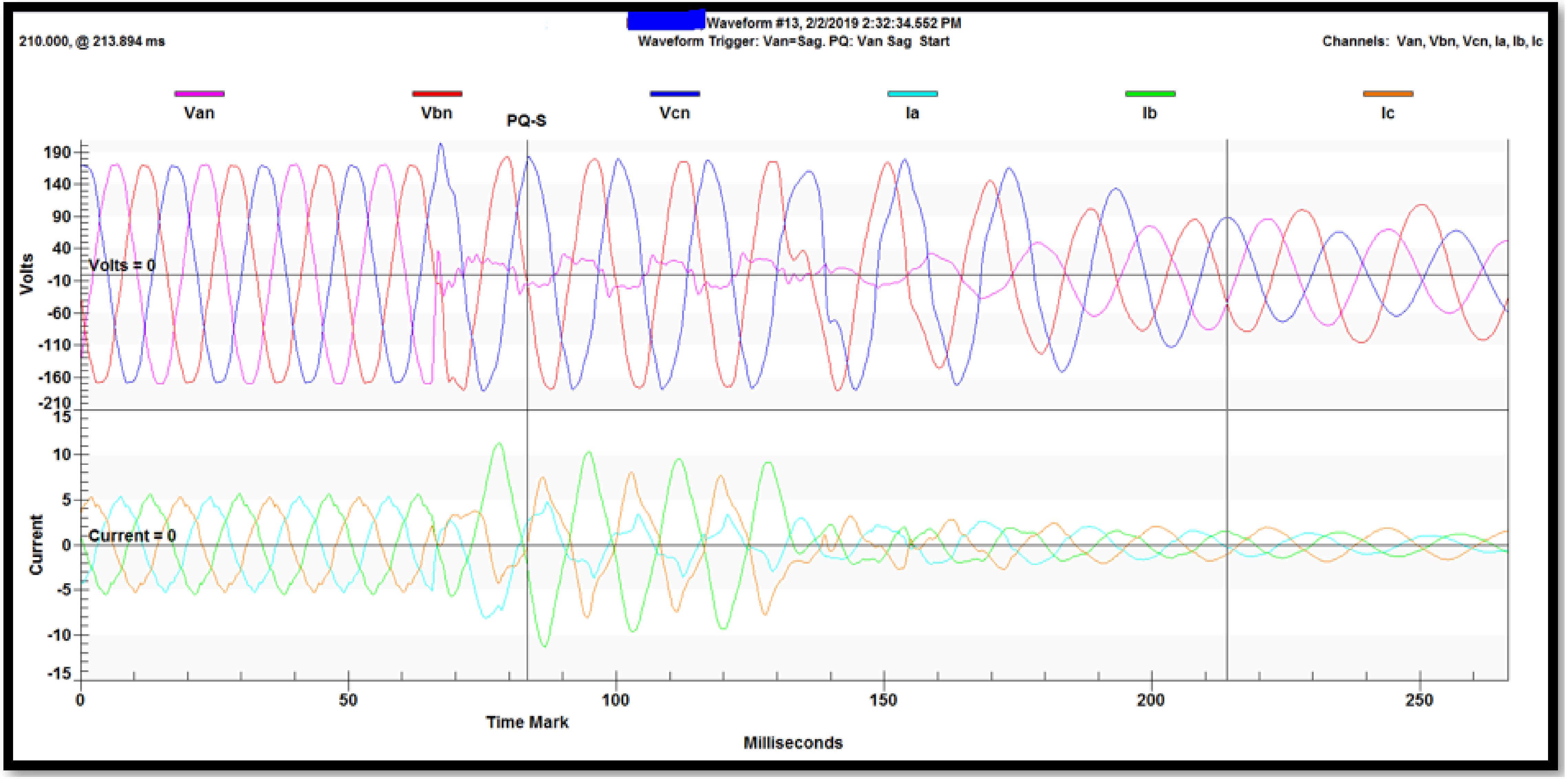
- Ringing depends on impedance characteristics of the circuit.

Peak of voltage, highest electric field stress point.
Older cable or weak point in the insulation.

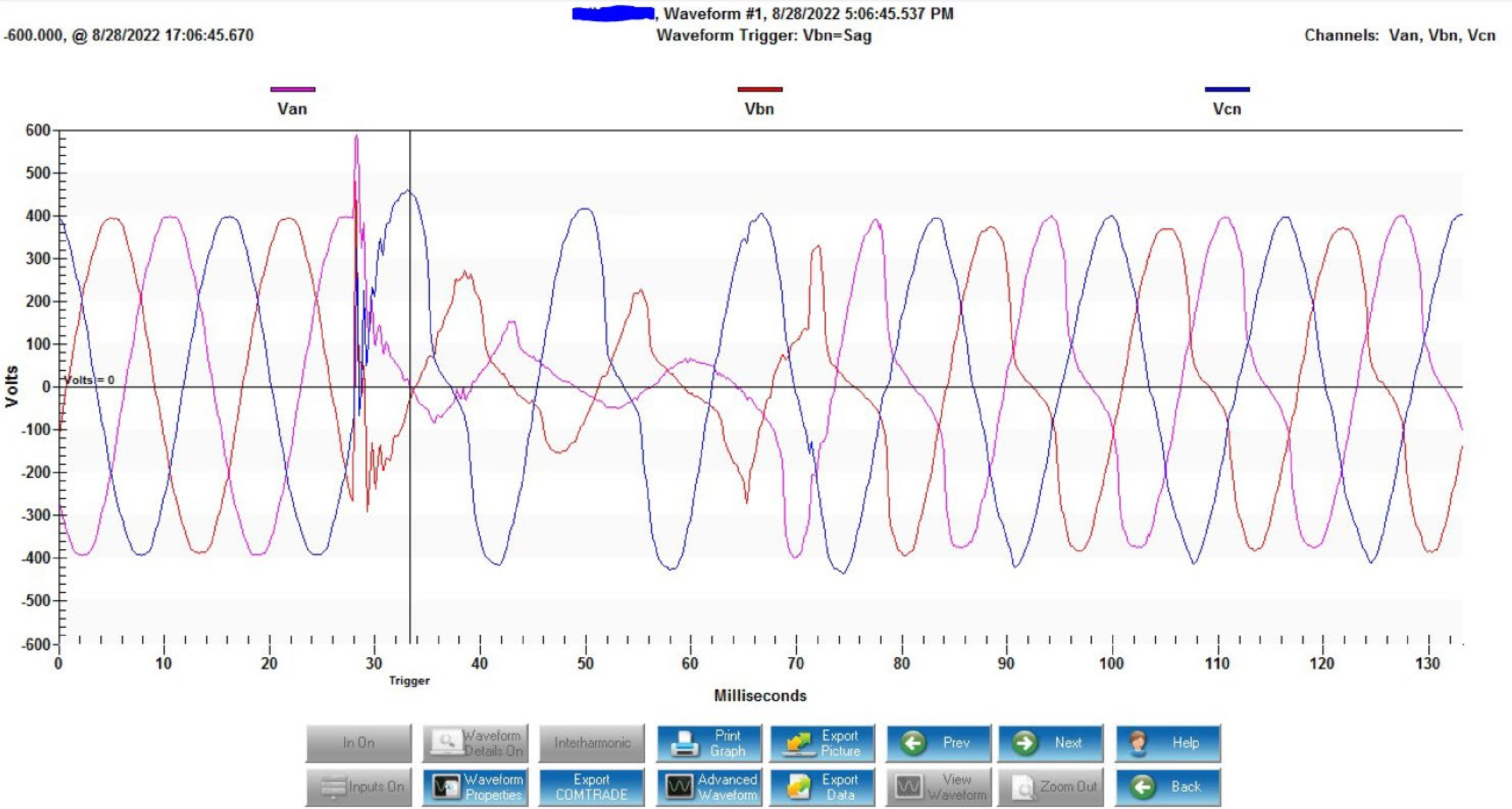
In this case, there were repeated instances, causing lockout of protective devices.



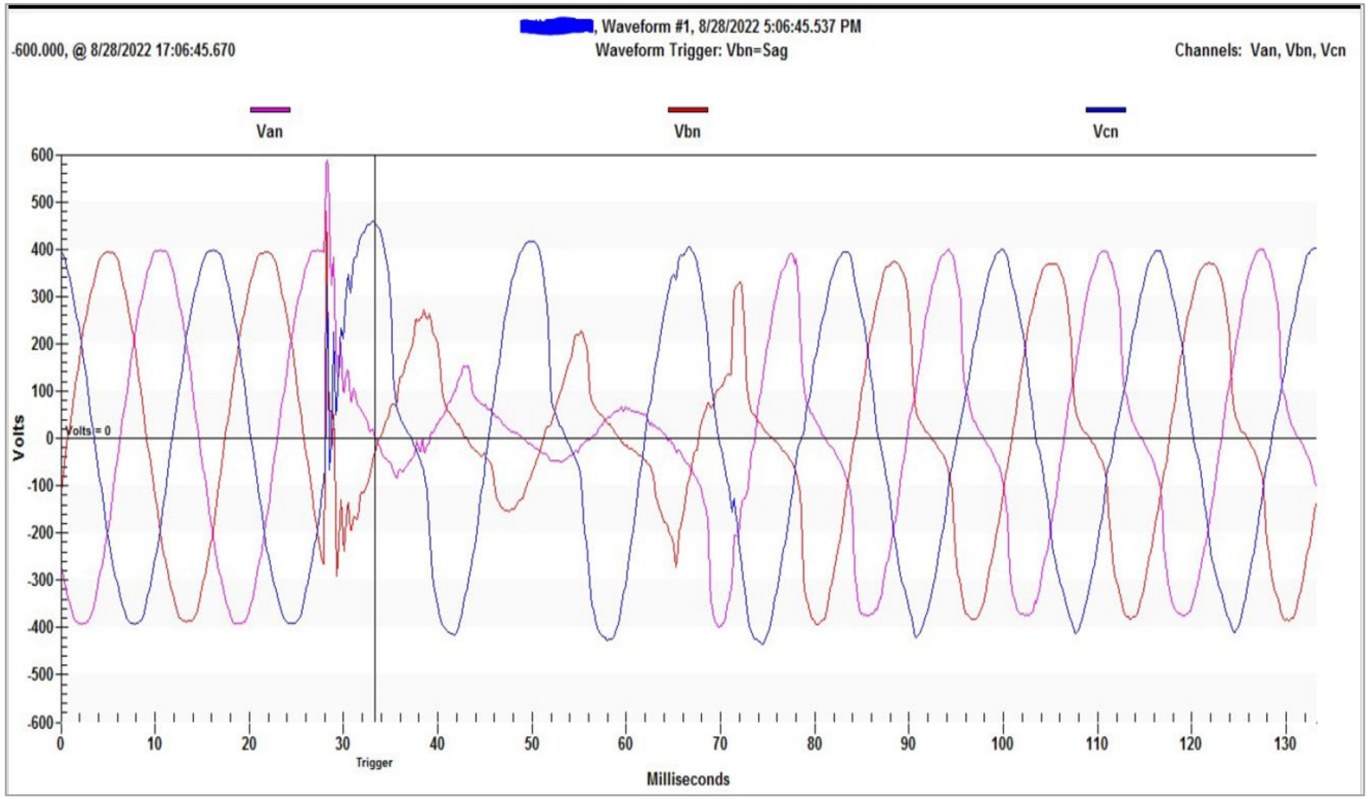
Power Quality Measurement – Waveforms



Power Quality Measurement – Waveforms



Lightning Strike

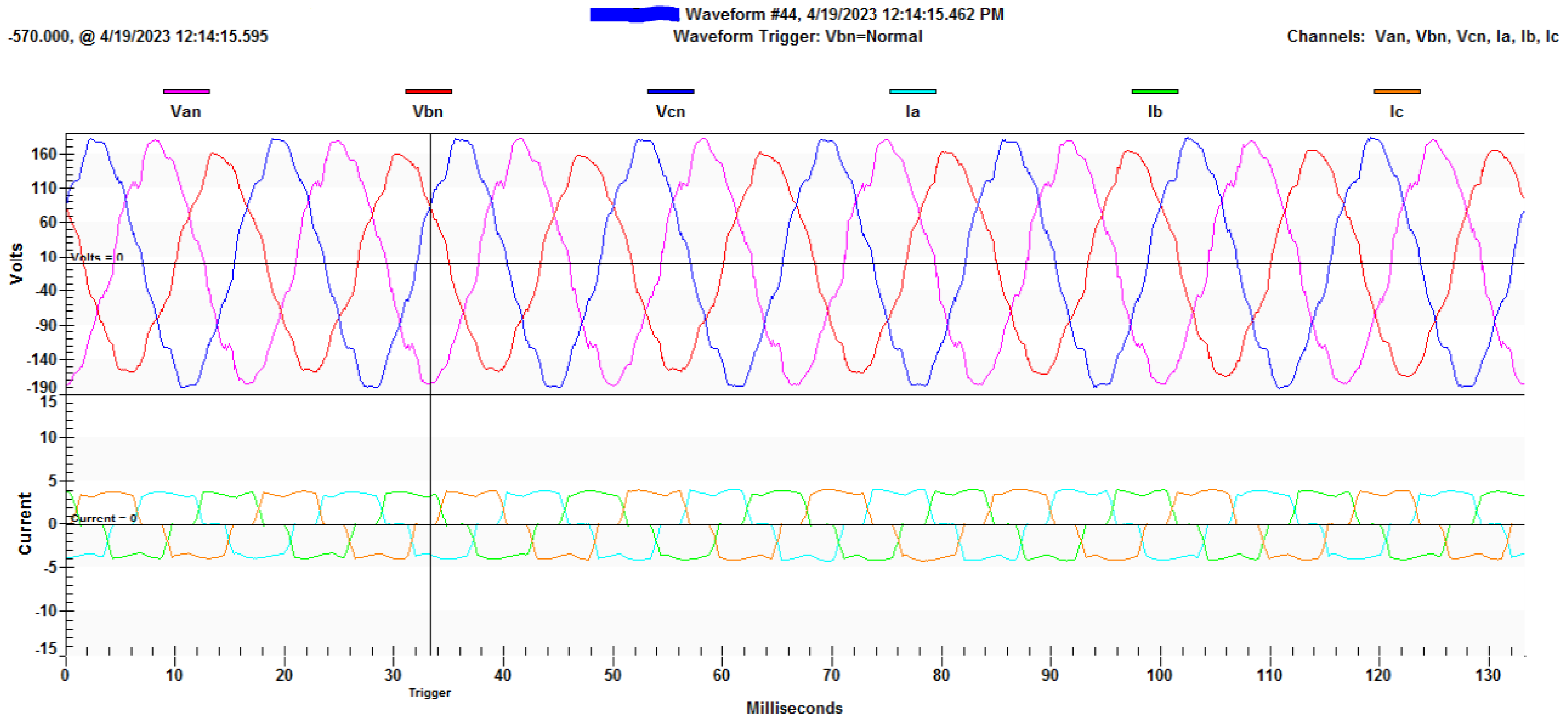


Sharp impulse on top of the voltage waveform.

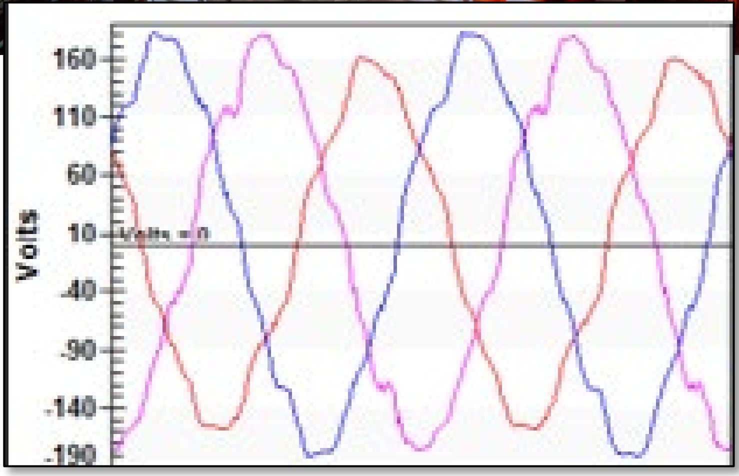
Very brief disturbance.

The arresters are clamping the voltage surge, preventing the surge and diverting its energy to ground.

Power Quality Measurement – Waveforms



6 Pulse Rectifier



6 Pulse Rectifiers are used in Electric Induction Furnaces (EIFs) to melt and refine metals like copper, lead, and aluminum using electric currents.

Power Quality:

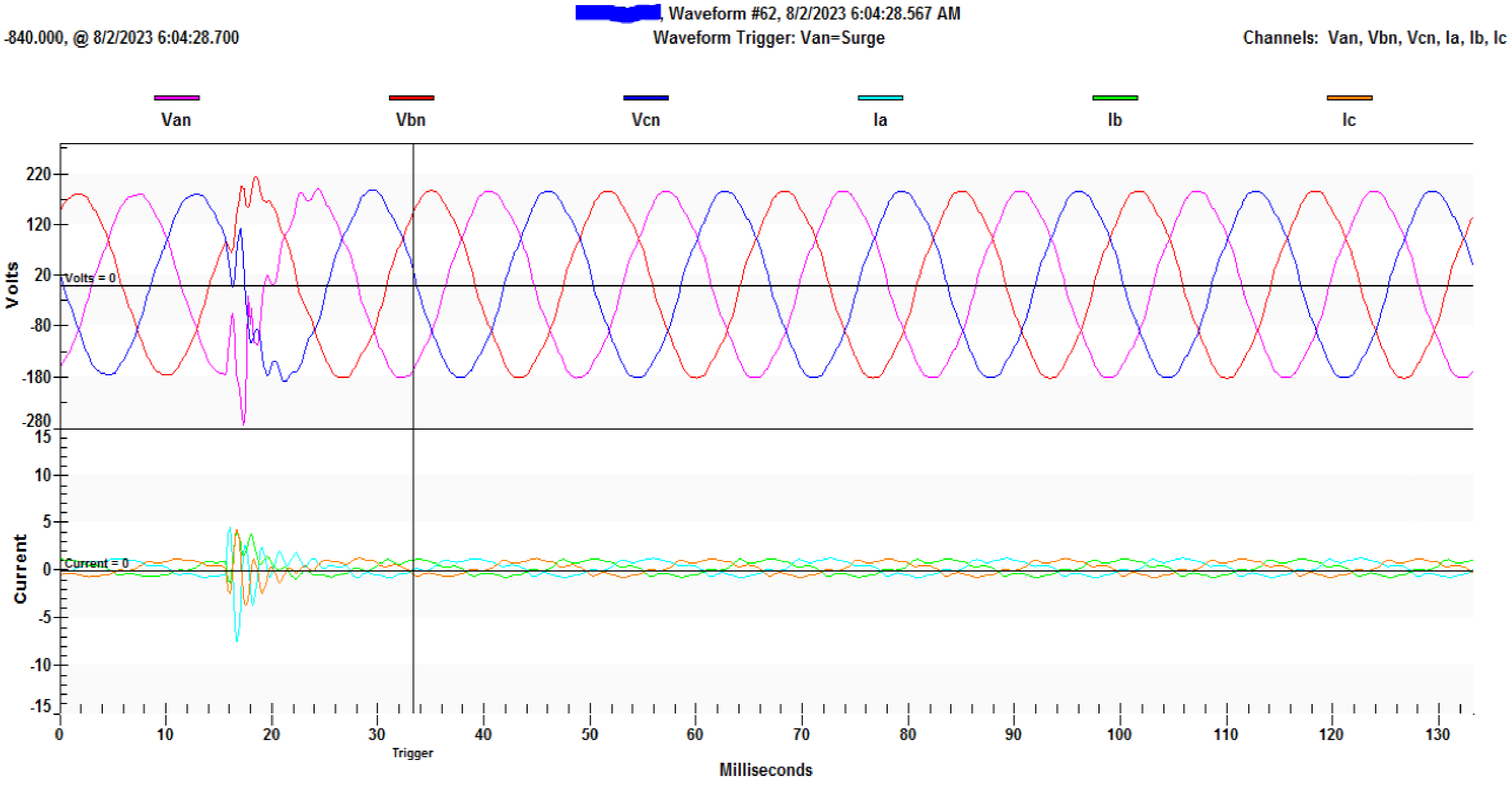
- Problems from EIF operations include:
  - Harmonics and interharmonics.
  - Voltage flickers.
  - Voltage instability.
  - Increased reactive power demand.

Impact:

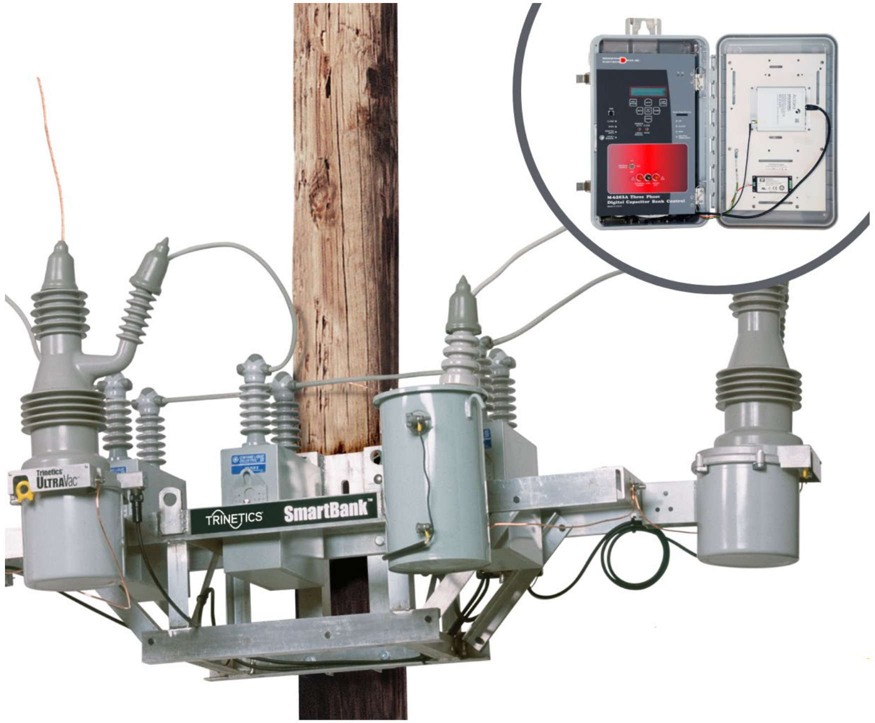
- EIFs draw heavy currents, leading to distorted current waveforms, which can cause system voltage distortion.

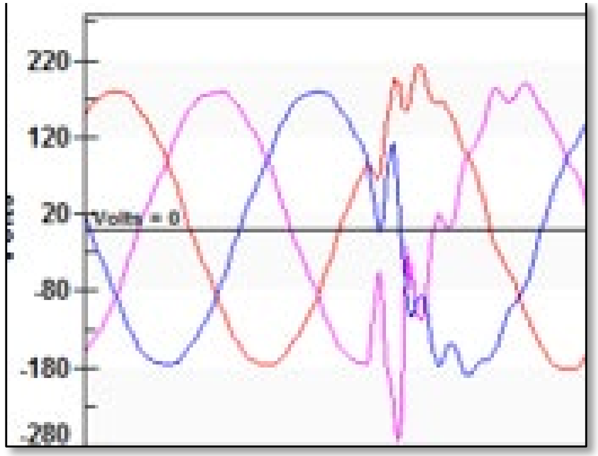
- Harmonic currents create additional heating of transformers, conductors, and fuse links.

Power Quality Measurement – Waveforms



Capacitor Banks





Capacitor Banks are critical for power system reliability and operations.

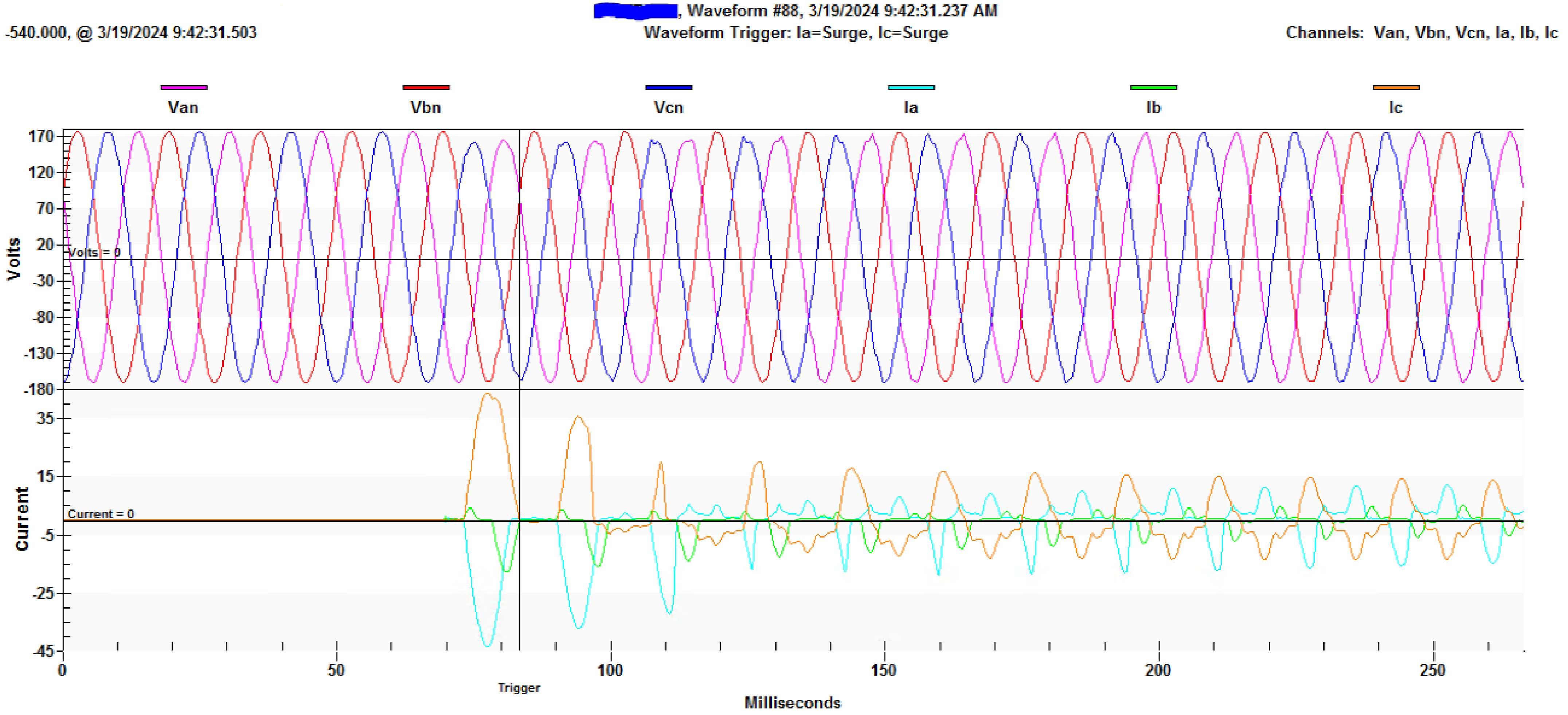
Benefits:

- Voltage Support: Stabilizes system voltage levels.
- Reactive Power Management: Reduces reactive power flow, improving efficiency.
- System Capacity: Increases ability to handle electrical load.
- Power Losses: Decreases energy lost in power transmission.
- Cost Efficiency: Lowers energy bills by optimizing power factor.

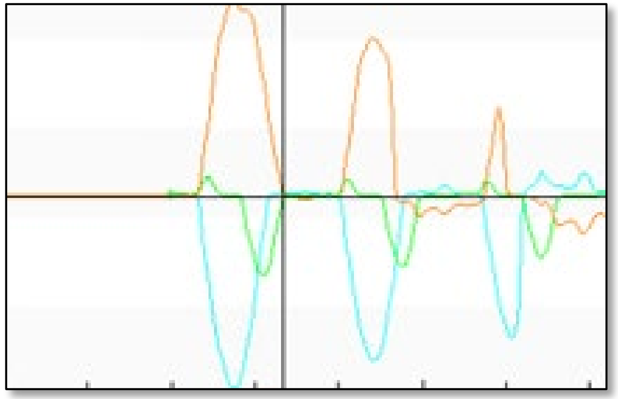
Power Quality:

Energization may lead to transient over-voltages, risking equipment insulation.

Power Quality Measurement – Waveforms



VFD Transformer Energization



VFD transformers enhance power quality by reducing harmonic distortion, a common issue in power systems with VFDs.

- Voltage Stabilization: They ensure stable voltage supply to VFDs, crucial for the consistent operation of motors and other equipment.
- Isolation Impact: By electrically isolating the VFD, these transformers prevent transmission of electrical noise and surges to other equipment.
- Harmonics Mitigation: VFD transformers are designed to handle the high harmonic currents generated by VFDs, thereby protecting the integrity of the power system.

Power Quality:

The surge in current energizing the transformer creates harmonic voltage distortion and voltage sags that may affect other equipment.

POWER QUALITY CONTROL

These are some of the measures that can be taken to improve and regulate power quality.

PQ Improvements

- **Surge Protection Devices:** These are cost effective nonlinear devices that can clamp to prevent transient voltages. (Transient are cause of 85% of the power quality issues which can be minimized). Transient voltage surge suppressors (TVSS) is used most often for this application.

- **Filters**: Filters are mostly inductor/capacitors circuits which are used to attenuate the harmonic components in the power system to filter the harmonics. Filters also can be used to attenuate the high frequency components created by electromagnetic interference (EMI).

- **Line Conditioners:** Line conditioners are used to regulate the voltage. This is very common in electrical distribution and industries. Two types of line conditioners are in use: Ferro resonant type and electronic tap changing type. Ferro resonant type devices, since they have energy storing, are capable of riding through up to 1 cycle.

PQ Improvements

- **Isolation Transformer:** These can be used to isolate sensitive loads from the electrical noise generated by noisy sources due to poor ground connection. This can be used as a filter to cut off certain frequency signals and prevent conduction of transients.

- **Regulators:** Voltage regulators are used to maintain the voltage level within the limit when the input voltage fluctuates or the connected load changes. Online tap changers and voltage regulators are used to implement this technique.

- **Uninterruptable power supply (UPS):** This can be used to enable the device to continue operating when the power is interrupted. UPS has a battery source which will be converted to AC to maintain the operation.

- Thyristor based Static switch and VAR compensator.

- Using Energy storage system:

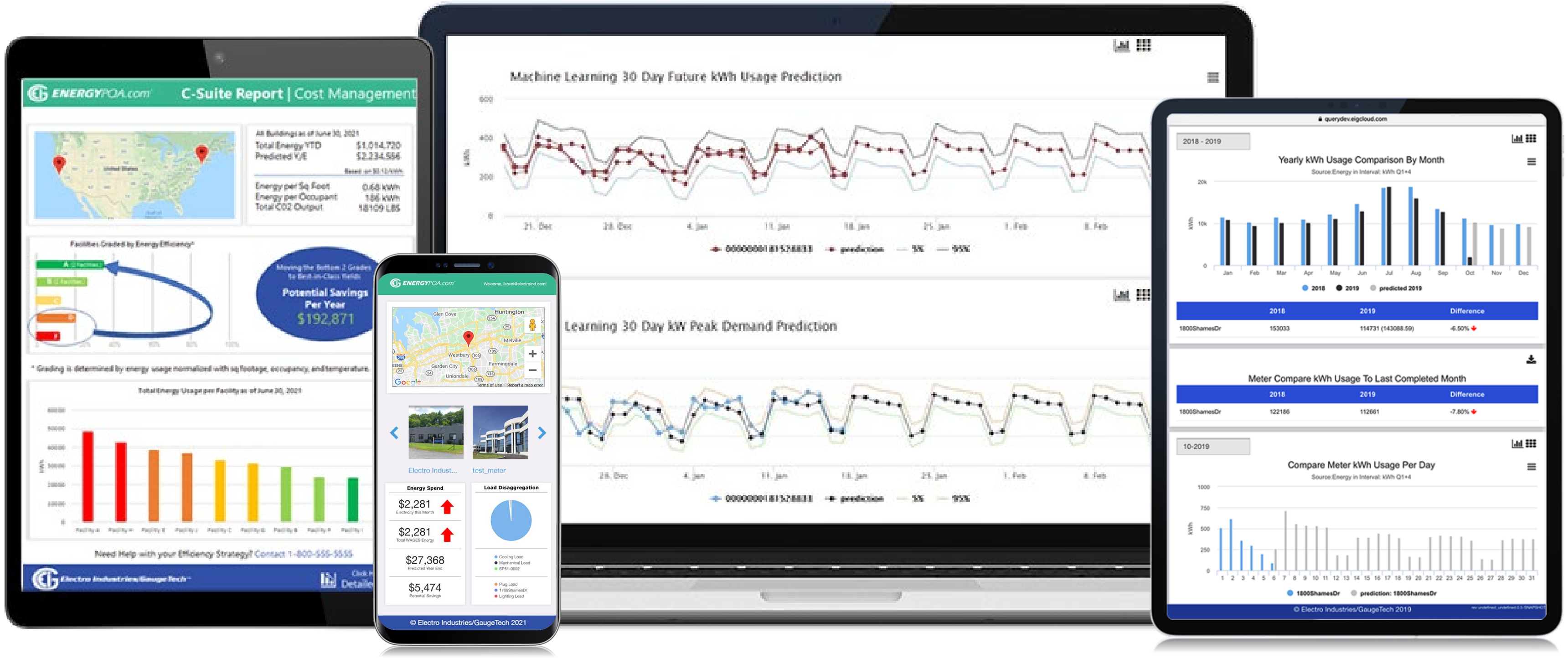
  - **Flywheels:** Ride-through time can be achieved up to 1-100 seconds.
  - **Super capacitors**: Help to override power outages in the electronics for a specific amount of time, based on the size of the super capacitor.

EnergyPQA.com® AI Driven Energy Management Software

AI Driven Energy Management System, providing energy predictions to reduce costs and improve power system reliability.

Determines the most energy wasteful facilities and circuits to maximize energy efficiency improvements.

Identifies the least reliable facilities and circuits using deep power quality insights to improve electrical reliability.



EnergyPQA.com® AI Driven Energy Management Software

How does this software work?

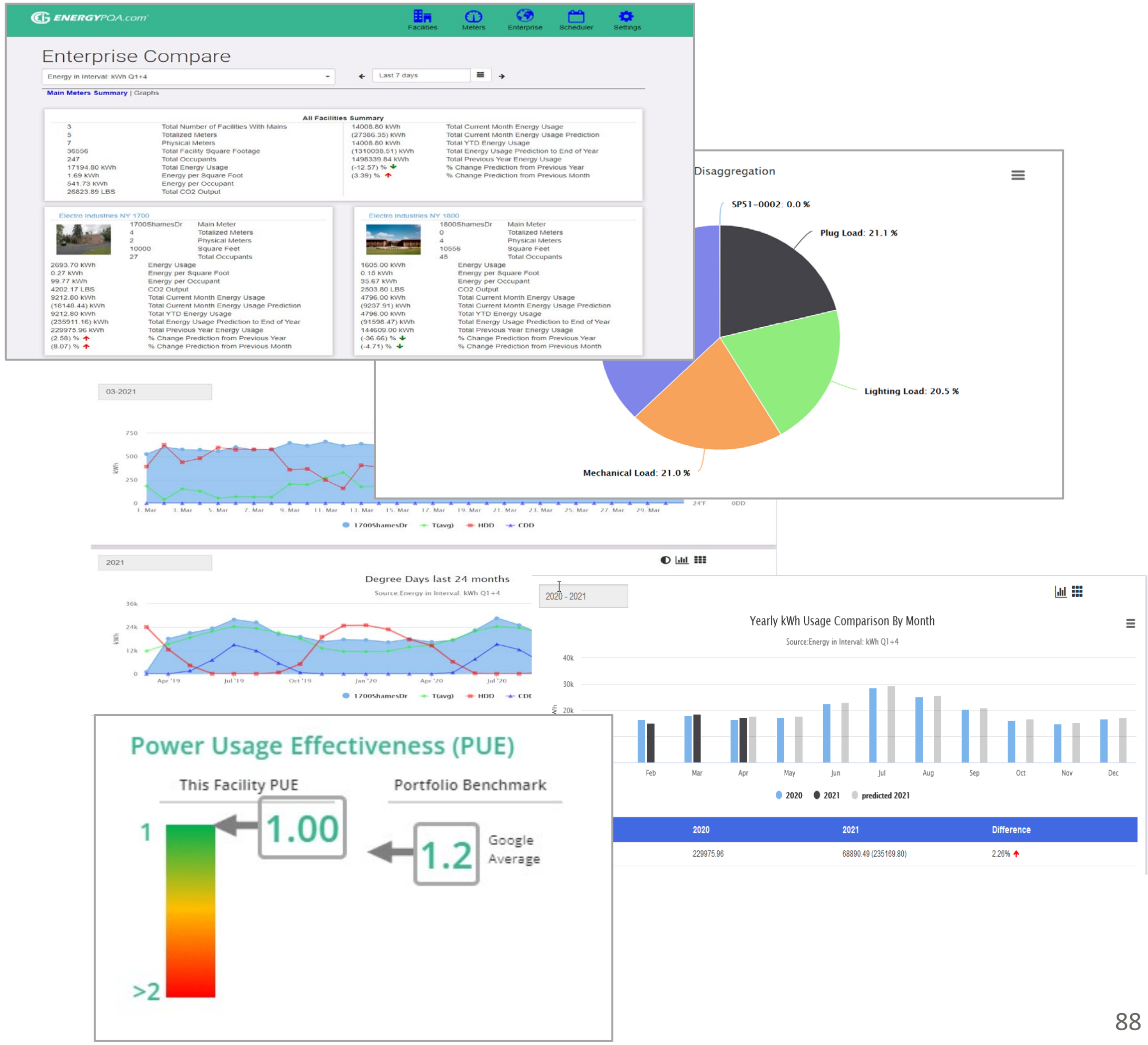
- PQM meters are connected to the cloud using the TCP/IP network.
- PQM are set to capture logs with all the required parameters.
- Captured logs are saved in the cloud, which is storage provided by the external party.
- The captured data is used by the software to analyze the power quality and perform prediction and forecasts.
- Collected data is used for the software’s machine-learning.
- All the predictions use learned data combined with internal algorithms.

EnergyPQA.com® AI Driven Energy Management Software

Identify Poorly Performing Buildings. Energy Efficient Buildings Can Consume Up to 85% Less Power

Key Features:

- Compare energy usage across facilities.
- Grade facilities and identify potential savings.
- View energy and other commodity dashboards with predictive intelligence.
- Report on highest demand and highest energy usage contributors.
- Determine your impact on the environment by monitoring carbon footprint per location and in total.
- Report on degree days, temperature, and usage.
- Perform load disaggregation analysis.
- Measure PUE (power usage effectiveness) to determine the energy efficiency of a data center.

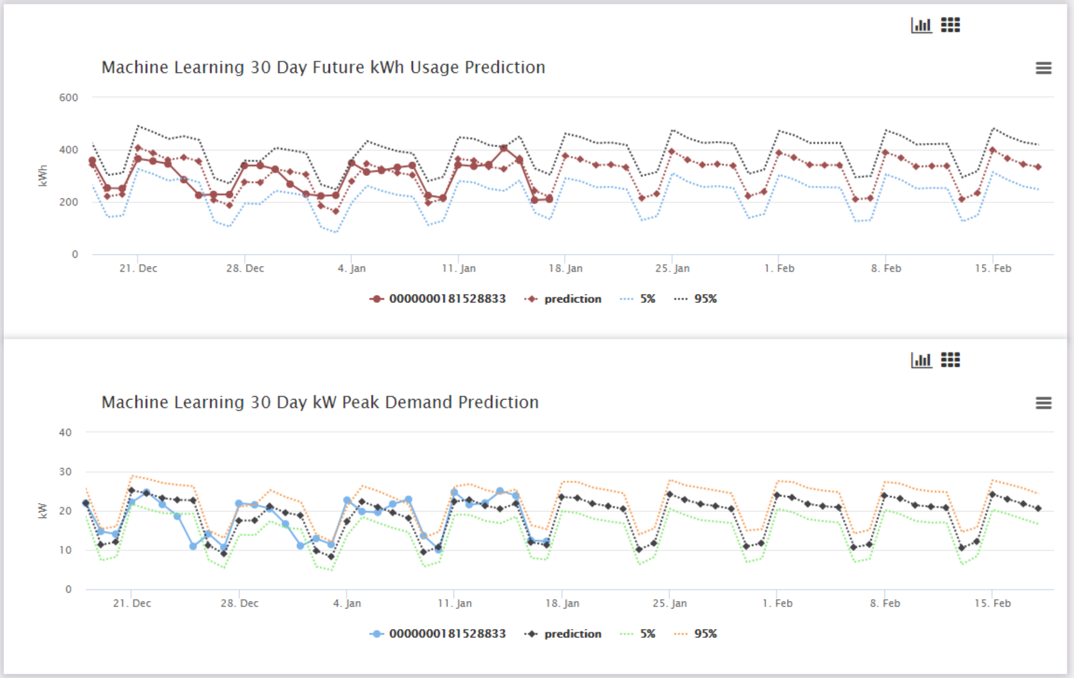


EnergyPQA.com® AI Driven Energy Management Software

Immediate and Significant Cost Savings by Implementing Even Modest Demand Reduction

Key Features:

- Take corrective action on peak demand predictions to mitigate utility penalties and save money.



- Uses advanced AI and machine learning to accurately predict demand and energy usage into the future.

- Continuously learns and improves over time.

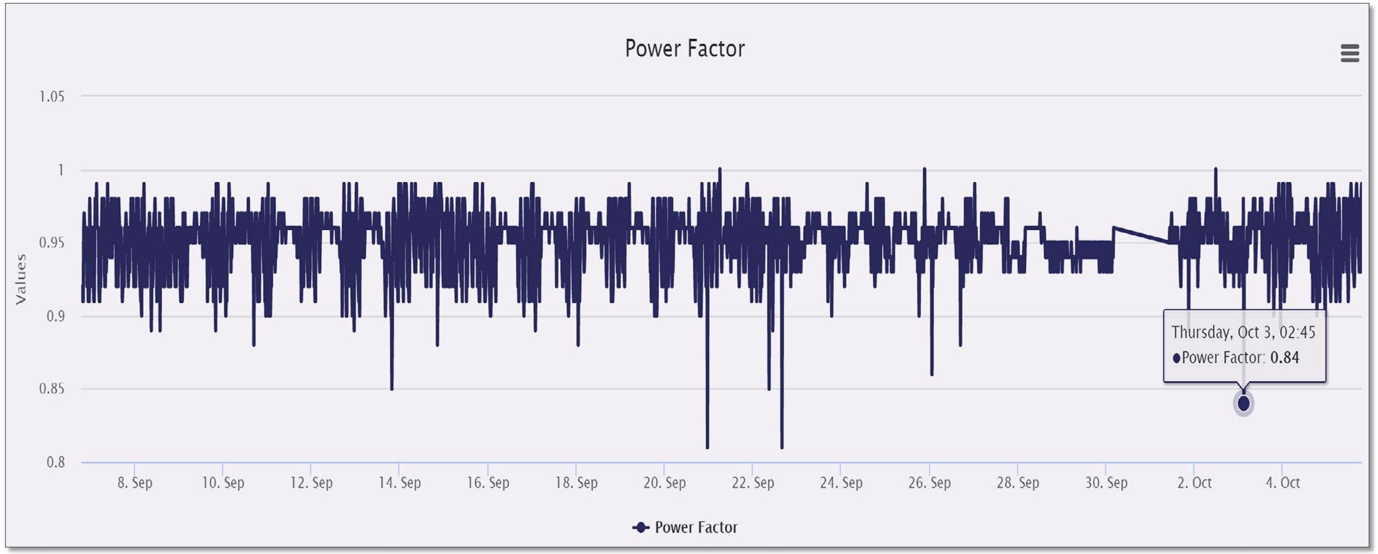
- Uses historical weightings and future weather forecasts to provide highly accurate results.

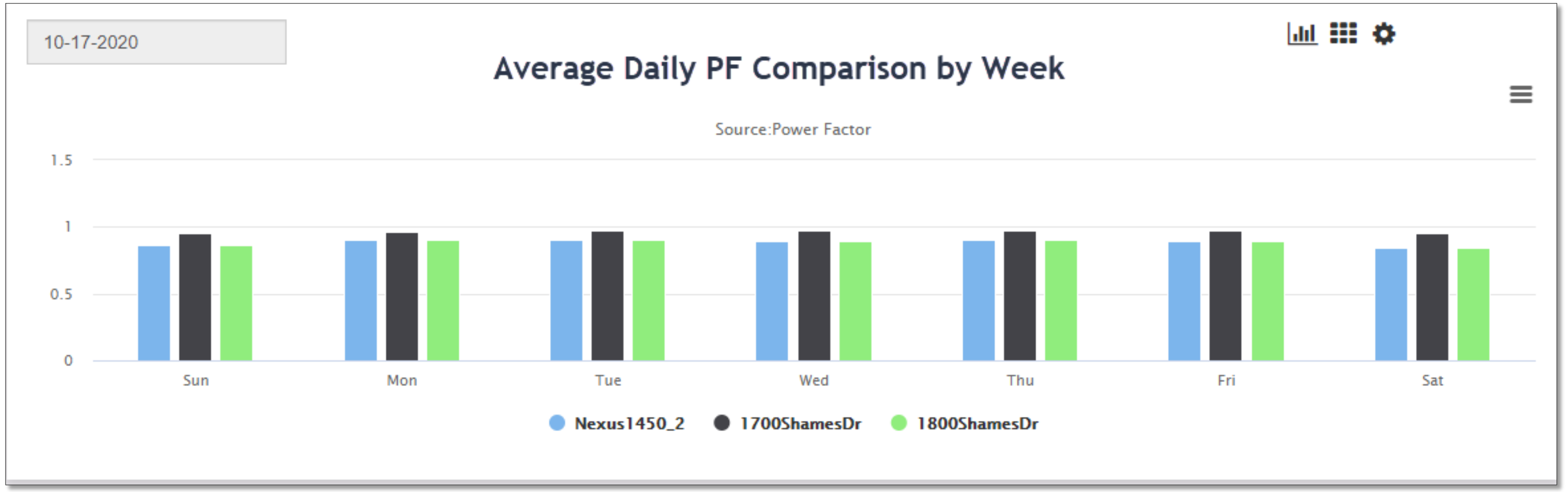
- Peak demand prediction provides the day and the specific hour of the anticipated peak.

EnergyPQA.com® AI Driven Energy Management Software

Power Factor

- Power Factor data collection.
- Automated Enterprise wide Power Factor reporting.
- Alarming on poor Power Factor.





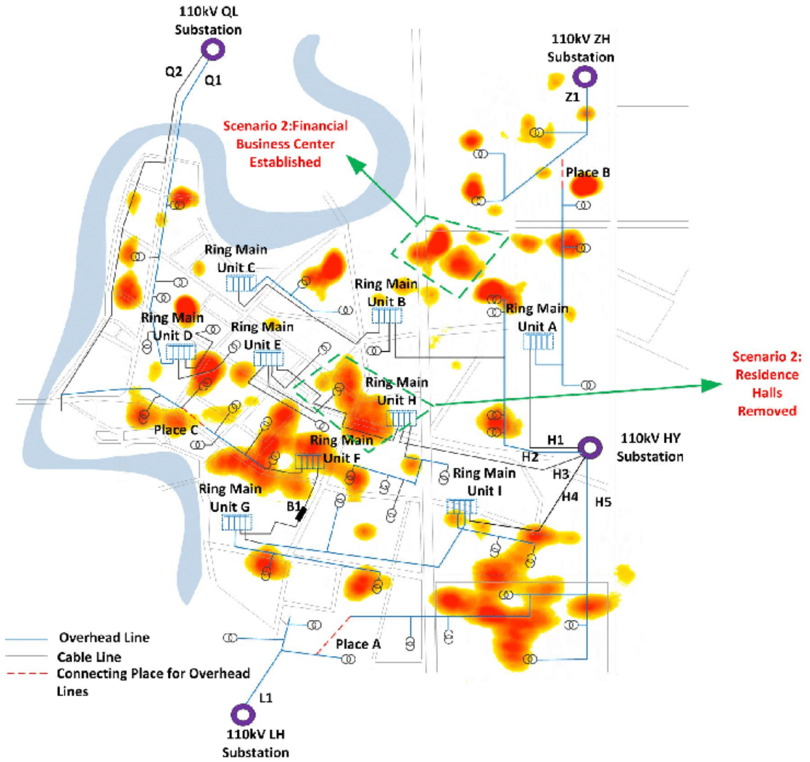
Key Challenges and Considerations

The key Challenges:

- PQ is an issue in the distribution system. To investigate and address the issues need to collect data. This may need to install the devices and monitor for a long time period of time.
- Evaluating the data needs tools typically software type. Available software may require data in a specific format which may be a challenge.
- Installations are old and may require upgrades to comply with standards. Some Utilities having issues to perform power quality studies due to funding.
- Educate the customers to evaluate the devices before install.

Best practices & implementation strategies

Strategies to overcome challenges



Invest on collecting PQ data and Turn the data into actionable information

- Develop PQ indices by Station/Feeder/Lateral/Area
- Rank the PQ indices by
    - Worst performing feeder overall
    - Power Factor
    - Number of PQ Events
    - Voltage Stability
    - Harmonic Distortions
- Allocate resources/budget for further PQ analysis on a PQ hot spot
- Justify equipment upgrades or process changes in the next Utility rate case filing with tangible data
- Improve overall grid reliability and power delivery efficiency.

QUESTIONS AND ANSWERS

REFERENCES:

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