Harmonics in the Power Grid

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Abstract

Over the past 20 years, the power system has undergone significant transformation. Power generation has transitioned from large synchronous machines to inverter-based resources that convert a direct current (DC) to an alternating current (AC) for grid compatibility. In addition to changes in generation, grid design now employs other active components to regulate voltage. Furthermore, the nature of power consumption has evolved from primarily resistive loads to increasingly electronic loads. Together, these developments have contributed to a grid environment that is richer in harmonics.

Harmonics on the grid are well known to cause a variety of equipment issues from overheating to malfunction to outright failure. There are many case studies that show that excessive harmonics can negatively affect grid-connected equipment. Consequently, many standards organizations have imposed limits to ensure that equipment can function properly.

However, as more active electronics are integrated into the grid, the noise on the grid continues to increase, posing a challenge for standard bodies. Striking a balance between technical feasibility and economic impact has made it difficult to reach consensus on appropriate harmonic limits.

This document describes the nature of harmonics and their effects on grid-connected equipment, summarizes current standards for harmonic measurement and testing, and presents case studies involving harmonic measurements on both distribution and transmission electric systems.

Introduction / Background

Historically, the power system was comprised of three sectors: generation, transmission, and distribution (see Figure 1). The generation sector created the alternating current (AC) sine wave that remains the standard for most grid operations today. The transmission sector was responsible for moving large quantities of energy, typically at high voltages, from the point of generation to substations, where the voltage was stepped down for use by bulk consumers (e.g. large industrial customers) or distribution providers. The distribution sector then delivered this reduced voltage to retail consumers, completing the supply chain.

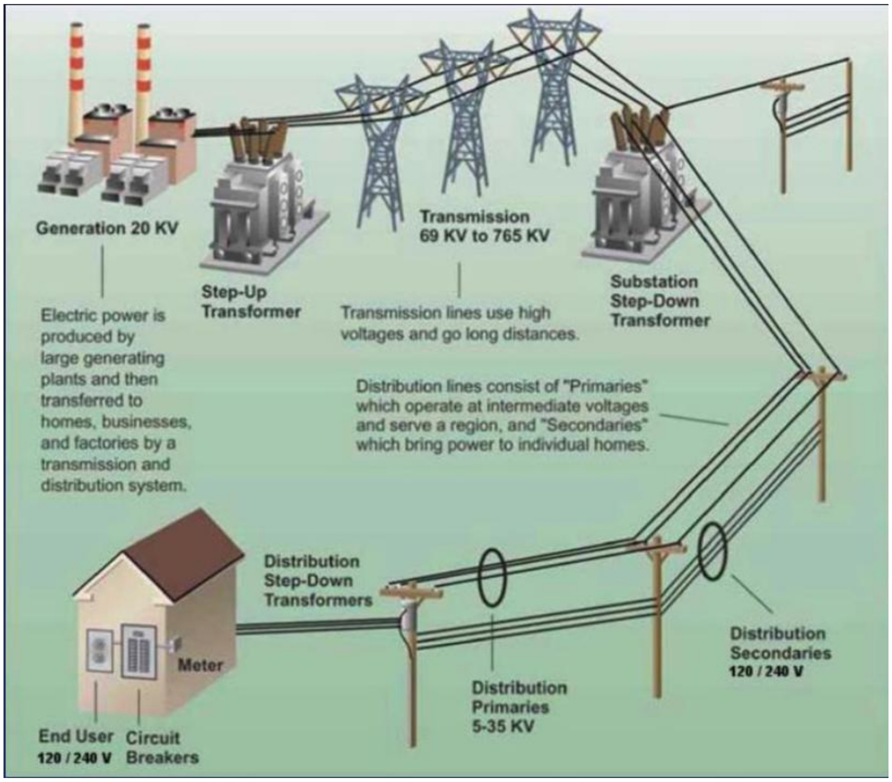


Figure 1 - Historical Power System

The generation sector of the power system traditionally relied on large electric generators (see Figure 2), consisting of a rotor mechanically coupled to a large stator [1]. The size of the machine made it difficult to start, but the large mass of the components resulted in inertia greatly stabilized the frequency of the generator. The design of the stator was such that the harmonics produced by the machine were negligible at 50 or 60 Hertz commonly used in grid operation.

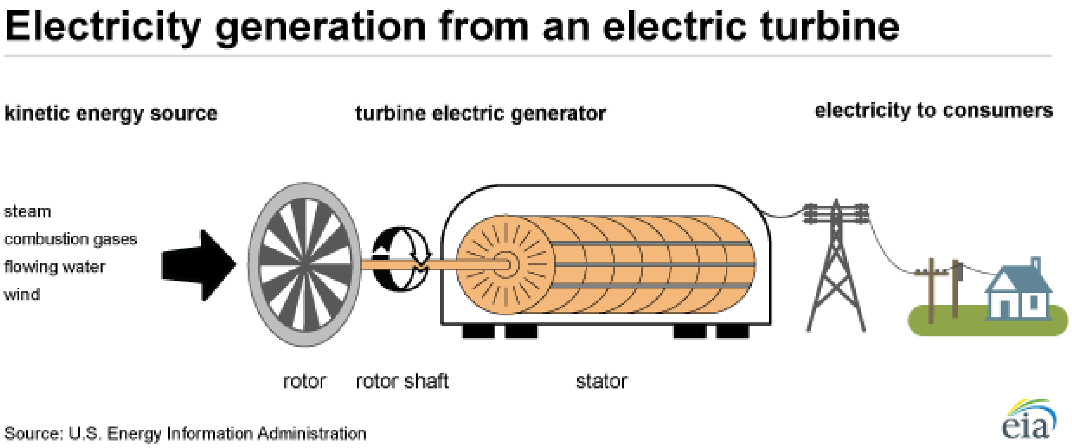


Figure 2 - Electric Generation from An Electric Turbine

The transmission sector of the power system is comprised of high-voltage lines to minimize resistive losses. In general, the transmission system is connected as a network such that the loss of a single path does not cause widespread outage to downstream consumers. Periodically, capacitor banks or inductors are used to keep the voltage within agreed operating ranges. These nonlinear elements can create distortion on the nearly perfect sine wave coming from the generation system. However, transmission system operators carefully design the system to minimize the amount of distortion created on the system.

The distribution sector of the power system is designed to distribute power to consumers. The distribution system has been typically operated in a radial fashion, meaning that if there was a problem along the power line, the whole line and any consumer connected to it may lose power. The point of common coupling (PCC) is used to delineate the area of responsibility between the consumer and the distribution operator. In general, consumers create noise by connecting disturbing loads to the system. Emissions have been managed through customer contracts or remediated, when a customer complained about malfunctioning equipment.

The power flowed in one direction (from generation to distribution) and as such any voltage quality issues (like harmonics) have been the responsibility of the grid operator to balance generation and load. There was no storage in the grid. Load patterns were heavily influenced by weather.

By comparison, the modern grid concepts have complicated the landscape. Consider Figure 3 below [2]. The generation, transmission, and distribution elements are hard to distinguish. The IEEE Grid Vision 2050 Roadmap decided to reframe these historical terms to Make, Move and Use [3]. Where “make” is roughly equivalent to generation, “move” is roughly equivalent to transmission and distribution and “use” is roughly equivalent to a consumer or end user.

Figure 3 - Contemporary Grid

In the make area, there are many sources of generation: rooftop solar, wind, battery energy storage and electric vehicles which in some cases can be used as a source of energy. In contrast to the large thermal generation, renewable generation is dependent on weather (i.e., wind, solar). The generation is also located not only connected to transmission but may also be connected to the distribution system or even at the consumer location. In addition, these sources provide variable output based on weather conditions. Consequently, the sine wave being generated is much more variable than the spinning machines previously used. Furthermore, the generation itself uses power electronics instead of an electromechanical machine to generate a sine wave. Power electronics can introduce noise to the system at comparatively high frequencies. This will be discussed more in the section labeled What are supraharmonics?

In the move area, there are many locations that can produce power, which still needs to get to the locations where it is consumed. In some cases, as with battery storage, the power may flow in one direction at some times (for charging the batteries) and in the opposite direction at other times (to use the batteries as a source). In some cases, the power may move from the consumer back to the grid if the rooftop solar is providing excess capacity. Moreover, the utilities have deployed conservation voltage reduction (CVR) programs that intentionally to reduce voltage at the substation and thereby to reduce power consumed by the loads. To improve the voltage along the lines, capacitors have been installed for voltage support. However, these devices can also introduce harmonic resonance points on the grid. This effect will be discussed more in Effects of Harmonics on Power Systems.

In the use area, the loads have changed in many ways. Historically, consumer load was mostly linear thanks to resistive lighting and electric heating. Many utilities have incentivized high efficiency technologies. These technologies typically use some sort of active component that is coupled to the power system yet can be a source of distortion and can increase the overall noise on the grid. Government policy (at least in the US) has incentivized people to look beyond fossil fuels for traditional approaches in industries like transportation. Electric vehicles must be charged and the process of converting AC to DC to be used in the vehicles can be a source of noise. Finally, the digital economy has created a need for large data centers that can produce a lot of noise on the system.

In summary, the grid is changing, creating a new electrical environment where harmonics are much more common than in previous iterations of the grid. While the environment has changed, the emissions have changed, and the standards/limits have changed, our understanding of the consequences of those changes have yet to be fully understood.

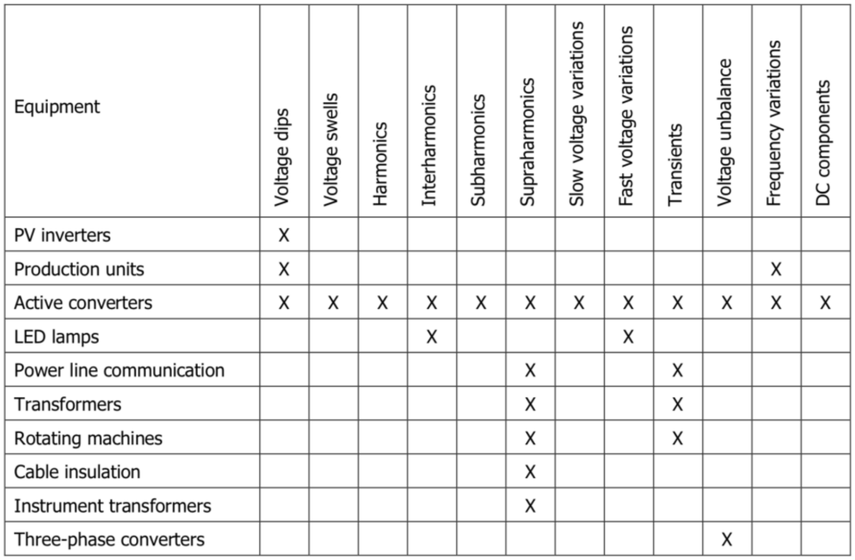
Why are harmonics important?

The grid is designed to operate at 50/60 Hertz. When other frequencies are present, this can lead to malfunction of electronic controls, thermal impacts to grid connected equipment, and in extreme cases, catastrophic failure of grid-connected equipment. This is covered in more detail in sections entitled Effects of Harmonics on Power Systems and Effects of Harmonics on Grid Connected Equipment.

How are harmonics generated?

Harmonics are generated by non-linear loads, which draw currents that are not proportional to the applied voltage and thereby distort the voltage waveform. Such loads include electronic switching devices such as computer power supplies, EV chargers, variable-frequency drives (VFDs), and LED lighting, arc welders and furnaces, and magnetic devices, such as motors and transformers. Table 1 below shows the equipment and typical emissions generated by those pieces of equipment [4].

Table 1 - Harmonic Types Generated by Equipment



Equipment	Voltage dips	Voltage swells	Harmonics	Interharmonics	Subharmonics	Supraharmonics	Slow voltage variations	Fast voltage variations	Transients	Voltage unbalance	Frequency variations	DC components
PV inverters	X											
Production units	X										X	
Active converters	X	X	X	X	X	X	X	X	X	X	X	X
LED lamps				X				X				
Power line communication						X			X			
Transformers						X			X			
Rotating machines						X			X			
Cable insulation						X						
Instrument transformers						X						
Three-phase converters										X		

What are harmonics?

Waveform distortion or deviation from a pure 50 Hz or 60 Hz sine wave are generically termed harmonics. These distortions are grouped into several categories: harmonics, interharmonics, subharmonics, and supraharmonics. These distinct categories sometimes leverage different measurement techniques. The limits for each of these categories are found in different standards.

Figure 4 shows a perfect 60 Hz sine wave. As distortion increases on a voltage sine wave, so does the probability of equipment malfunction or damage.

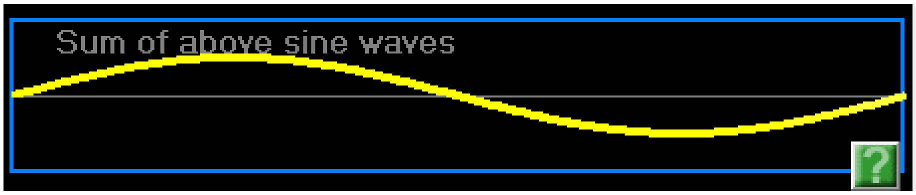


Figure 4 - Perfect 60 Hz Sine Wave

Harmonics are defined as “Components of order greater than one of the Fourier series of a periodic quantity.” For example, in a 60 Hz system, the harmonic order three, also known as the “third harmonic,” is 180 Hz. [5] In the case of the power system, the fundamental frequency is 50 or 60 Hertz. Typically, a harmonic component is referred to as the harmonic order it represents. Odd harmonics are generated during normal operation of nonlinear passive loads. Even harmonics though rare, are important because they are not symmetric and indicate a DC offset in the voltage, which can cause severe malfunction in transformers.

Figure 5 shows the perfect sine wave above with a second harmonic added. The second harmonic doubles the frequency of the fundamental. This results in a negative sequence current flowing in the electrical circuit. The negative sequence creates heating in motors and transformers because it creates a magnetic field that rotates in the opposite direction to the fundamental voltage's magnetic field. Other negative sequence harmonics are the fifth, and eighth harmonic.

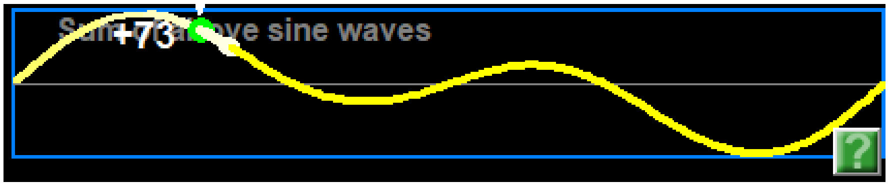


Figure 5 - 2nd Harmonic

Notice in Figure 6 below, that by introducing a modest amount of third harmonic to the perfect sine wave that the waveform has been distorted. The third harmonic is also part of a series of harmonics called "Triplen" harmonics. These are harmonics that are multiples of three from the fundamental frequency (e.g., 3rd, 6th, 9th). These harmonics generate zero sequence current in the power system and can be quite damaging [6], since they are in phase on all three phases and typically flow in the neutral of a three-phase system.

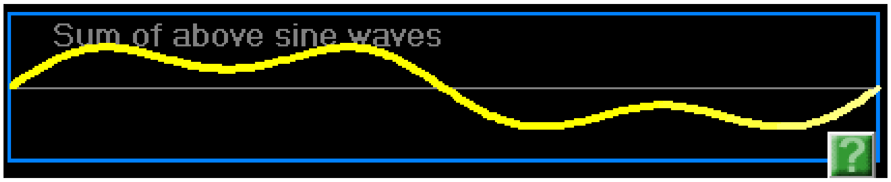


Figure 6 - 3rd Harmonic

The positive sequence harmonics (e.g., 4th, 7th, 10th) rotate in the same direction as the fundamental frequency. These can also create heating in transformers and motors. In motors, they may assist with torque output as the harmonics are moving in the same direction as the fundamental.

Often, multiple harmonic frequencies are present. This is often summarized in a couple of ways. The first way is to define the total harmonic distortion (THD) of the waveform. THD is defined as "The ratio of the root-mean-square of the harmonic content, considering harmonic components up to the 50th order and specifically excluding interharmonics, expressed as a percent of the fundamental [5]." In the case above, the THD would be about 40%.

$$THD = \sqrt{\frac{\sum V_{harmonics}^2}{V_{fundamental}^2}} = \sqrt{\frac{20^2}{49^2}} = \sqrt{\frac{400}{2401}} \approx 40\%$$

Equation 1 - THD Calculation

As additional harmonics are added, it can be helpful to look at a spectrum associated with the measurement to understand what the dominant frequencies are. Figure 7 shows the harmonic spectra associated with three different wind turbines [4]. Each harmonic order corresponds to a particular frequency.

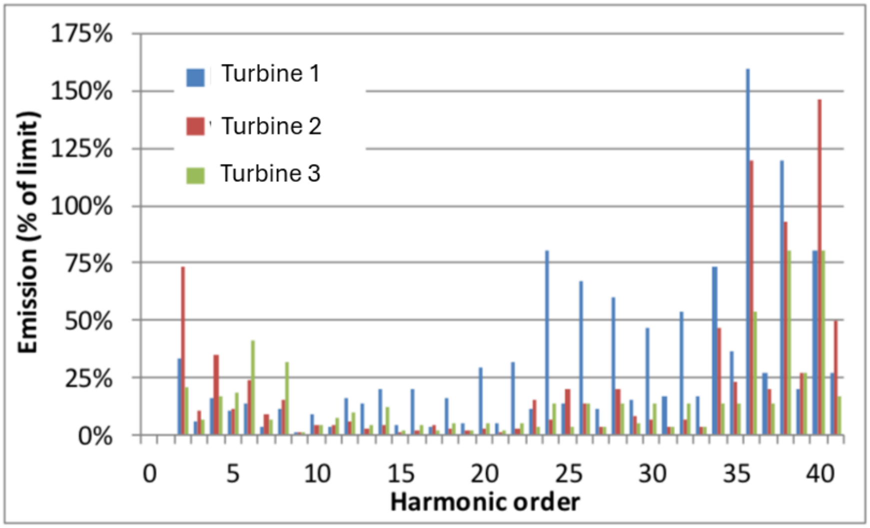


Figure 7 - Harmonic Spectra

What are interharmonics?

Sometimes distortion to the waveform occurs at non-integer harmonic orders from the fundamental frequency. These typically occur with active switching circuits that operate at frequencies not related to the fundamental power frequency. For example, if a 50 Hz system has a distortion with a frequency of 130 Hz, this is a frequency that is a non-integer fundamental. The nearest harmonic order would be the third harmonic which has a frequency of 150 Hz. Figure 8 shows the frequency response curve [7]. The curve shows the harmonic frequencies (e.g., 50, 100, 150), but also shows the frequencies that make up the distortion that are not multiples of the fundamental. In some cases, these can be significant contributors to the overall distortion of a waveform.

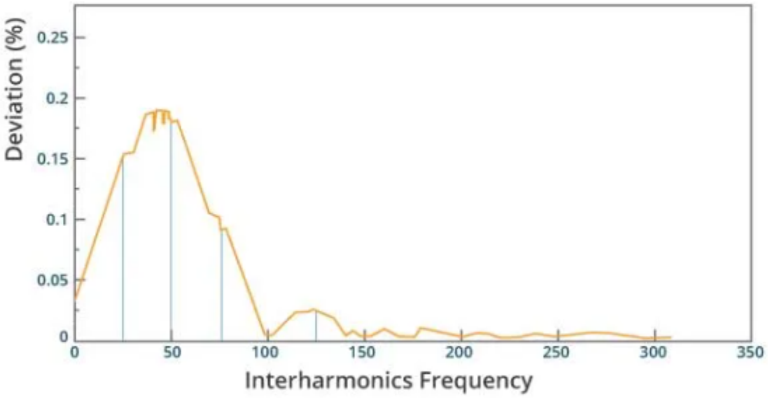


Figure 8 - Frequency Response

What are subharmonics?

When distortion to a waveform occurs at a frequency below the fundamental, this is known as a sub-harmonic. Figure 9 shows a graph of subharmonic spectra [8]. The emissions occur at approximately 12 Hz which is well below the system frequency of 60 Hz.

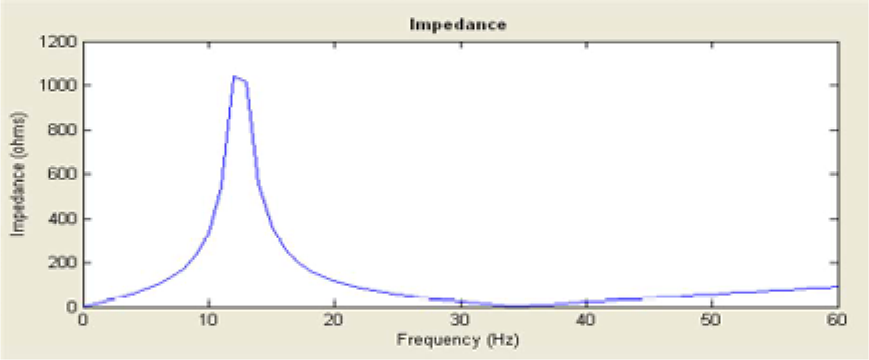


Figure 9 - Subharmonic Spectra

What are supraharmonics?

Supraharmonics are distortions that occur in power systems when the frequencies are between 2 kHz and 150 kHz. Figure 10 shows a trend of supraharmonics that were observed at an electric vehicle charging station. There are a variety of frequencies present that are being trended over time. Since multiple frequencies are being tracked (y-axis), the color represents the intensity of the distortion in that frequency band (in the background of the image). While the foreground shows trends over time for each of the different harmonic voltages.

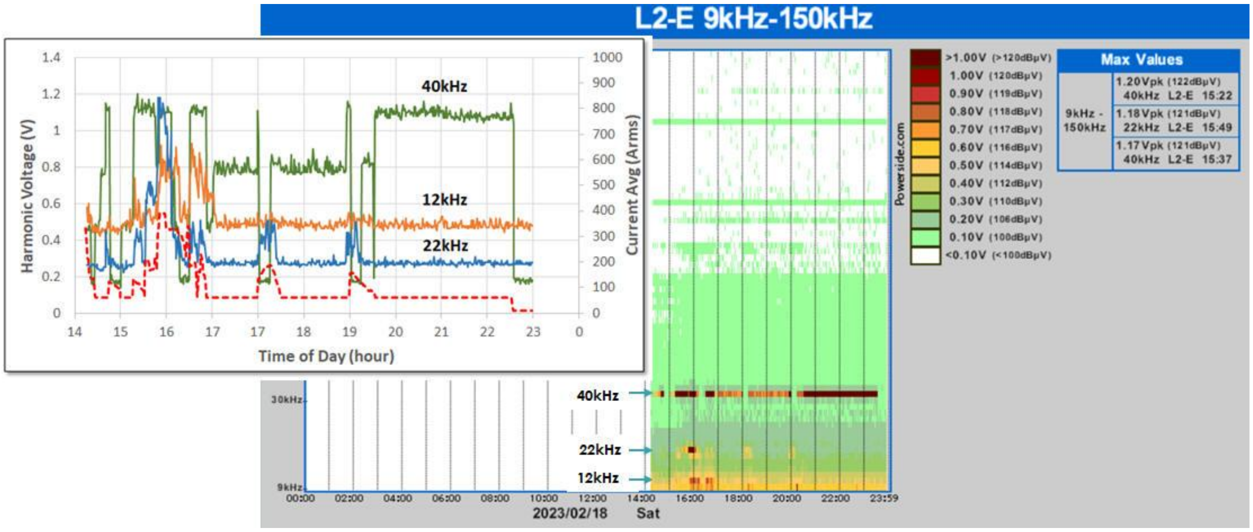


Figure 10 - Supraharmonics Trends – Captured by ORNL Field Trial

Harmonics Measurement

Measurement of harmonics involves three distinct aspects: sensor frequency response, sampling rate, and filtering.

Sensor Frequency Response

Almost all measurements of high voltage and high current are done through a potential or current instrument transducer, PT and CT respectively, to produce lower amplitudes (and energies) acceptable to recording devices. These devices utilize a variety of transduction technologies, including conventional iron-core transformers, Rogowski coils, optical coupling, resistive and capacitive dividers, or combinations. Typical distribution grid voltages start at 4,600 volts and transmission voltages can be as high as 700 kilovolts. Consequently, a transducer steps the voltage down from the operating voltage to a voltage that is safe for instrumentation. Most modern instrumentation expects voltages up to 600 volts. Figure 11 shows divider-type instrument transducers installed at a TVA substation.

Figure 11 – Three RC voltage dividers at a 161 kV TVA substation

The frequency response of a transducer is its ability to capture accurately the waveforms over a desired bandwidth including harmonics and transients of interest. Figure 12 shows the magnitude accuracy of a variety of different voltage transducers [4]. Because the sensors can have significant accuracy errors even below 5 kHz, care should be given to select a transducer to meet the measurement requirements.

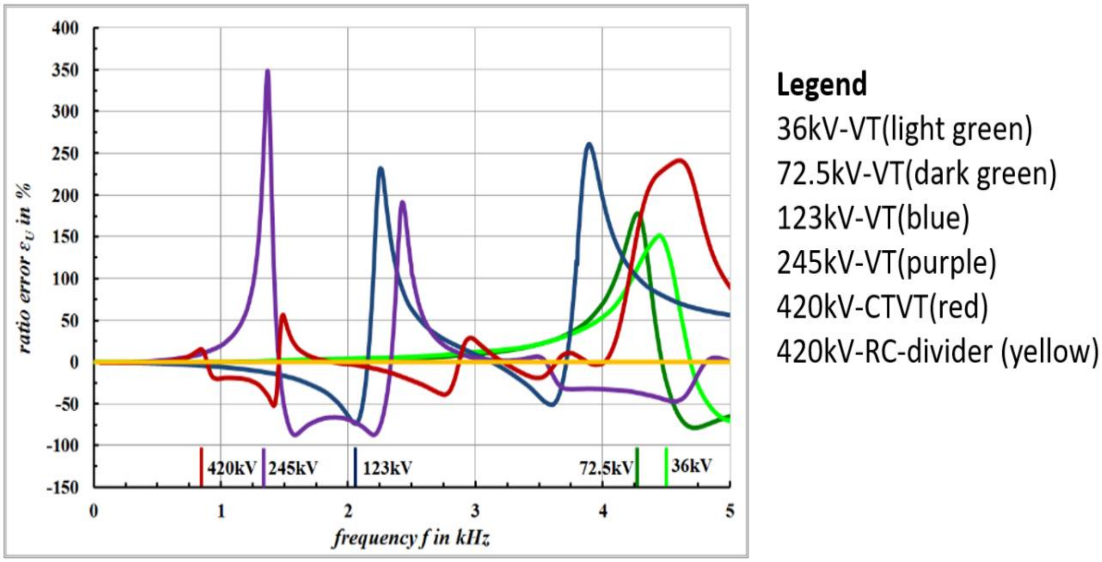


Figure 12 – Magnitude Accuracy at Different Frequencies for Multiple Transducers

Iron-core instrument transformers have very accurate transduction at the power fundamental frequency but typically exhibit resonances at frequencies that can exaggerate the effects of a voltage transient to a measurement device. Figure 13 directly compares an iron-core PT data recorded at the substation shown in Figure 11 with that from RC dividers. These RC dividers have been designed to exhibit a flat frequency response to beyond 10 kHz [4]. The figure shows that the iron-core PT has a resonance at approximately 2.8 kHz. The RC divider does not have a resonance condition and faithfully reproduces the transient step voltage change.

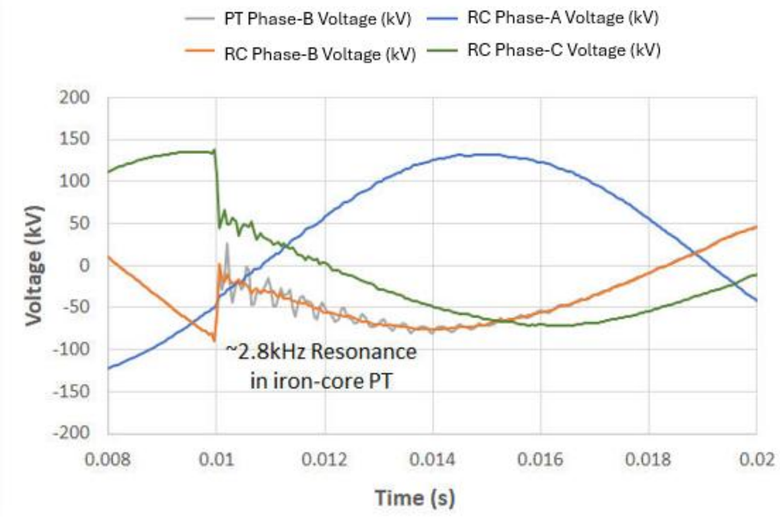
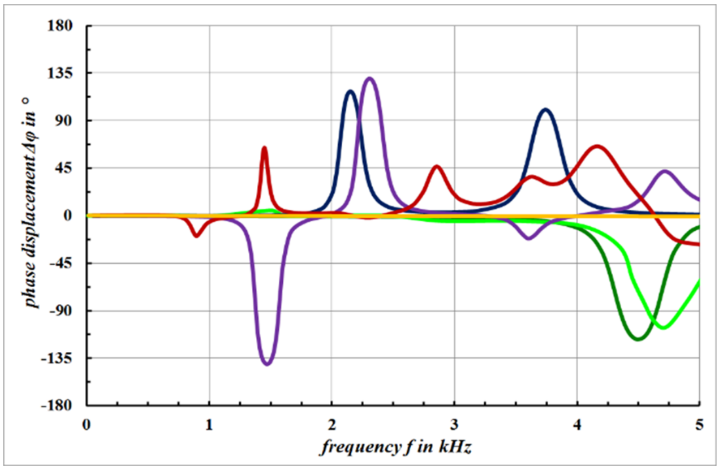


Figure 13 - Voltage Measurements Using RC Divider and Iron Core PT

In addition to magnitude errors, the sensors may produce an error in phase shift. Figure 14 shows the phase shift accuracy of several voltage transducers [4]. A change in phase displacement may alter the apparent magnitude of a transient based on the frequency.



Legend
36kV-VT(light green)
72.5kV-VT(dark green)
123kV-VT(blue)
245kV-VT(purple)
420kV-CTVT(red)
420kV-RC-divider (yellow)

Figure 14 - Phase Shift Accuracy

Sampling Rate

Many instrumentation systems rely upon analog-to-digital conversion (ADC) to process analog signals. ADCs sample the analog data and create a digital snapshot in time of the analog signal. The Nyquist rate is the minimum sampling rate that can be used to accurately describe and reconstruct a signal with minimal error and is double the frequency of the phenomenon of interest. Therefore, to measure a 60 Hz phenomenon the minimum sampling rate required is 120 Hz.

Since most of the energy on a power grid is at 50 or 60 Hz depending on the region, much of the measurement equipment installed to measure the grid was focused on 50 or 60 Hz phenomena. Consequently, the sampling rates for this equipment only needed to be 100 or 120 Hz to accurately describe the primary energy on the grid.

Today higher frequency components exist on the grid. In the case of supraharmonics, this may be as high as 150 kHz. To accurately describe the phenomenon, equipment with higher sampling rates is necessary since lower sampling rates may hide or obfuscate what is happening. Figure 15 below shows an event recorded at several different sampling rates. If a 375 Hz sampling was the maximum speed used to record the event, then the user might incorrectly think that the maximum voltage for the event was 133 volts while the actual maximum voltage was nearly 153 volts. The lower sampling rates also fail to show the ring down effect revealed in the 6 kHz recording.

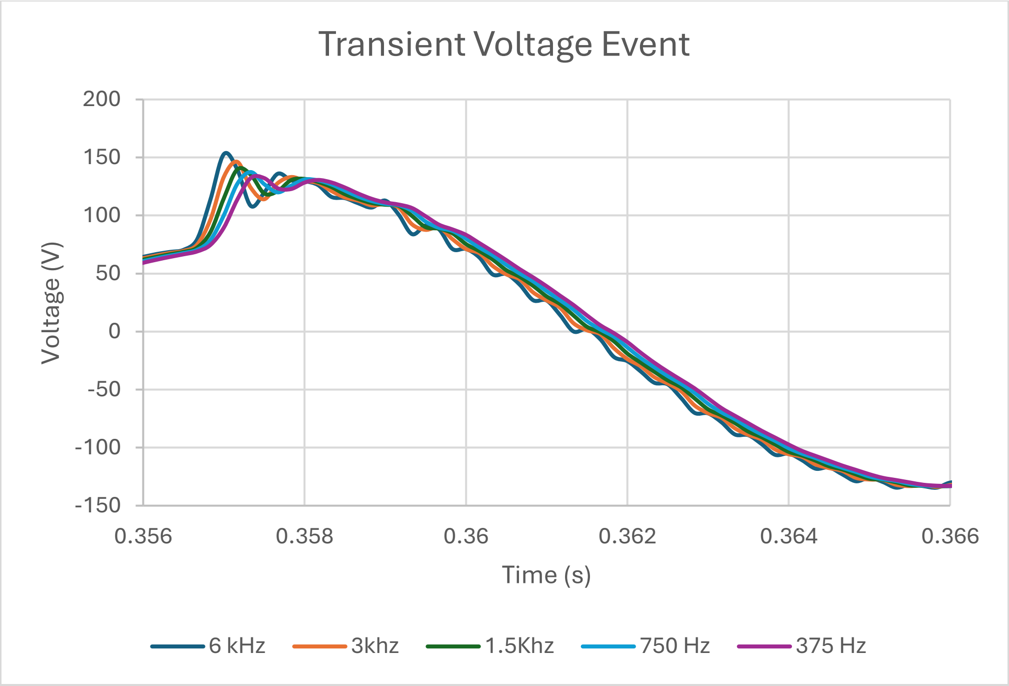


Figure 15 - Transient Event Captured at Different Sampling Rates

Filtering

ADC systems leverage anti-aliasing systems to remove higher frequency content from the signal. These filters are designed to remove components above the Nyquist rate of the instrumentation to eliminate aliasing. Aliasing occurs when frequency components present in a signal being sampled occur above the Nyquist rate. The components result in distortion if not filtered out. However, the filtering may also remove signals below the Nyquist rate.

Effects of Harmonics on Power Systems

Utilities are often obligated to ensure that harmonics do not cause deleterious effects on power system equipment. They do this by ensuring that equipment connected to the power system performs within acceptable limits. Harmonics can cause the following issues [9]:

- Capacitor fuse blowing
- Circuit breakers tripping
- Transformer overheating at less than full load
- Audible Noise

Harmonic resonance is a condition where a naturally occurring frequency in the power system matches the frequency of a current source. The result is an amplification of the voltage distortion at a particular frequency. Capacitors are often the culprit of the amplification. Figure 16 shows a scenario where different capacitor bank sizes create different resonance points [9].

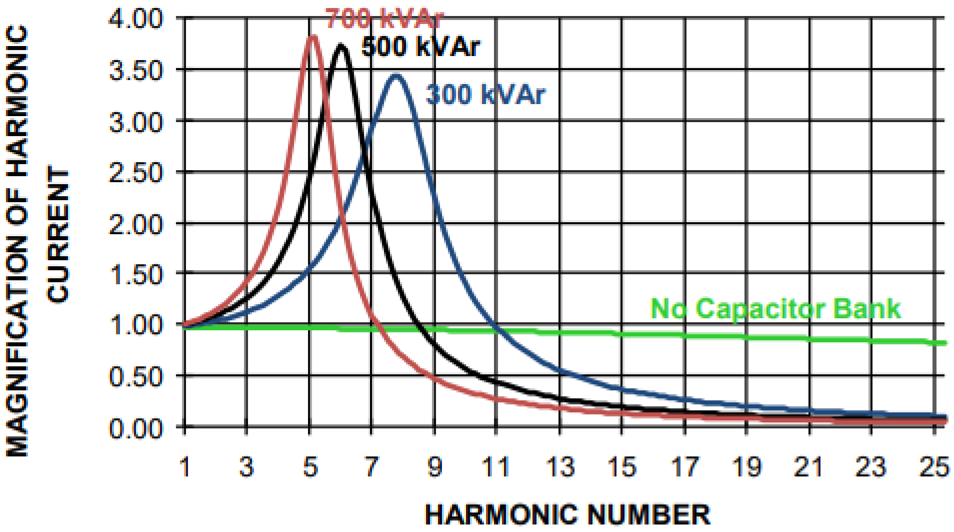


Figure 16 - Resonance vs. Capacitor Size

Effects of Harmonics on Grid Connected Equipment

Customers employing high-efficiency motors and other equipment within their facilities may be connected to the grid at transmission or distribution voltages. Typically, though, the voltages are reduced via one or more transformers at the customer service entrance. In large industrial facilities, multiple transformers may be used to supply the equipment in the facility with the necessary power to operate.

When harmonics are present, equipment may degrade or malfunction. Common problems are [9]:

- Motor overheating – which reduces motor life
- Equipment malfunction
- Capacitor or transformer failure
- Fuses blowing
- Breakers tripping unnecessarily
- Reduced transformer capacity
- Clocks running fast
- High neutral currents which can result in stray voltages
- Telephone interference

Harmonics Standards / Limits / Testing

Standards for measurement, limits, and testing of harmonic components are readily available for power systems. The following sections describe many of the standards though these are not comprehensive.

IEEE 519 – Limits

IEEE Standard 519 is entitled “IEEE Standard for Harmonic Control in Electric Power Systems”. The scope of the document is to establish recommended limits for distortion at the point of common coupling (PCC) between sources and loads. The standard also points to IEEE Std 1547 or IEEE Std 2800 for current distortion limits at inverter-based resource (IBR) installations. The standard leverages IEC 61000-4-7 for establishing how measurements should be made and specifies the limits to be applied at various voltage levels.

The standard asserts that managing harmonics is a joint responsibility between both end-users and system owners or operators. As such, the standard provides limits for both voltage and current distortion. Table 1 shows the voltage distortion limits from IEEE 519 at various bus voltage levels through the years. The limits are expressed in percent of the rated power frequency voltage.

Table 2 - Voltage Distortion Limits Over Time (%)

PCC Bus Voltage	<= 1kV		1 - 69 kV		69 - 161 kV		> 161 kV	
Year / Limit	Individual	THD	Individual	THD	Individual	THD	Individual	Total
1992	3	5	3	5	1.5	2.5	1	1.5
2014	5	8	3	5	1.5	2.5	1	1.5
2022	5	8	3	5	1.5	2.5	1	1.5

The standard also provides limits for harmonic current injection limits compared to the maximum load current at PCC. The standard assumes that by limiting the current harmonic injection that the voltage distortion can be kept below levels that would cause interference. Figure 17 shows the current distortion limits for systems rated 120v through 69kV from the standard [5]. The values are expressed in percent of the maximum demand load current. The standard has additional current distortion limits for higher voltage systems though they have not been reproduced in this document.

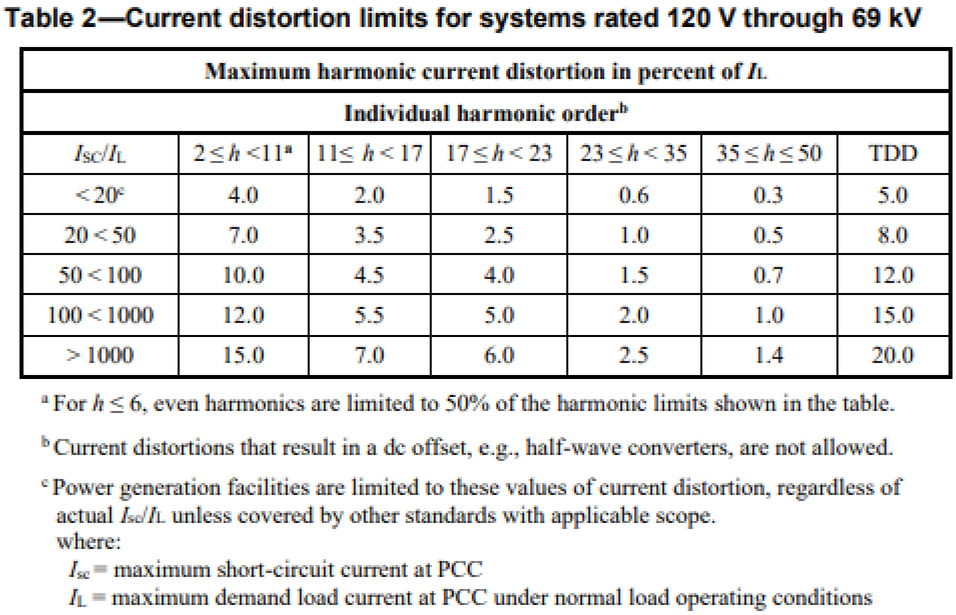


Table 2—Current distortion limits for systems rated 120 V through 69 kV

Maximum harmonic current distortion in percent of I_L						
Individual harmonic order[b]						
I_{SC}/I_L	$2 \leq h < 11$[a]	$11 \leq h < 17$	$17 \leq h < 23$	$23 \leq h < 35$	$35 \leq h \leq 50$	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

[a] For $h \leq 6$, even harmonics are limited to 50% of the harmonic limits shown in the table.

[b] Current distortions that result in a dc offset, e.g., half-wave converters, are not allowed.

[c] Power generation facilities are limited to these values of current distortion, regardless of actual I_{sc}/I_L unless covered by other standards with applicable scope.
where:
I_{sc} = maximum short-circuit current at PCC
I_L = maximum demand load current at PCC under normal load operating conditions

Figure 17 - Table 2 with Footnotes from IEEE 519-2022

To comply with the voltage and current limits, these percentages must be below the limit 95% of the time for 10-minute averages to be compliant with the standard. The evaluation period should be a minimum of 7 days to assess compliance.

IEC 61000-4-7 – Measurement

The IEC Standard 61000 Part 4-7 is entitled “Testing and measurement techniques – General guide on harmonics and interharmonics measurements and instrumentation, for power supply systems and equipment connected thereto”. The scope of the document is to define measurement instrumentation in accordance with emission limits given in other standards (e.g., IEEE 519). The standard applies to frequency ranges up to 9 kHz and is applicable to both 50 and 60 Hz systems.

The standard provides for two classes of accuracy (I and II). Class I instruments are recommended for precise measurements as the allowable maximum error is lower. Class II instruments are recommended for survey or in cases where the increased uncertainty is not likely to produce problems. The standard also specifies the use of filtering of frequencies outside the measurement range. The standard provides guidance on grouping and smoothing of spectral components of the sampled signal.

IEEE 1547 – Limits for DER on Distribution

IEEE Standard 1547 is entitled “IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces”. The scope of the document is to establish requirements for interconnecting distributed energy resources with electric power systems. The requirements apply at the time of interconnection and remain active as long as the DER remains in service.

The standard provides a series of requirements including those pertaining broadly to power quality and more specifically to harmonics. This document uses the term reference point of applicability (RPA) instead of point of common coupling. The main difference is that the RPA can be mutually agreed upon by the electric system operator and the DER operator.

This standard differs from IEEE 519 in that it expresses limits in terms of total rated current distortion (TRD) instead of total demand distortion (TDD). Essentially, 1547 bases distortion on the capacity of the DER system, I_{rated}, whereas 519 bases distortion on the demand, I_L. Tables 26 (odd harmonics) and 27 (even harmonics) in the standard specifies limits in percent of the DER unit rated current capacity [10]. TRD is defined in equation 2 of the standard. Table 26 is shown in Figure 18 below.

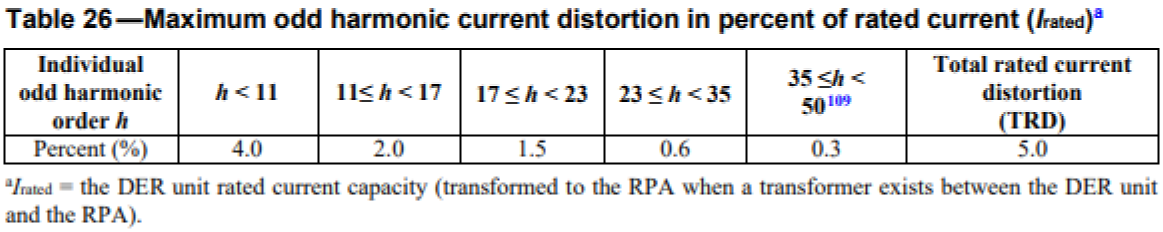


Table 26—Maximum odd harmonic current distortion in percent of rated current (I_{rated})[a]

Individual odd harmonic order h	$h < 11$	$11 \leq h < 17$	$17 \leq h < 23$	$23 \leq h < 35$	$35 \leq h < 50$[109]	Total rated current distortion (TRD)
Percent (%)	4.0	2.0	1.5	0.6	0.3	5.0

[a] I_{rated} = the DER unit rated current capacity (transformed to the RPA when a transformer exists between the DER unit and the RPA).

Figure 18 - Table 26 from IEEE Standard 1547

Finally, the standard specifies that the limits are exclusive of any harmonic currents that result from harmonic voltages that were present before the DER was connected. This ensures that the electrical environment had limited noise before connecting the DER. The standard also allows the DER to be used as an active filter and can exceed the harmonic current limits when used in this manner.

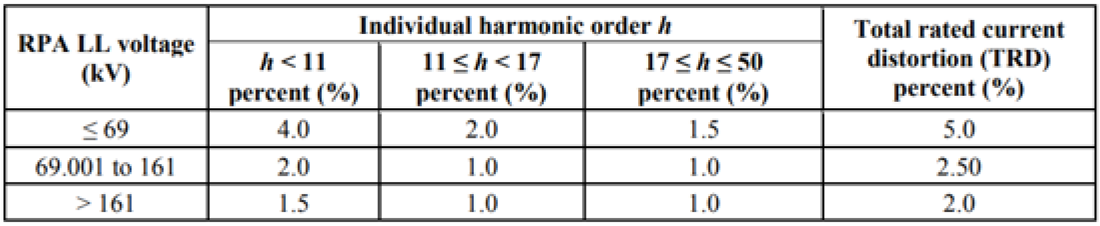
IEEE 2800 – Limits for DER on Transmission

IEEE Standard 2800 is entitled “IEEE Standard for Interconnection and Interoperability of Inverter-Based Resources (IBRs) Interconnecting with Associated Transmission Electric Power Systems”. The scope of the document is to establish requirements for interconnecting inverter-based resources with bulk (a.k.a. transmission) power systems. This includes high-voltage direct current (HVDC) applications.

Similarly to IEEE 1547,the standard provides a series of requirements and specifications for connecting IBRs to the transmission system including power quality and harmonics. This document also uses the term reference point of applicability (RPA) instead of point of common coupling.

Neither IEEE 1547 nor IEEE 2800 specify voltage distortion limits. In the case of IEEE 2800-2022, the standard declares “At the time of development of this standard, there is no consensus on industry accepted harmonic voltage distortion limits. Harmonic voltage limits or requirements are recommended to be established in a possible future revision of this standard following more research and industry discussion.” [11]

The standard prescribes different limits based on voltage class. While the limits differ from IEEE 1547, the approach to calculating the harmonic contribution is the same. Figure 19 shows table 17 from the standard. The harmonic contribution from even order harmonics is prescribed as 1%, 2%, and 3% for the 2nd, 4th, and 6th harmonic orders, respectively.



RPA LL voltage (kV)	Individual harmonic order h			Total rated current distortion (TRD) percent (%)
	$h < 11$ percent (%)	$11 \leq h < 17$ percent (%)	$17 \leq h \leq 50$ percent (%)	
≤ 69	4.0	2.0	1.5	5.0
69.001 to 161	2.0	1.0	1.0	2.50
> 161	1.5	1.0	1.0	2.0

Figure 19 - Table 17 from IEEE Std 2800-2022

IEEE 1409 – Mitigation

IEEE Standard 1409 is entitled “Guide for Technology Methods for Power Quality Improvement in Electric Power Systems”. The scope of the document is to provide an overview of approaches for mitigating power quality issues including harmonics. The guide begins by describing how often various power quality issues occur. Next, the guide provides a list of possible solutions for each phenomena type. Finally, the guide provides some case studies on various harmonic compensation projects.

The standard provides optics on the frequency that harmonics issues occur as provided by the EPRI DPQ project which recorded data from ninety-five substations between 1993 and 1995. At the time, the substation average voltage THD was 1.35% while the feeder average THD was 1.68%.

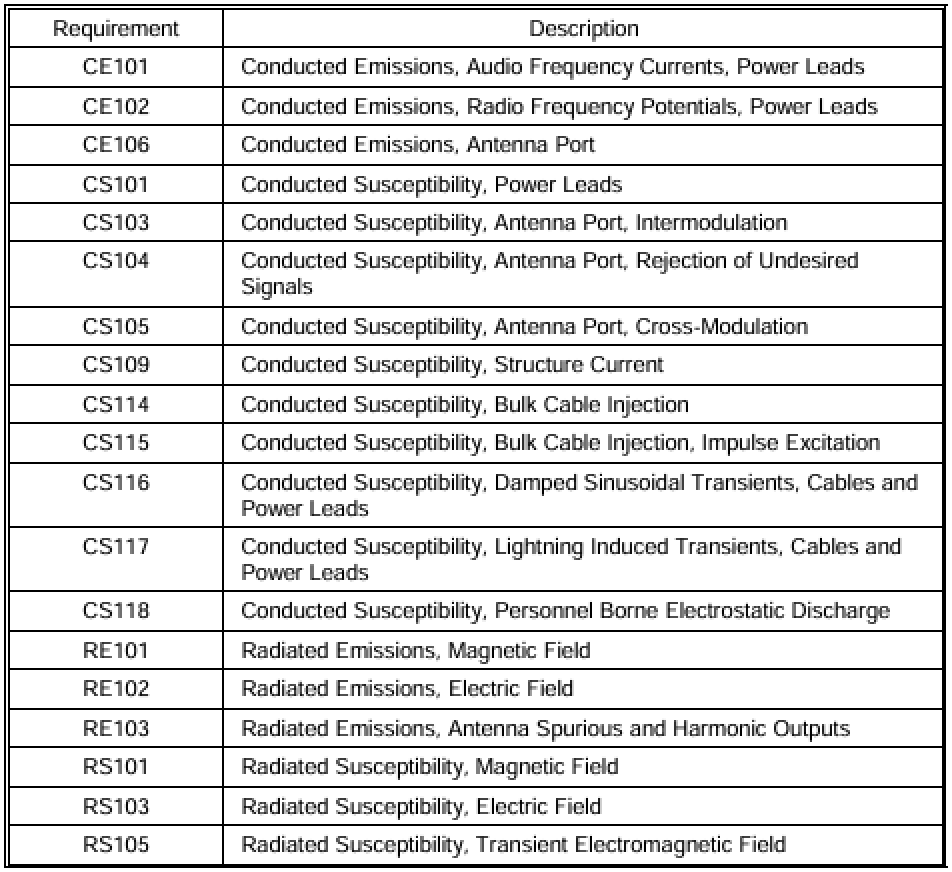
The guide suggests a few different harmonic compensation devices. The static shunt compensator (STATCOM) combines voltage source inverters with a standard distribution shunt transformer. This approach is capable of injecting high frequency waveforms to cancel the current harmonics generated by non-linear loads. Meanwhile, the static var compensator (SVC) combines a thyristor-controlled reactor or a switched capacitor to turn on the reactive element with fine grained detail. In some cases, the SVC will include a fixed set of capacitors to provide additional harmonic filtering.

The guide provides two case studies. The first case study involved a rock crushing operation that wanted to add a third production line where several motors were to be added to the existing facilities near seventeen motors. Prior to construction, models of the facility revealed that starting multiple motors would have negative impacts on the facility voltage. The solution was the installation of a STATCOM device to provide voltage and VAR support for the motor starting operations. The second case study described a marine cargo terminal that leveraged several rail-mobile cranes to move cargo to and from the ships. The customer had very severe power factor penalties. The solution was to install an SVC. The SVC was used to improve the power factor and reduce the facility billing.

Mil-STD-461 – Military Requirements

MIL-STD-461 is entitled “REQUIREMENTS FOR THE CONTROL OF ELECTROMAGNETIC INTERFERENCE CHARACTERISTICS OF SUBSYSTEMS AND EQUIPMENT”. The Department of Defense (DoD) interface standard establishes requirements for the control of electromagnetic interference (EMI) for systems deployed by the DoD. It specifies conducted and radiated emission limits as well as susceptibility of equipment. The standard specifies testing emissions at several frequency ranges starting at 30 Hz and continuing above 1 GHz. The standard also requires susceptibility testing from 30Hz to 40 GHz. The emissions are broken down into requirements subsets as shown in Table 3.

Table 3 - MIL-STD-461G, Table 4 Requirements



Requirement	Description
CE101	Conducted Emissions, Audio Frequency Currents, Power Leads
CE102	Conducted Emissions, Radio Frequency Potentials, Power Leads
CE106	Conducted Emissions, Antenna Port
CS101	Conducted Susceptibility, Power Leads
CS103	Conducted Susceptibility, Antenna Port, Intermodulation
CS104	Conducted Susceptibility, Antenna Port, Rejection of Undesired Signals
CS105	Conducted Susceptibility, Antenna Port, Cross-Modulation
CS109	Conducted Susceptibility, Structure Current
CS114	Conducted Susceptibility, Bulk Cable Injection
CS115	Conducted Susceptibility, Bulk Cable Injection, Impulse Excitation
CS116	Conducted Susceptibility, Damped Sinusoidal Transients, Cables and Power Leads
CS117	Conducted Susceptibility, Lightning Induced Transients, Cables and Power Leads
CS118	Conducted Susceptibility, Personnel Borne Electrostatic Discharge
RE101	Radiated Emissions, Magnetic Field
RE102	Radiated Emissions, Electric Field
RE103	Radiated Emissions, Antenna Spurious and Harmonic Outputs
RS101	Radiated Susceptibility, Magnetic Field
RS103	Radiated Susceptibility, Electric Field
RS105	Radiated Susceptibility, Transient Electromagnetic Field

This standard is a requirement for military applications and may be useful for configuring a test environment to test the emissions from a device in addition to the susceptibility of a component or device.

ANSI C63.4 – Measurement, Facilities, Test Equipment

IEEE/ANSI C63.4 is entitled “American National Standard for Methods of Measurement of Radio-Noise Emissions from Low-Voltage Electrical and Electronic Equipment in the Range of 9 kHz to 40 GHz”. The scope of the document is to provide methods, instrumentation, and facilities for measurement of *radiated* emissions (rather than *conducted* emissions) in the 9 kHz to 40 GHz range. The standard applies to all sizes of devices and can apply to a single device (e.g., cell phone) or groups of devices (e.g., servers in a data center). The standard is generic and may not be applicable to some specific industrial, scientific, and medical equipment. The standard provides guidance on measurement instrumentation, test facilities, and approaches for some specific equipment types.

This standard overlaps with supraharmonics and may be appropriate for consideration during testing of equipment.

IEEE P473 – Site Surveys

IEEE P473 is entitled "Recommended Practice for an Electromagnetic Site Survey (10 kHz to 40 GHz". The scope of the document is to provide guidance on measuring noise between 10 kHz and 40 GHz. The guide primarily focuses on radiated emissions. The guide provides methods to plan a site survey. The guide can be applied to a variety of environments including industrial, commercial, aircraft, vehicles, and several other domains.

Since this standard applies primarily to radiated emissions it does not have direct applicability to the power system. However, the supraharmonics overlap the frequency range and therefore this may be an appropriate standard to reference if considering supraharmonics.

Case Studies

The following case studies have been divided between transmission and distribution. For most of the case studies, this distinction is sufficient. In one case, Solar Storm May 2024, the measurement was performed by a distributed sensor network on the distribution system. However, solar storms typically influence transmission assets. Consequently, the case study was put into the transmission category.

Distribution

As described earlier, the distribution system is historically where harmonic injection occurred. This was generally because the point of common coupling (PCC) between the consumer and the utility is where the harmonics were injected by nonlinear loads. The following case studies show that in some cases, the consumer still produces or is responsible for the harmonics, while in other cases, the utility has deployed technology that is the source of harmonics.

Chicago

In January of 2024, Whisker Labs deployed firmware to an entire fleet of IOT sensors (~700k sensors across North America) [12] which added the ability to record the voltage THD. Most of the country was found to be well within IEEE 519 limits. However, there were a few hotspots around the country. Upon closer inspection, these hotspots were not necessarily regional but were found to be more localized to specific feeders or substations. Figure 20 shows the hotspots around the U.S.

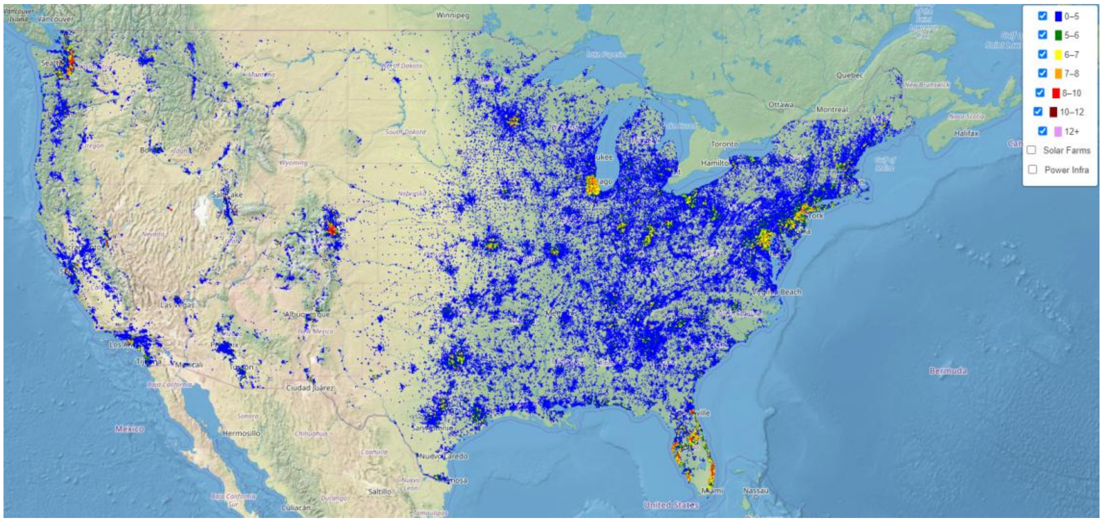


Figure 20 - THD Hotspots

The Chicago region generally showed significant THD values. Many of the sensors exceeded the IEEE 519 limit of 8%. While this appeared to be a systemic problem, it was not over the whole of the Chicago grid. Upon close inspection, there were groupings of higher THD areas. Figure 21 shows an enlarged view of the Chicago sensors. Each dot represents the THD as measured at each sensor.

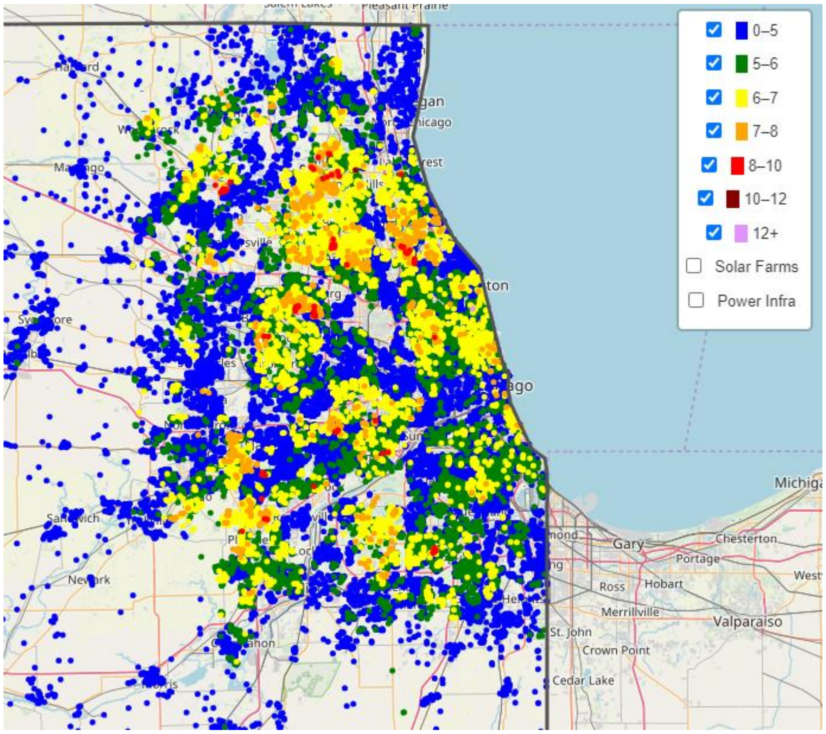


Figure 21 - Sensors in Chicago

Figure 22 shows THD trends from several of the sensors in a geographically close area of Chicago. Each line represents a measurement from a different sensor. Several of the sensors have alignment in the THD measurements. This suggests that the harmonic distortion is coming from the grid.

While the sensors are geographically close, they are clearly on different feeders. Some of the feeders exceed 8% during parts of the day, while other feeders are well within the IEEE 519 limit.

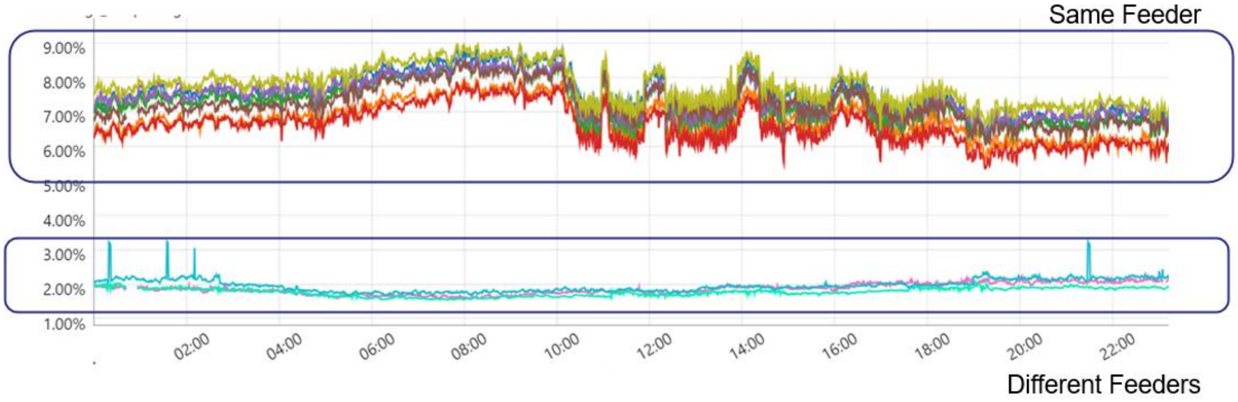


Figure 22 - THD Trend at Geographically Close Sensors

In this case, ComEd, the utility supplier for the Chicago area, had deployed a conservation voltage reduction (CVR) program to improve energy efficiency. CVR programs typically lower the voltage at the substation which can result in customers near the end of the feeder receiving voltage that is too low. Consequently, a frequent practice with CVR programs is to install capacitor banks along the distribution feeder to help ensure the voltage is within acceptable limits. In this case, the capacitors may be creating resonance conditions that increase THD along the line.

EV Charging

In February of 2023, ORNL in cooperation with Electric Power Board of Chattanooga (EPB) installed a power quality monitoring system at EPB's Ooltewah substation. This location was chosen specifically because of the recently installed charging station and battery energy storage device that were connected to a 2MVA transformer to the substation.

The study monitored both harmonics and supraharmonics. During the study supraharmonics were observed to be present during the charging cycle. Figure 10 shows the supraharmonics collected. Several frequency bands were observed in the data. There was a 40 kHz, 22 kHz, and 12 kHz trend observed. The 40 kHz band reached about 1.2 V during periods of operation.

Harmonic voltage and current reports were generated from December 2023, through April, 2024 [13]. The reports showed that the substation passed voltage harmonic limits for both the THD and the individual harmonics up to the 50th harmonic. The substation also passed the current harmonic limits for both TDD and the individual harmonics up to the 50th harmonic. While the TDD was well within the limit (5%), the trend line for TDD increased over the period measured, suggesting the importance of continuing to monitor the location for issues.

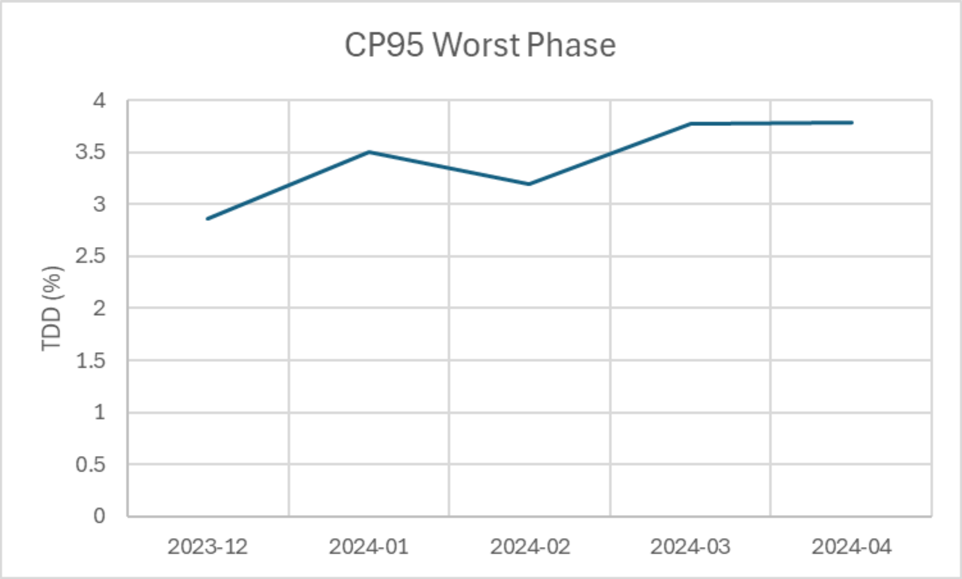


Figure 23 - TDD From ORNL Reports

PV Case Studies

Southern Company and TVA both conducted studies on inverter-based (IBR) generation connected to their respective grids [9]. In both cases, the companies found that the transmission-connected IBR did not create excessive distortion on the power system. However, both companies observed that the PV plant had deployed capacitor banks in conjunction with the IBR to support reactive power control.

In both cases, excessive harmonic currents were observed when the capacitor banks were switched online. Figure 24 shows the IEEE limit was exceeded when the capacitor bank was switched online at a facility in the Southern Company operating region. The root cause was determined to be a parallel resonance condition. In one case, a filter bank was deployed to remediate the harmonic injection. In a separate case, the firmware of the IBR was modified to reduce the harmonic injection.

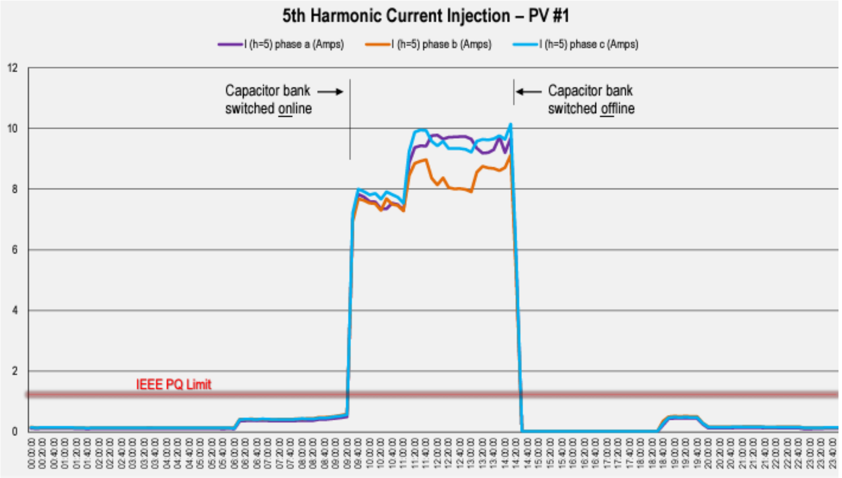


Figure 24 - Current Harmonic Injection

Transmission

The ramifications of harmonic distortion on the transmission system may have widespread impacts. Unsurprisingly, the limits of THD on transmission voltages are necessarily lower than on distribution. For example, IEEE 519 prescribes a THD of less than 1.5% for voltages more than 161kV.

Harmonic Resonance

In April of 2016, excessive voltage caused a variety of substation equipment to fail [14]. The excessive voltage was caused by a harmonic resonance condition between the substation capacitor banks at a remote substation and a harmonic load at the local substation. The transmission system in the area was also being operated in an unusual configuration as part of a fossil plant retirement effort.

Figure 25 shows a single line of the system configuration at the time of the event. As the diagram shows, the local generation station was isolated from the local substation. This served to reduce the system strength at the local station. The remote substation had two capacitor banks used to support the voltage during the plant outage. A large industrial customer with a 24-pulse rectifier was connected to the local substation. The system voltage was 161kV.

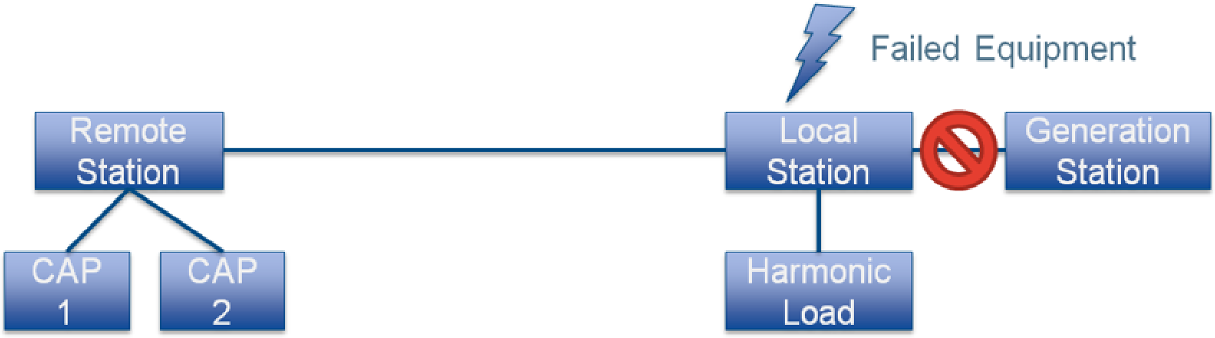


Figure 25 - System Configuration

Figure 26 shows the voltage in the hours leading to the equipment failure. Initially, it was unclear why the voltage at the local substation was at 200kV (124% of nominal). The system operators indicated that all the SCADA telemetry indicated that the voltage was around 161kV. Later inspection revealed that the SCADA systems were using RMS fundamental normalized values which ignored any higher order harmonics.

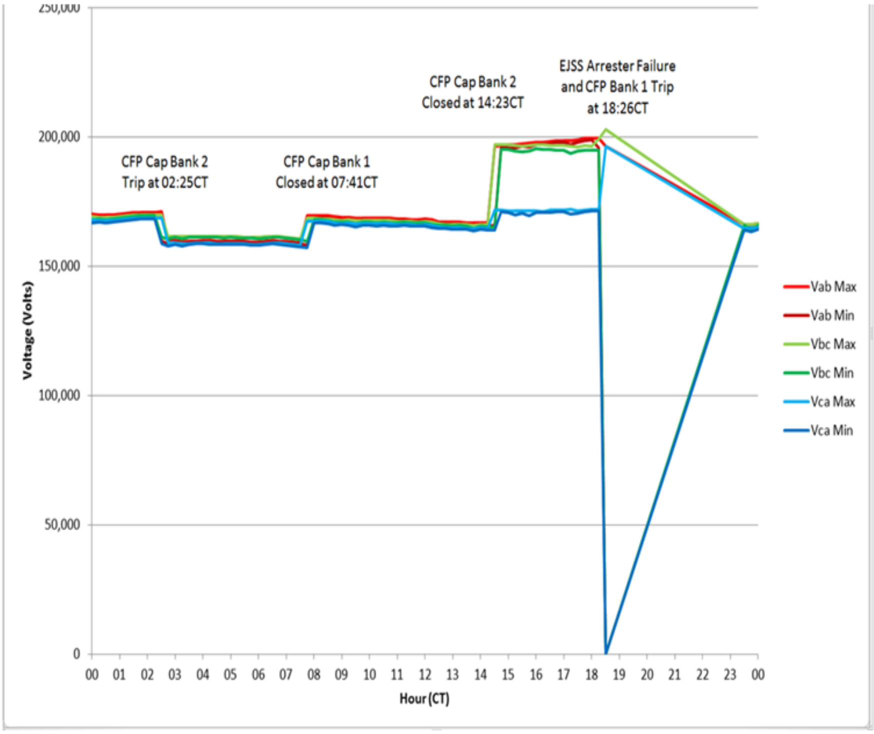


Figure 26 - Voltage at Local Station

As Figure 26 shows, the voltage was at approximately 200 kV for approximately 4 hours, at which time the 161kV lightning arrester failed catastrophically. Figure 27 shows the damage to the station equipment.

Figure 27 - Failed Station Equipment

The investigation revealed that there were two components to the issue. The first was the abnormal bus configuration which led to a reduction in the ability of the system to consume harmonic currents on the local bus. Harmonic current distortion limits are set in IEEE 519, Table 3 and are limited by the short circuit ratio of the bus serving the load. The ratio at the location station was 156 when the local generation was in service. However, the ratio dropped to around nine without the generation in service. This meant that the Total Demand Distortion (TDD) was also reduced from 7.5 to 2.5.

The second component to the failure was a resonance condition between the remote capacitor banks and the 24-pulse rectifier of the industrial facility. Figure 26 showed when both capacitor banks at the remote substation were switched on the voltage increased to nearly 200kV. Further investigation revealed that the harmonic current was approximately 74 amps compared to 150 amps of total load. Nearly all (73 amps) of the harmonic distortion was centered on the 23rd harmonic. The current waveform is shown in Figure 28.

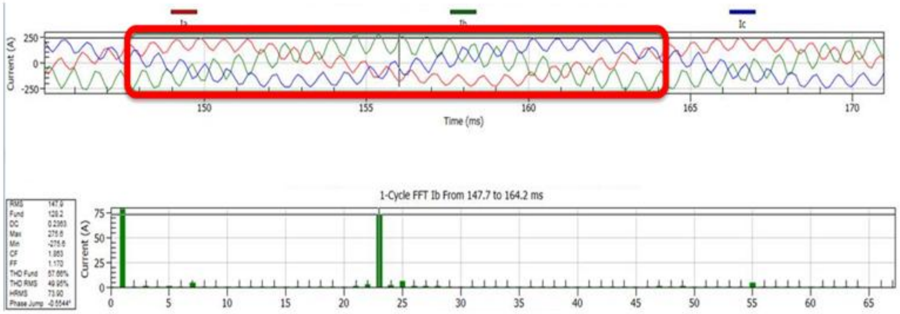


Figure 28 - Current Waveform

The interaction between the industrial equipment and the grid configuration was confirmed using electromagnetic transient (EMT) software. The model was also used to test different remediation strategies. Finally, it was decided that a special operating instruction should be developed whenever the local generation source needed to be removed from service.

Harmonic resonances are common at lower frequencies (e.g., 300 Hz). Particular care is often given to grid-connected equipment which operates near those frequencies and filters are often put in place to limit current injection and mitigate resonance conditions. Resonance conditions from the system at higher frequencies is uncommon and the industrial process had chosen 24-pulse inverters at the utility recommendation. Prior studies had not revealed a potential resonance condition at this frequency.

Solar Storm May 2024

The Sun's magnetic field flips every eleven years in what is known as a solar cycle [15]. Near the maximum of the solar cycle, sunspot and coronal mass ejection (CME) activity increases. CMEs are large plasma and magnetic field expulsions from the Sun's corona that create large currents near the earth. Figure 29 shows several CMEs from the Sun as captured by the National Oceanic and Atmosphere Administration (NOAA) [16].

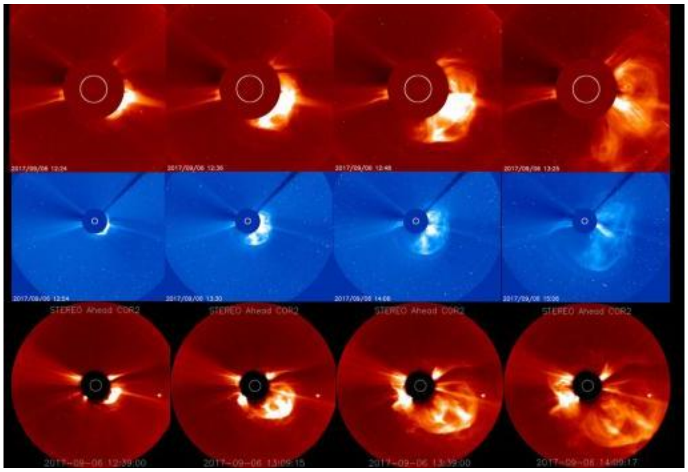


Figure 29 - CME

CMEs can cause geomagnetic disturbances (GMD), a disturbance in the Earth's magnetosphere. As the GMD progresses, it may cause geomagnetically induced currents (GIC) which may negatively impact the power grid by induction. Transmission lines act as a conductive path for GIC which may induce quasi-DC currents in transformer neutrals. Excess current in the transformer neutral can saturate the transformer's magnetic core. In such cases, harmonics may be created on the power system.

In May of 2024, NOAA measured a CME that interacted with the Earth's magnetosphere. Figure 30 shows the Kp index during a four-day period [17]. NERC considers a Kp index greater than seven as significant. For approximately two days the Kp index was more than seven.

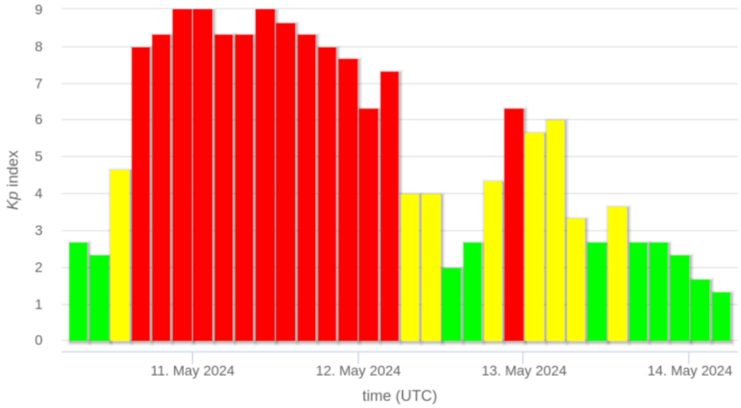


Figure 30 - Kp Index During May Storm

At the same time, the sensor network detected elevated THD measurements across seven northern states: Arkansas, Maine, Minnesota, New York, and Washington. Figure 31 shows the THD trends for the sensors. Conspicuously, the THD measurements during the solar event were extremely elevated. The IEEE 519 limit for THD is 8% for systems with less than 1000V. During the storm, some locations experienced as high as 24% THD.

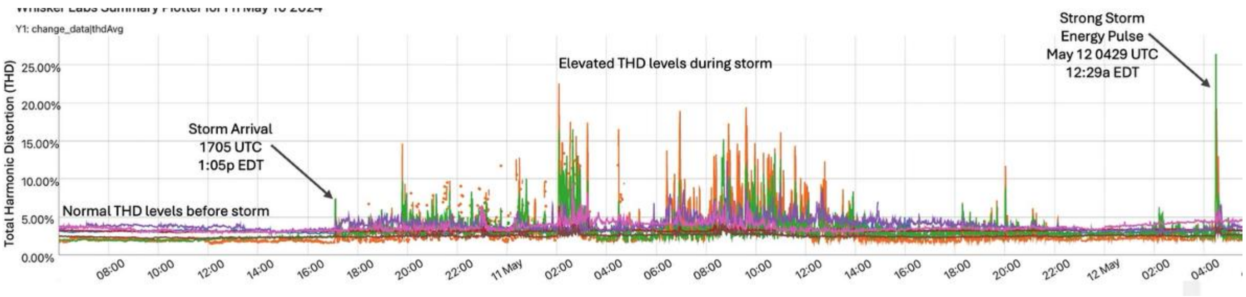


Figure 31 - THD Measurements During Solar Storm

While no significant outages were reported during the storm, the data shows that the grid was significantly influenced by space weather.

Conclusion / Next Steps

The grid is becoming a noisy place. There have been several standards developed to limit the emissions from grid connected equipment in both the conducted and radiated emissions frequency ranges. There is general understanding of the impacts of harmonics to grid connected equipment (heating, malfunctions, etc.). However, there is little qualitative data on how much harmonics the system can withstand before heating results in premature aging of grid infrastructure. There is even less information on the costs associated with harmonics on the grid. Consequently, research is needed to conduct a thorough evaluation of the impacts to better inform standards bodies about what limits can be set to without creating a compromised grid.

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