In-situ Frequency Response Measurements for Medium Voltage Sensors and Their Applications

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***Abstract*—Power system voltage can depart from its expected, nearly-clean sinusoidal waveshape due to various reasons, chief among them being the flow of harmonics of the fundamental frequency through system impedances. Traditionally, the phenomenon of harmonics has been associated with integer multiples of the power system frequency, typically up to the 50^{th} harmonic or $3\,\mathrm{kHz}$. As a result, most legacy Power Quality (PQ) monitoring systems sold in the United States (US) are designed to be accurate in this frequency range and most regulation is designed to restrict the flow of harmonics in this range. However, with the advent of inverter-interfaced Distributed Energy Resources (DER) and consumer load utilizing active power electronic switching, in addition to the traditional harmonics of the fundamental power system frequency, emission in the frequency range between 2 and $150\,\mathrm{kHz}$, also known as 'supraharmonics', is also being observed. In recent years, the high frequency emission from DER and other consumer electronic load has been associated with problems of Electromagnetic Interference (EMI) with other end use load. In the light of this change in the character of emission, it is not immediately clear if traditional voltage sensors can measure supraharmonics or the range up to which they can accurately do so. Further, it is not immediately clear how any limitations in measurement capability can be overcome in a timely and economic manner. This paper addresses this gap in knowledge and capability. In this paper, first the changing power system paradigm, and increasing grid complexity are analyzed. Next, the growing demands placed on voltage sensors in light of increasing grid complexity are examined. Finally, the paper shows practical measurements that demonstrate the limitations of legacy voltage sensors and discusses solutions to overcome these limitations.**

***Index Terms*—sensors, harmonics, high frequency, gain, solar PV**

I. Introduction

Traditionally, voltage and current harmonics have been associated with integer multiples of the power system frequency, typically up to the 50^{th} harmonic or $3\,\mathrm{kHz}$ [1], [2]. This is because traditionally, nonlinearities caused by magnetic circuits or by passive power electronic circuits contained dominant components in the frequency range up to $3\,\mathrm{kHz}$. As a result, most PQ monitoring systems and regulations use the $3\,\mathrm{kHz}$ value as a 'cutoff' i.e., most legacy PQ monitoring systems are designed to be accurate in this frequency range and most regulation is designed to restrict the flow of harmonics in this range. With the advent of inverter-interfaced Distributed Energy Resources (DER) and consumer load utilizing active power electronic switching, however, this situation has begun to change [3]. In addition to the traditional harmonics of the fundamental power system frequency, such devices also produce emission that is a byproduct of the high speed switching of the active power electronic switches they employ [4]–[9]. This emission, also known as 'supraharmonics', may or may not be synchronized to the fundamental system frequency and is typically produced by the device in the frequency range between 2 to $150\,\mathrm{kHz}$. In recent years, the high frequency emission from DER and other consumer electronic loads has been associated with problems of Electromagnetic Interference (EMI) with other end use load [10]–[12]. As a consequence, there is growing concern in the PQ community about regulating such emission. In this scenario, accurate detection and measurement of high frequency emission is of utmost importance. However, given the bandwidth limitations of existing sensors, such measurements are difficult to make and suspect in accuracy. Given the sheer number of such legacy sensors in the North American power system, sensor replacement and upgrade is an expensive and difficult proposition. This document details EPRI and TVA's attempts to bridge this gap in knowledge and capability.

In this paper, first the capabilities and limitations of existing voltage sensors are analyzed. Next, the growing demands placed on voltage sensors in light of increasing grid complexity have been examined. Finally, the paper addresses the problem of overcoming the measurement limitations of legacy voltage sensors. One solution in this regard is the characterization of voltage sensor frequency response. Based on this response, correction factors for high frequency measurements made by such legacy sensors can be developed. Finally, the document closes with a discussion of a cheap alternative detection method for high frequency emission which shows promise and can be possibly utilized in situations where sensor frequency characterization is not a possibility.

II. The Traditional Harmonics Paradigm

A. Historic perspective on power system harmonics

The topic of harmonics of the fundamental power system frequency is an old one and well understood and characterized in the PQ community. A mention of the word "harmonics", can be found in papers on alternating current theory at least

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as far back as 1903 [13]. Traditionally, it has been understood that any non-linearities in voltage or current give rise to harmonics and that harmonics in current and voltage can have adverse effects on utility grid infrastructure as well as end use load. These adverse effects include increased thermal stress in grid connected equipment and utility grid assets, increased insulation losses leading to a breakdown of insulation in cables and load disruption and misoperation in grid connected equipment [14], [15]. The sources of current and/or voltage harmonics are wide and varied. In the historical or 'traditional' context, harmonics have been associated with devices with magnetic saturation, arcing devices and devices with passive power electronic switching [15]. At the present moment, in addition to the traditional sources of harmonics, 'modern' sources have also emerged. These modern sources of harmonics are typically devices that utilize active power electronic switching.

This addition of 'modern' harmonics sources to the traditional harmonics paradigm has had profound effects on harmonic emission in the power grid, some of which have been grouped under the umbrella term of 'increased grid complexity'. Broadly speaking, this addition has represented a shift in the emission spectrum of harmonics from end use load. While 'traditional' harmonics sources typically produced emission in the frequency range up to the 50^{th} order ($3\,\mathrm{kHz}$ in a $60\,\mathrm{Hz}$ system), 'modern' sources of harmonics are typically capable of emitting much higher in the frequency range. This point can be better understood by analyzing measurements of emission from traditional harmonics sources and comparing and contrasting them against those from modern harmonics sources. As a part of this comparison, the emission from traditional harmonics sources is presented next.

B. Frequency signature of traditional harmonics

Fig. 1 shows the input current drawn by a diode rectifier circuit, which is the most basic power electronic circuit and used in a myriad number of applications, ranging from large industrial loads such as hydrogen electrolyzers to smaller consumer electronic load used domestically. The time domain waveform of this current shows a sharply non-linear characteristic, indicating the presence of harmonics. Indeed, the spectrum of this input current shows that it contains odd harmonics of the fundamental frequency. In addition, the harmonic spectrum indicates that the magnitude of the harmonics in current decreases with increasing frequency. This magnitude is inversely proportional to frequency and can be expressed as:

$$I_h \alpha \frac{1}{h}$$

In this equation, I_h is the current at a harmonic order 'h'. This equation indicates that, the current drawn by a diode rectifier will have significant harmonic content up to a certain harmonic number and the magnitude of harmonics will decrease with frequency, becoming insignificant after a point. It is worth mentioning that for diode rectifier circuits this point is usually taken to be around the 15^{th} to 17^{th} harmonic or around $1\,\mathrm{kHz}$. This is not a blanket rule however, and for large industrial converters, harmonics above this limit may sometimes become a concern.

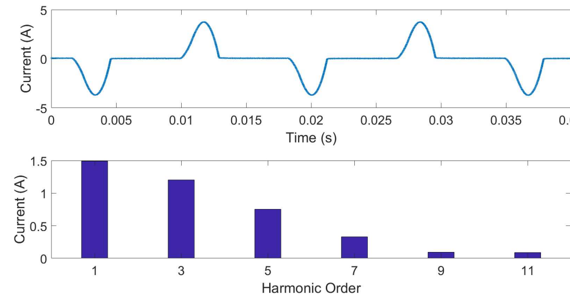


Fig. 1: Input current drawn by a diode rectifier circuit (top) and its frequency spectrum (bottom).

The particular point of harmonics of the fundamental frequency becoming insignificant after a certain frequency is not just restricted to passive power electronic circuits utilizing line commutated switches. In fact, other traditional loads such as the ones using saturable magnetic circuits also exhibit this behavior. An example of this is shown in Fig. 2, which shows the slot harmonics in the voltage produced by a diesel generator. As with the example shown in Fig. 1, the reader will notice that the spectrum of this voltage contains odd harmonic frequency components with magnitudes that diminish with increasing frequency. The magnitudes of the harmonics become nearly imperceptible beyond the 30^{th} harmonic in this particular instance.

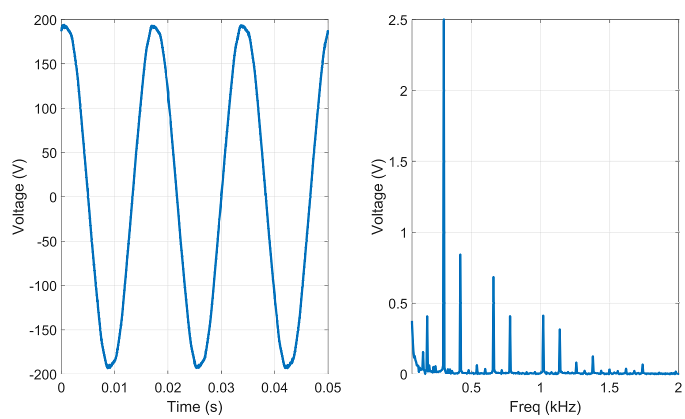


Fig. 2: Time domain waveform of phase A voltage produced by a Diesel Generator (left) and its spectrum (right). For the sake of clarity, the fundamental frequency component is not shown in the spectrum.

C. Impact on standards

The previous section showed that the traditional sources of harmonic emission display a few peculiar characteristics such as an inversely proportional relationship between harmonic magnitude and frequency and a general character of mostly emitting at the odd harmonic frequencies. To put this into historic perspective, it is important to look at the evolution of IEEE PQ standards through their history. At the beginning of the electrification of the North American continent, most of the harmonic distortion in the grid was attributable to the saturation of devices utilizing magnetic circuits for their operation. Since such saturation was generally a transient phenomenon, the levels of harmonics in the grid remained relatively low (or at least low enough to present little to no risk of EMI with other equipment). This situation of Electromagnetic compatibility (EMC) in the power grid rapidly changed during the 1960s and 1970s with the advent of consumer passive power electronic devices and large industrial converters. The harmonic currents drawn by these devices, along with pre-existing voltage distortion produced by generators raised concerns about increased harmonic distortion (and hence increased grid losses) and reduced grid compatibility. To counter this growing concern, standards and regulations to limit the amount of allowable harmonic voltage distortion in the grid began to emerge. In the United States, the first iteration of the now familiar IEEE 519 emerged in 1981 [16]. This standard was sponsored by the Static Power Converter Committee of the Industry Applications Society. Predictably, the focus of this standard was static power converters and the harmonics generated by them. The primary aims of this standard were:

- To prescribe limits for the allowable voltage distortion in the North American power grid.
- To develop charts for the maximum allowable size of a converter that could be connected at a Point of Common Coupling (PCC) so that the voltage harmonic limits were not exceeded.

The first objective of this standard was achieved through surveys of the existing voltage distortion in power grids which had already been conducted in Europe [17] and the UK [18]. These surveys provided maximum voltage distortion levels at which grid EMC would be maintained. By adapting these surveys and standards to the North American power system, the first objective of the standard was realized. To achieve the second objective, the typical emission from an industrial converter was first characterized. Utilizing the previously derived maximum voltage distortion limits at a PCC, the typical emission from a converter and knowledge of the Short Circuit Ratio (SCR) at a PCC, typical charts of the allowable size of a converter at a given PCC were then derived.

IEEE 519-1981 was the first in a series of iterations of the IEEE 519 standard and provided a blue print for all the regulation that followed. Allowable current limits for load connected at a PCC were developed from the voltage limits prescribed in 1981 and later iterations [1], [19] of the standard have largely been developments of these current limits introduced in 1992. A survey of these limits reveals an interesting characteristic of IEEE 519 limits that has had important and far-reaching consequences: Although the harmonic limits were theoretically prescribed for all possible frequencies, quantities such as the Total Harmonic Distortion (THD) and Total Demand Distortion (TDD) were suggested to be calculated only up to the 50^{th} harmonic. Furthermore, the even harmonic current limits were much lower than the odd harmonic current limits. This observation generally falls in line with the earlier observation made in this paper i.e., traditional sources of harmonics typically do not emit large quantities of even harmonics and the odd harmonics they typically emit have magnitudes that diminish with frequency. In effect then, the IEEE standards suggest that:

- For the purposes of grid PQ, harmonics above the 50^{th} do not have much bearing on grid distortion and grid compatibility. In other words, above the 50^{th} harmonic, the magnitudes of frequency components are not significant enough to cause concerns.
- Even harmonic magnitudes in the grid are insufficient to be a major nuisance.

These ideas are further reinforced by specific language introduced in IEEE 519 [1] that states that for the purposes of PQ compliance evaluation, measurements must be made at least up to the 50^{th} order. In effect then, the first observation outlined above has had the effect of making the 50^{th} harmonic the default 'cutoff point' for most PQ measurement instruments and transducers. In other words, the fact that IEEE 519 currently prescribes measurement compliance and evaluation up to the 50^{th}, which is in turn based on the traditional harmonics paradigm of traditional harmonics sources, has created an entire ecosystem of sensors and measurement instrumentation with bandwidth limitations up to the 50^{th} harmonic. As the next section shall show, the modern grid harmonics paradigm, characterized by increasing grid complexity has slowly begun to pose a fundamental challenge to this established ecosystem of regulations and instrumentation that supports it.

III. The Modern Harmonics Paradigm

A. Origins of the change

In the last two decades, power electronic switches have evolved considerably. As opposed to passive electronic switches, the newer generation of power electronic switches can be rapidly turned on and off independent of the polarity of voltage applied to them. This evolution in technology has caused end use devices to become more efficient and has shrunk their footprint considerably. These switches, grouped under the umbrella term 'active switches' have led to a situation where the emission from devices employing them, is no longer restricted to the 3 kHz point. As previously discussed, regulation laid down by power quality standards had imposed strict requirements on the harmonic emission produced by such circuits, but these limitations apply to frequencies up to 3 kHz. Conveniently then, the utilization of active power electronic switching also helps in meeting such regulations by shifting some of the spectrum of emission from end use load to the frequency range above 3 kHz which is currently unregulated in both the US and major parts of Europe.

B. Factors driving the modern harmonics paradigm

In order to understand the extent to which the established traditional harmonics paradigm has changed in the last two decades, it is important to consider the changes occurring in the power system and end use load. These changes and the likely outcomes from a PQ perspective have been discussed extensively in [20], and summarized in Fig. 3.

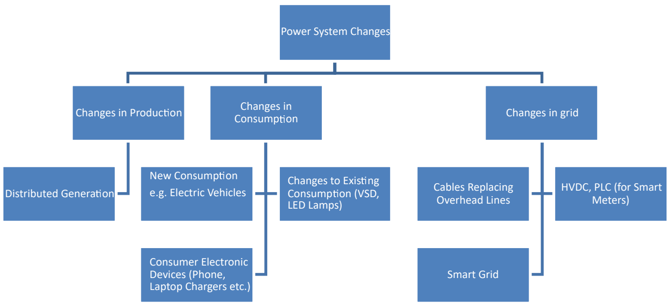


Fig. 3: Summary of changes in the power system.

A direct outcome of these changes in the power system has been a change in the spectrum of the emission that is being observed by PQ engineers in the system. This point can be further emphasized and understood by observing examples of emission from each category of change. To this end, the time domain waveform of the voltage produced by a Medium Voltage (MV) connected solar PV plant in the US, and its spectrum are shown in Fig. 4. These waveforms were captured at the PCC of the solar PV plant and are scaled by the Potential Transformers (PTs) by a ratio of $175:1$. This figure shows that in the frequency range up to $2\,\mathrm{kHz}$, the solar PV plant produces the odd harmonic frequencies that we have come to expect from passive power electronic switches. However, in addition to the odd harmonic frequencies, the solar PV plant produces significant frequency components all the way up to the frequency of $7.5\,\mathrm{kHz}$.

The high frequency emission from the solar PV plant can be understood on the basis of the operating principle of the inverters utilized by such plants. In a solar PV plant, the DC energy produced by the solar panels is converted to grid frequency AC by an inverter consisting of active power electronic switches such as Insulated Gate Bipolar Transistors (IGBTs). These switches are generally capable of being turned on and off at extremely high frequencies (usually greater than $2\,\mathrm{kHz}$) using techniques such as Pulse Width Modulation (PWM). Since the average value of the PWM waveform is meant to be as close to the fundamental power system frequency as possible, odd harmonics of this frequency appear in the emission from the solar PV inverters. In addition, the emission spectrum also contains higher frequency components corresponding to the switching frequency of the IGBT switches, their sidebands and their harmonics. Since this switching frequency is not synchronized with the fundamental power system frequency but rather regulated by an internal clock in the inverter, this

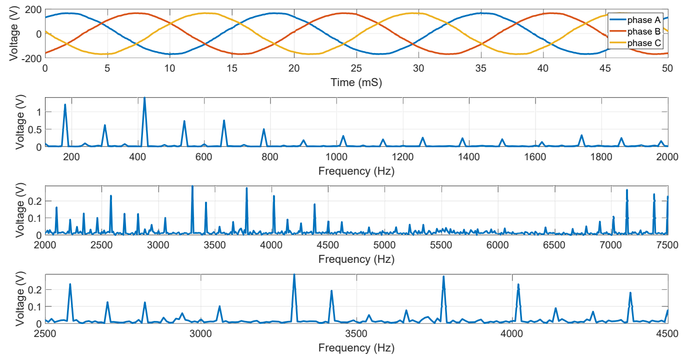
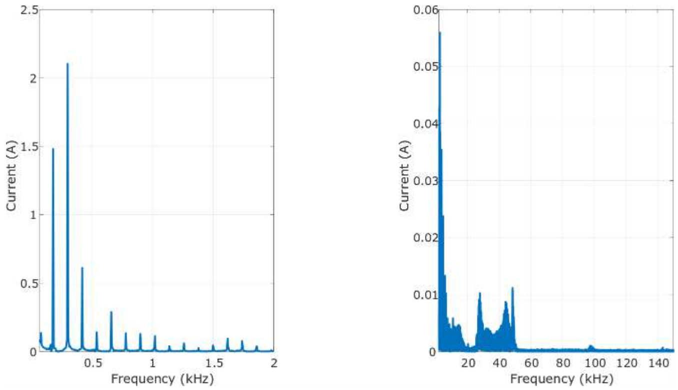


Fig. 4: Time domain waveforms of the voltage produced by a solar PV plant (top). Spectrum of phase A voltage is shown separately in the frequency range up to 2 kHz (second from top) and 2 kHz to 7.5 kHz (third from top). A zoomed in view of the switching frequency of the inverter and its residue in the frequency range 2.5 kHz to 4.5 kHz is shown at the bottom.

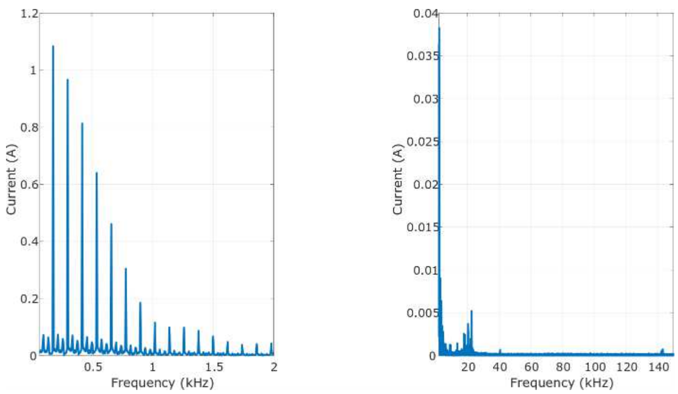
switching frequency emission may or may not appear at harmonics of the fundamental power system frequency.

The phenomenon of emission above the traditional harmonics is not unique to inverter interfaced DER alone. Extensive measurements done on common household equipment over the last decade show that many devices on the market inject emission in the frequency range 2 to $150\,\mathrm{kHz}$ [4]–[7], mainly due to the action of high speed active power electronic equipment. Some examples of this emission from domestic end use equipment sold in the United States are shown in Fig. 5. The examples shown in Fig. 5 all exhibit a similar behavior: The devices emit odd harmonics of the fundamental power system frequency up to $2\,\mathrm{kHz}$ and high frequency emission due to the switching of the active power electronic switches in their circuits above $2\,\mathrm{kHz}$. These examples are by no means exhaustive and more and more mass-market end use load has been found to be emitting in the supraharmonics range. In Europe, in addition to emission from loads connected in domestic households, the supraharmonics frequency band is also used for communication with smart meters using Power Line Communication (PLC).

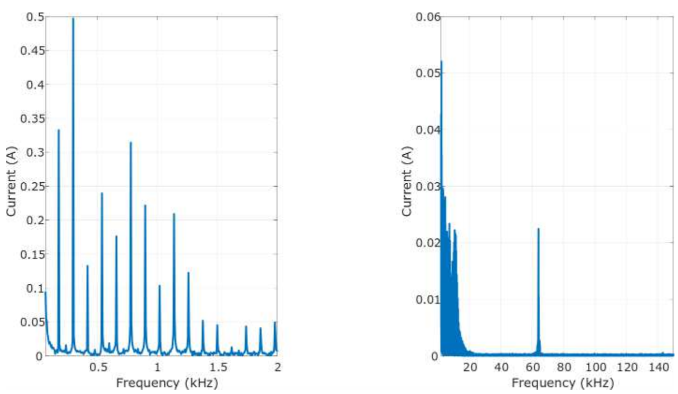
The previous examples show that almost every category of change associated with the grid that has happened in the past two decades has contributed to the emission from end use equipment changing in its frequency spectrum. Supraharmonics emission along with the traditional odd harmonic emission now becoming the norm rather than the exception and this has slowly changed the established harmonics paradigm. The modern sources of harmonics thus, are different from the old ones in that the extension of the frequency spectrum of emission has created a new set of associated PQ problems along with challenges in measurement and detection. Some of these problems and challenges are discussed in subsequent sections. A summary diagram showing the various sources of supraharmonics is shown in Fig. 6.



(a) Microwave Oven



(b) Refrigerator



(c) Electric Vehicle

Fig. 5: Emission from an inverter microwave oven (a), a refrigerator (b) and an Electric Vehicle (c). For each figure, emission in the harmonic ($< 2\,\text{kHz}$) range is shown on the left, while that in the supraharmonics ($2\,\text{kHz}$ to $150\,\text{kHz}$) range is shown on the right.

IV. The challenge to utility Potential Transformers

For the past 40 plus years, PQ standards in North America have typically necessitated the measurement of voltages and currents to be made up to the 50^{th} harmonic order i.e., $3\,\text{kHz}$. However, as was shown in the previous section, modern sources of generation and end use load both produce emission

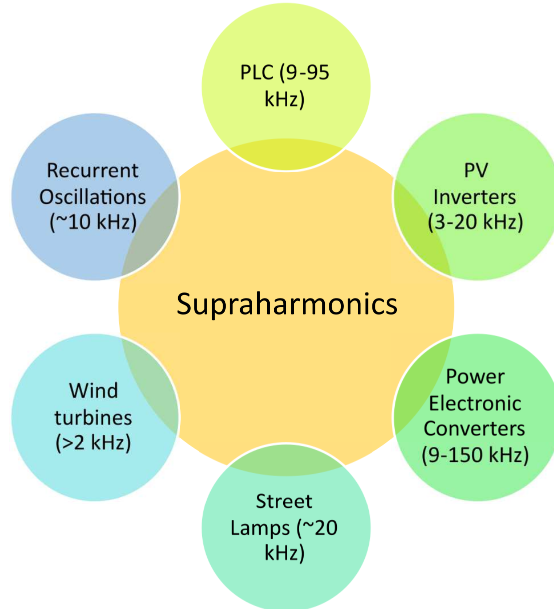


Fig. 6: Typical emission frequencies and sources of supraharmonics.

above this frequency and are sources of supraharmonics. This poses a challenge to most legacy PQ monitoring equipment, which was built to be accurate up to $3\,\text{kHz}$ and thus may not be capable of measuring and detecting supraharmonics. Replacement of this legacy equipment would be a daunting, time consuming task to say the least, given the sheer amount of equipment that would require to be changed. Furthermore, the cost associated with such a change would also no doubt be very high. In the past couple of years, the PQ groups at EPRI and TVA have spent considerable effort in understanding this problem and finding and evaluating potential solutions to it. The next section presents some of these ideas. The ideas broadly focus on two independent lines of thinking: one line of thinking focuses on repurposing existing PQ sensors and another for using alternate sensing and measurement methods. The basic principles behind these ideas, some practical experience gained in their implementation and the lessons learned in the process are presented in the rest of this paper. It is worth mentioning to the reader at this point that although the ideas are equally applicable to current sensors, the ideas presented here primarily focus on voltage sensors. Due to equipment limitations, current sensors have not been systematically studied yet and this topic is proposed to be addressed in a future iteration of this work. For now therefore, the focus is primarily on voltage sensors and this is addressed next.

V. Repurposing Existing Voltage Sensors

A. *The basic idea*

This paper has so far showed that detection and measurement of supraharmonics using existing grid infrastructure may be difficult, and consequently knowledge about how pervasive supraharmonics are in the system, is limited. Further, given the sheer volume of sensors that will need to be changed, retrofitting or replacing existing utility infrastructure to extend its frequency range is likely to be an expensive and time-intensive endeavor. A possible solution to this conundrum is to quantify the frequency gain of existing voltage and current sensors and simply use the results to predict the frequency content of the original signal that the sensor may have measured. For instance, for a device under test, such as a sensor, if a known, measured signal $\alpha(t)$ is applied to the input, then the output is related to the input by the transfer function $f(t)$ so that mathematically, the output $\beta(t)$ can be written as:

$$\beta(t) = f(t) * \alpha(t)$$

By measuring the signal applied $\alpha(t)$ to the device under test, and its response $\beta(t)$, the transfer function of the device can be quantified as:

$$f(t) = \frac{\beta(t)}{\alpha(t)}$$

By using the fast Fourier transform (FFT), the measured input and output signals can be converted into the frequency domain. With such a conversion, it can be easy to see that the calculation of the transfer function effectively boils down to a calculation of the frequency response (or "frequency gain" or simply "gain") of the system. In other words, the frequency response can be quantified as:

$$Gain = \frac{FFT(\beta(t))}{FFT(\alpha(t))}$$

Knowledge of the transfer function of the device under test can also thus be used to predict the original signal. Mathematically, it is apparent that:

$$\alpha(t) = \frac{1}{f(t)} * \beta(t)$$

Alternatively:

$$FFT(\alpha(t)) = \frac{FFT(\beta(t))}{Gain}$$

It is precisely this idea of measuring the output and using a calculation of the transfer function (or frequency response) to predict the input signal that is explored in this section, as a possible means to extend sensor capability over a larger frequency spectrum. In a nutshell, the idea can be stated thus: by calculating the frequency response (or transfer function) of a sensor over the supraharmonics range, correction factors can be developed. These correction factors essentially tell the user the expected error and attenuation at a given frequency beyond the sensor's expected operating frequency range. By applying the correction factors, the amplitude of the original frequency can then be estimated.

B. Practical Implementation

In order to obtain a method for calculating sensor frequency response that is fast, easily reproducible and portable for the purposes of practical implementation, a Vector Network Analyzer (VNA) was utilized. A VNA is a device that injects discrete frequencies into a Device Under Test (DUT) and can also measure the signal received at the input and output ports of the DUT. Based on these measurements of input and output, the VNA automatically calculates the frequency response of the DUT. A schematic of a setup employing a VNA, that can be used to characterize any de-energized PT, is shown in Fig. 7.

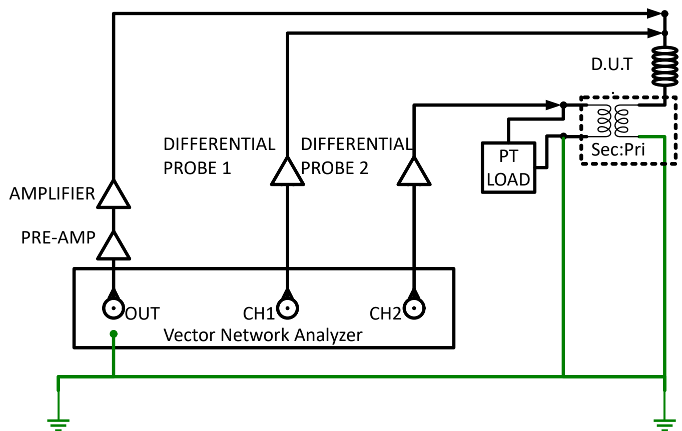


Fig. 7: Schematic of a circuit to use a VNA to characterize a PT's frequency response.

To prove the implementation of the method using the setup shown in Fig. 7, the frequency response of an MV PT ($14.4\,\mathrm{kV}/120\,\mathrm{V}$), was first calculated in a lab environment. The result of this characterization is shown in Fig. 8. This figure shows that the PT has a flat frequency response up to about $30\,\mathrm{kHz}$. After this point, the frequency response of the PT is dominated by resonance points and becomes a little more unpredictable. Stated differently, this figure shows that the PT retains its $120 : 1$ stepdown ratio for frequencies up to $30\,\mathrm{kHz}$, indicating that the PT can be used for sensing and measuring up to $30\,\mathrm{kHz}$ without any appreciable measurement error. After this point however, the measurements from the PT may not be accurate. To overcome this inaccuracy, on the other hand, the gain of the PT at each frequency of interest may be used, to appropriately scale the output. As stated previously, this scaling may provide an appropriate first approximation of the frequencies in the signal applied to the PT primary. Further, to improve accuracy of the correction, the resolution of the frequency response may be increased. Alternatively, the frequencies to be corrected may be narrowed down to the dominant frequencies in the distortion signal of interest. Some practical aspects of implementing this approach are discussed next.

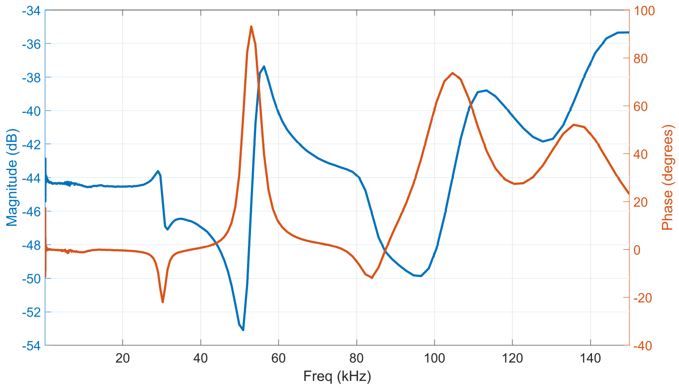
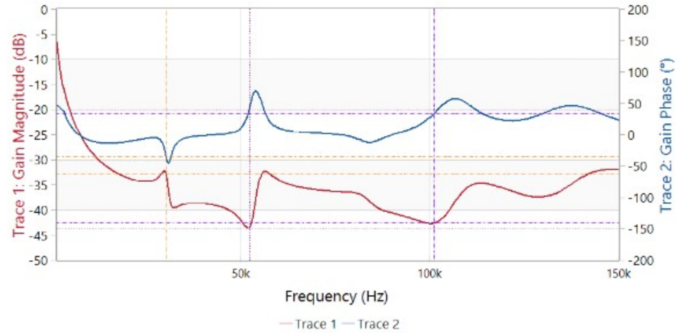
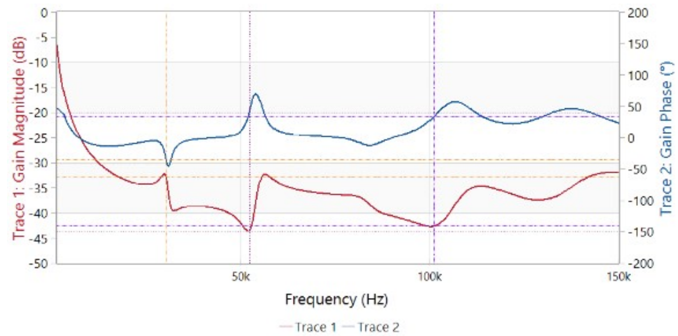


Fig. 8: Frequency response of an MV PT obtained using a VNA.



(a) De-Energized



(b) Energized

Fig. 9: Frequency response of an MV PT calculated in a de-energized condition (top) and while energized at line frequency voltage (bottom).

C. *Impact of sensor energization*

The previous section introduced the basic idea of utilizing the frequency response of a voltage sensor to develop correction factors to account for the errors in reproducing high frequency signals. Voltage sensors are typically utilized by electrical utilities on MV, High Voltage (HV) or Extra High Voltage (EHV) circuits, where they are usually connected between the line and ground terminals for each phase voltage. Sensors utilized at MV are mostly inductive while those utilized at HV/EHV may be capacitor coupled or purely inductive (the reader should note that capacitor coupled units still have inductive transformers inside). The natural question that arises from this piece of knowledge is: do the sensors need to be energized at power frequency voltage (as magnetic circuits often need to be) in order to perform frequency characterization tests on them? A natural follow up question would be to ask what impact, if any, does sensor energization at power frequency voltage have on the accuracy of the frequency characterization? To answer these questions, another MV voltage sensor with a ratio of 14.4 kV (wye)/120 V was utilized. The frequency response of this sensor in an a de-energized condition was first calculated using a VNA, in a laboratory environment. Next, the frequency response of the sensor was calculated again, albeit while energized at line frequency voltage. The results of these two tests are shown in Fig. 9. These results show almost identical frequency response characteristics being calculated by the VNA in two different operating conditions. These results are one of many that indicated that the energization of the voltage sensor does not make a difference to the accuracy of the obtained frequency response from the sensor. These results indicate that the frequency response of the sensor obtained in a de-energized condition would still be accurate enough to achieve the outcome desired. Furthermore, it also indicates that testing the sensor pre-energization would also give an accurate estimate of its frequency characteristics while energized, eliminating the safety hazard of testing the sensor while energized at Medium to High voltage levels.

D. *Impact of sensor circuit and sensor burden*

The previous section showed that the output of the VNA provides plots of the gain and phase response of the PT in the frequency range of interest. Furthermore, in theory, by using these plots, the original frequency content of a signal applied to the PT may be recreated, eliminating the issues of limited bandwidth of PTs. In order to implement this idea in practice, the frequency response of the voltage sensor must be faithful to the actual frequency response gain magnitude at the voltage measurement device (such as a PQ monitor). This gain magnitude is not simply the gain of the voltage sensor, although it is largely dominated by it. Rather, it is the composite of the gain of the sensor and the frequency characteristics of the circuit in which the sensor is connected. To illustrate this difference, the 14.4 kV voltage sensor that has been previously discussed was again utilized. The frequency response of this sensor was calculated in two conditions: with the sensor in an open circuit condition and then again while the sensor was connected in a circuit with some burden on it. The results of these calculations are shown in Fig. 10. This figure shows that there is a considerable amount of difference in the gain values and characteristics obtained through the sensor while it is connected in-situ (in a circuit) versus while it is in an open-circuit condition. The figure further shows that while most of the frequency response is shifted vertically while in-situ, at lower frequencies (below $20\,\mathrm{kHz}$) even more changes such as shifts in gain characteristics can be observed. This is likely due to the action of other inductances such as transformers that may be connected in the circuit. In the case of capacitive units connected in the circuit, other data points have revealed that changes to the gain characteristics can be observed in the high frequency region instead.

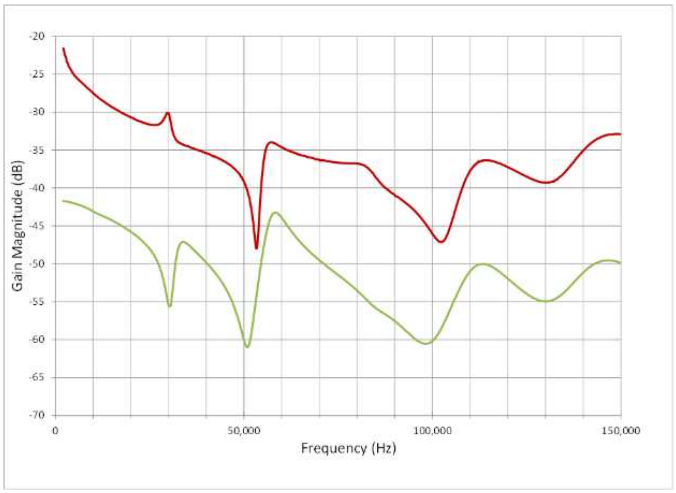


Fig. 10: Comparison of the gain of a voltage sensor while connected in-situ (red) and while open circuited (green).

E. Field Implementation and Initial results

The previous section demonstrated an approach to repurposing existing voltage sensors for measurement in the high frequency region by characterizing their frequency response. Research results obtained in a lab environment, showed that such measurements can be performed while the sensor is de-energized but must be done in-situ so that an accurate estimate of the sensor's frequency gain, as seen by the PQ monitor or voltage measurement device, can be obtained. Based on these results, EPRI has been working with TVA for the implementation of the method, at de-energized substations in their territory. The underlying idea of the project is to characterize the frequency response of substation components before the substation is commissioned and put into service. The results of the project have enabled TVA to understand the limitations and capabilities of their existing voltage sensors before they are commissioned. Furthermore, the testing has also enabled them to understand the sensitivities of measurement at higher frequencies. Understanding these sensitivities is particularly important for TVA, as it continues to see an increased penetration of solar PV in its service territory, as a part of the company's commitment to decarbonizing and moving towards cleaner, greener sources of energy generation. As of May 2022, the company reported about $600\,\mathrm{MW}$ of solar PV had come online (out of $2076\,\mathrm{MW}$ of signed purchase power agreements) and it further expects up to $10,000\,\mathrm{MW}$ of solar PV to come online by 2035 in its territory. Thus, supraharmonic emission from solar plants, their measurement and detection are of prime concern to the TVA PQ team.

An example of the initial results obtained from the in-situ testing performed at one of TVA's $161\,\mathrm{kV}/69\,\mathrm{kV}$ substations has been shown in Fig. 11 (for the sake of brevity, only one representative result has been discussed in this paper). This figure shows the frequency response gain of an inductive MV Potential Transformer through its X winding and Y winding. The results show that this inductive unit had a flat frequency response up to $2\,\mathrm{kHz}$, while its response was dominated by resonance points thereafter. This indicated that the sensor was largely unsuitable for making supraharmonic measurements in an in-situ condition, even though the response may have been different while the PT was open circuited. Further, the results show that even though the X and Y windings are wound on the same PT unit, their results at the higher frequencies of interest can be slightly different which affects the measurement results through them.

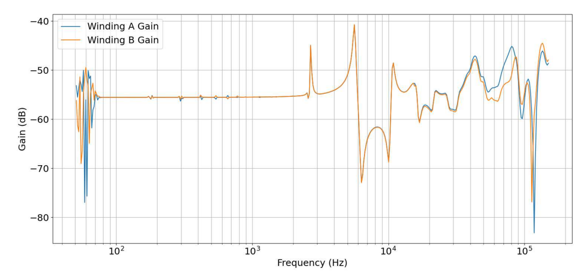


Fig. 11: Frequency response gain characteristics for an MV PT through its two windings.

Tests carried out at HV and EHV substations in TVA's territory, further enabled comparison of different voltage sensor technologies to understand the capabilities and limitations of each. For example, the results from the inductive PTs shown in this document show that a linear response can be expected from these devices up to at least $2\,\mathrm{kHz}$. Fig. 12 shows the results from a $69\,\mathrm{kV}$ capacitor coupled sensor, and indicates that the same performance cannot be expected from Capacitive Coupled units where the linear region of the frequency response curve lasts for a short period of time and the characteristics are otherwise dominated by resonances. The results indicate that for capacitive coupled units, the gain characteristics are linear for only a short bandwidth and in general, the gain of the sensor rolls off sharply as the frequency of measurement increases. As a last point, it is worth mentioning that at present the method is in the process of implementation at the back end i.e., the correction factors are being developed for the sensor tests. In addition to voltage sensors, the approach has also been extended to characterize the frequency response of transformers and other substation assets of note. The ultimate objective is to extend the frequency characterization method described here to enable utilities to select suitable voltage sensors and transformers according to the application. For example, by characterizing the frequency response of transformers and voltage sensors, selection of appropriate equipment for a solar PV plant can be made. Since such a plant is a source of supraharmonics, such a development will enable utilities to have a complete understanding of the emission characteristics of their plants and the capability of their equipment to measure it.

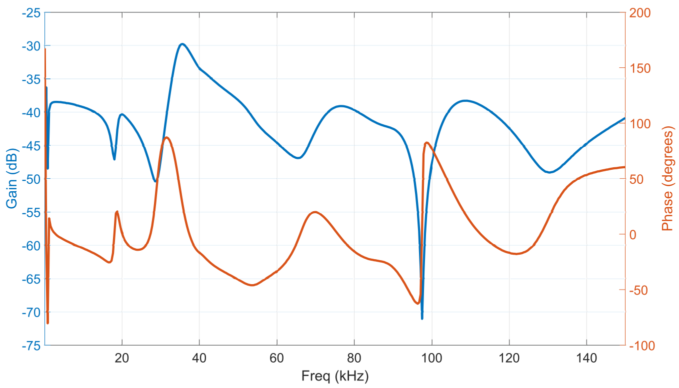


Fig. 12: Frequency response characteristics of a 69 kV capacitively coupled PT.

F. *Limitations of the method*

The previous sections described a method to repurpose existing voltage sensors to cope with the modern harmonics paradigm. Although it was mentioned that by enabling high resolution frequency response, the characterization of many frequencies of interest is possible using this method, it also points out a practical limitation. It is impossible to capture the frequency response of the voltage sensor to every conceivable frequency. Hence, the method must rely on lookup tables and correction factors for a few discrete frequencies that may be of particular interests. Methods to overcome these limitations are actively being researched along with ways to extend this method to test existing current sensors installed in utility locations.

VI. Detection and Measurement using Radiated Emission

In addition to repurposing existing sensors, another approach to sensing and detecting supraharmonics that avoids the traditional problems of conducted measurements is also under active research at the moment at EPRI. This idea relies on the fundamental principle that when current flows through a wire, some energy is also radiated as an electromagnetic field. By detecting this electromagnetic field around wires that carry supraharmonics currents, supraharmonics can be accurately sensed and detected. Cheap, commercially available off-the-shelf electromagnetic field sensors have been demonstrated to have enough fidelity for this purpose. The method has further been utilized in a myriad of PQ investigations and proven in a utility environment. For the details of the method, its basics and its implementation, the reader is encouraged to refer to [11].

VII. Conclusions

This paper presented two approaches to overcome the bandwidth limitation of existing voltage sensors, caused by the changing grid harmonics paradigm. While both approaches are clearly still in the development stage, they both show enough promise to pursue development in the years to come. While the sensor frequency response characterization approach may be used for post-processing data containing supraharmonics, it may also be used ultimately as a screening approach by utilities to arrive at the right sensor and transformer for an application involving supraharmonics. For problems requiring detection of supraharmonics, the utilization of radiated fields has proven to be extremely useful and has been utilized in investigations of EMI issues already. At the present moment, no regulations around supraharmonic emission exist. As a result, both methods may be used interchangeably in PQ investigations. However, in case PQ regulations around these frequencies evolve, retrofit or replacement solutions may have to be ultimately considered by utilities, depending on the application and financial considerations.

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