

Interharmonics: What They Are, Where They Come From and What They Do

Michael B. Marz
American Transmission Company
Waukesha, WI
mmarz@atcllc.com

INTRODUCTION

The use of sophisticated power electronics and communication systems to improve power system efficiency, flexibility and reliability is increasing interharmonic distortion and adding equipment sensitive to that distortion to the system. Knowledge of interharmonics, their sources, effects, measurement, limits and mitigation, will help the industry prevent interharmonics from adversely affecting the power system.

INTERHARMONIC DEFINITIONS

The IEEE defines interharmonics as:

“A frequency component of a periodic quantity that is not an integer multiple of the frequency at which the supply system is operating (e.g., 50 Hz or 60 Hz).”¹

The IEC defines interharmonics as:

“Between the harmonics of the power frequency voltage and current, further frequencies can be observed which are not an integer of the fundamental. They can appear as discrete frequencies or as a wide-band spectrum.”²

Simply put, interharmonics are any signal of a frequency that is not an integer multiple of the fundamental frequency. If f_1 represents the fundamental frequency and n is any nonzero integer, nf_1 is a harmonic of f_1 . For the special case when n is zero, nf_1 is also zero, i.e. dc. For m , any positive non-integer number, mf_1 is an interharmonic of f_1 . When m is greater than zero and less than one, mf_1 is sometimes referred to as a subharmonic of f_1 . These definitions are summarized in Table 1.

Table 1 – Harmonic and Interharmonic Definitions

f_1 = fundamental frequency	
If n is any positive integer	If m is any positive non-integer
nf_1 is the n^{th} harmonic	mf_1 is the m^{th} interharmonic
If $n = 0$, nf_1 is DC	If $m < 1$, mf_1 is a subharmonic

One characteristic of all periodic signals is that they can be represented by their fundamental component and a Fourier series of harmonics of various magnitudes, frequencies and angles.³ By definition interharmonics are not periodic at the fundamental frequency, so interharmonics can be thought of as a measure of the non-periodicity of a power system waveform. Similarly, any waveform that is non-periodic on the power system frequency will include interharmonic distortion.

INTERHARMONIC SOURCES

Power system interharmonics are most often created by two general phenomena. The first is rapid non-periodic changes in current and voltage caused by loads operating in a transient state (temporarily or permanently) or when voltage or current amplitude modulation is implemented for control purposes. These changes can be quite random or, depending on the process and controls utilized, quite consistent. Changes in current magnitude or phase angle can also create sidebar components of the fundamental frequency and its harmonics at interharmonic frequencies.

The second source of interharmonics is static converter switching not synchronized to the power system frequency (asynchronous switching). Thyristor switched converters are triggered into forward conducting mode and keep conducting until their current falls below its holding current. By turning off at the same voltage each cycle, thyristor devices are synchronized to the power system frequency and do not produce interharmonics. Insulated gate bipolar transistors (IGBTs), which can be turned off as well as on at any time, are replacing thyristors in converters because their greater flexibility allows for reactive as well as real power regulation and power system oscillation damping. The asynchronous switching of converters using IGBTs produces interharmonics.

Oscillations between series or parallel capacitors or when transformers or induction motors saturate can also produce interharmonics. Some specific sources of interharmonics include arcing loads, induction motors (under some conditions), electronic frequency converters, variable load drives, voltage source converters and power line communications.

Arcing Loads include arc furnaces and welding machines. For most large industrial arc furnaces, transient loading and interharmonics vary throughout the melt cycle. Load variability and the resulting interharmonics are usually greater at the beginning of the melt cycle. Welding machines produce a more continuous frequency spectrum that includes many interharmonic frequencies.

Induction Motors have slots in their stator and rotor iron that can produce interharmonics when their magnetic circuits saturate. These interharmonics can increase during startup. Motor asymmetry can also produce interharmonics. Variable torque loading can also cause motors to produce interharmonics.

Electronic Frequency Converters use a dc link to convert one frequency to another. Filtering on the dc bus is used to decouple the voltage and current on each side of the link, but this filtering is never perfect and interharmonic distortion can pass between the two ac systems.

Variable Load Dives such as traction system power supplies that use IGBTs or experience sudden load changes can produce interharmonics, usually at fixed frequencies.

Voltage Sourced Converters (VSCs) are used for a variety of applications including modern wind generator dc to ac conversion, static compensators (STATCOM) and HVDC applications. The use of IGBTs in VSCs has advantages over line commutated converters (LCC) that use thyristors. Among these advantages are the ability to independently regulate reactive power at each converter, operate under very weak system conditions and blackstart one dc terminal from the other. The ability of IGBTs to turn off at any time also allows near instantaneous control that can be used to improve system stability by damping oscillations.

One consequence of the increased control provided by VSCs is the production of interharmonics. The level of interharmonics produced by a VSC device depends on its type. Earlier types used pulse width modulation (PWM) that produced much higher interharmonics than the newer modular multilevel (MML) designs. Other types (Cascaded Two Level, etc.) also produce interharmonics. Examples of voltages produced by PWM and MML VSCs are shown in Figure 1. In addition to type, the frequency and level of interharmonics produced by a specific VSC converter depends on a number of design factors (pulse number, levels, etc.) that are chosen for reasons usually unrelated to interharmonic generation.

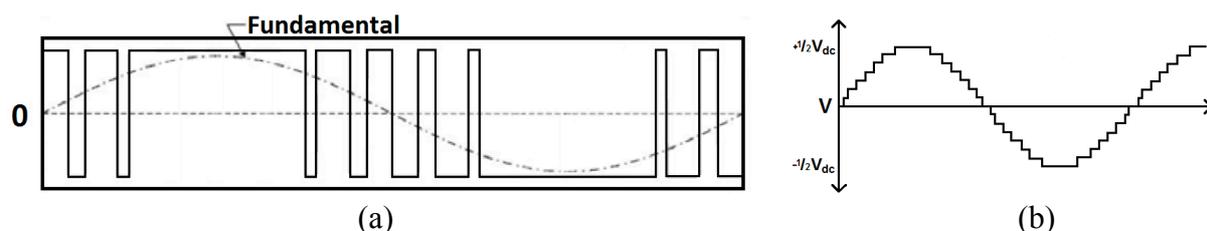


Figure 1 – (a) Pulse Width Modulation (PWM) and (b) Modular Multilevel MML VSC Voltage Waveforms

Power Line Communications are used by some utilities to transmit system protection information, control certain loads or reactive resources or provide two way communications to customer “smart” meters. All of these systems use non-periodic signals added to the power frequency waveform to communicate. Protection information is usually transmitted using frequencies in the 100’s of Hz range and are intended to be transmitted from one location to another and prevented from reaching the wider system by wave traps. Load or reactive resource control signals in the 100 to 3000 Hz range, sometimes called ripple control signals, reach the wider system, but are generally of low magnitude, short duration and used infrequently. Both protection and load control signals usually use a minimal number of frequencies that are meant to communicate simple instructions (trip, block, turn on or turn off). Higher frequency signals, up to the 100’s of kHz, may be used in smaller areas for commercial communication applications.

Smart meter communication over power lines have been used for a variety of purposes with varying levels of data intensity. Generally, either the current, voltage or both are briefly shorted to ground to send a step signal that is interpreted as a binary bit. Series of bits are interpreted to identify the meter and the information it is sending. Multiple meters can send signals at the same time, but with multiple communication attempts and error checking, communications can be quite reliable. These signals include a wide range of interharmonic frequencies, but their magnitude generally decreases as their frequency increases.

Interharmonics can be generated at and transferred to any voltage level. Although a relatively limited number of interharmonic measurements are available publically, low levels of interharmonics (0.01-0.02%) have been measured at transmission level voltages with no known large interharmonic sources. Even with known interharmonic sources voltage interharmonic levels rarely exceed 0.5% of the fundamental voltage, except under resonance conditions.⁴ These interharmonic magnitudes are approximately an order of magnitude below applicable harmonic distortion limits.

INTERHARMONIC EFFECTS

Interharmonics, like harmonics, add additional signals to the power system. These additional signals can cause a number of effects, particularly if they are magnified by resonance. The wider the range of frequencies present, the greater the risk of resonance. Many of the effects of interharmonics are similar to those of harmonics, but some are unique to interharmonics as a result of their non-periodic nature.

Effects of interharmonics similar to those of harmonics caused by an additional signal superimposed on the fundamental can be separated into three categories: overloads, oscillations and distortion. The effects of overloads include additional energy losses that can contribute to heating, overloading filters or other system components and current transformer saturation. Depending on their frequency, these additional signals can cause oscillations in mechanical systems, acoustic disturbances, or interfere with telecommunication signals. Distortion of the fundamental frequency waveform can interfere with the operation of equipment synchronized with system zero-crossings or dependent on a consistent crest voltage, such as fluorescent lights, timing devices and some electronic equipment.

Two of the most common and impactful effects of interharmonics that are not problems with harmonic distortion are light flicker and power line communication interference, both of which require non-periodic signals to occur.

Light Flicker is caused by variations in rms voltage magnitude. The perceptibility of flicker varies with the frequency and magnitude of these voltage variations. The dependence of rms voltage variation on the frequency of a constant 0.2% amplitude interharmonic is shown in Figure 2.⁵ This figure shows the impact on flicker of interharmonic frequencies above the second harmonic is minimal. Virtually all types of lighting can be susceptible to flicker, but flicker intensity can vary for different types of lighting when they are exposed to voltage deviations of the same magnitude and frequency.

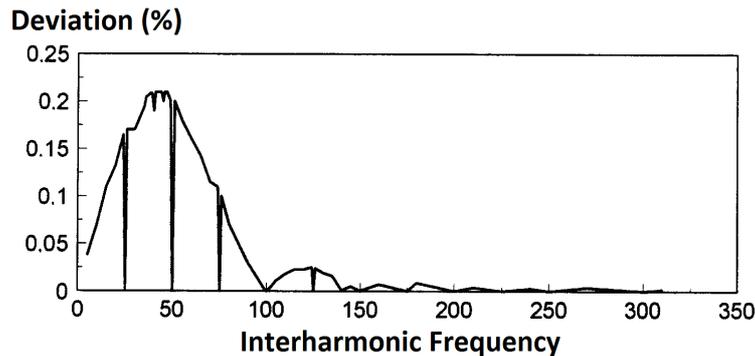


Figure 2: RMS Voltage Deviation with a 0.2% Distortion (50 Hz System)

Power Line Communications were discussed earlier as a source of interharmonics. Protection and ripple control signals usually consist of a single interharmonic frequency. They are usually not affected by other interharmonics that are of lower magnitude or do not match their frequency. Two way communications that rely on step changes in system voltage or current to send bits of information consist of multiple interharmonic frequencies. The interharmonic distortion created by power line communications carries information that, once the 60 Hz signal and its harmonics are removed, can be interpreted. If interharmonics from other sources are in the same frequency range as the power line communication signals, they can interfere with signal interpretation making it difficult for the power line communications to be completed.

Power line communications signals can also cause flicker. While these communication signals are designed to be too small to cause flicker, they have been known to cause very sensitive lighting (compact fluorescent with inductive ballasts) to flicker. If a power line communications system is not reliable, one fix may be to increase signal magnitude. This fix has limitations as increasing signal magnitude too much could cause flicker even in less sensitive lighting.

MEASURING INTERHARMONICS

Methods commonly used to measure the frequency components of a waveform use a phase locked loop to synchronize the measurement with the fundamental frequency. The signal is then analyzed using a Fourier Transformation (FT) of one or more cycles. This accurately represents the waveform only if it does not contain any non-periodic (interharmonic) components. The FT uses a specific measuring window (time period – T, $1/T = \text{frequency}$) and a limited number of samples (M) of that window. The signal outside the window is assumed to be identical to that inside the window. For North American power system waveforms periodic at the fundamental frequency $1/T$ is 60 Hz and a sample of 16.67 milliseconds is sufficient to fully analyze a waveform’s harmonic frequency components. The measurement of interharmonics, which are non-integer multiples of the fundamental frequency and may vary with time is more difficult.

With interharmonic components present, the greatest common divisor of all component frequencies in a signal, the Fourier Frequency, is not the fundamental frequency and can be quite small. This can dramatically increase the minimum acceptable sampling time, required sample size and overall computational complexity. For example, a signal with a 60 Hz fundamental, a 71.2 Hz interharmonic and a 3000 Hz harmonic has a fundamental Fourier Frequency is 0.2 Hz. The corresponding period is 5 seconds and, using the Nyquist criteria, a minimum sample frequency of 12,000 Hz. This results in a sample size, frequency (12,000 Hz) times period (5 seconds), of 60,000. With no interharmonic, the minimum sample frequency would remain the same (12,000 Hz) but the minimum measurement time would be one 60 Hz cycle, 16.67 milliseconds resulting in a sample size of 200 (12,000 Hz * 0.01667 seconds). In this example, including the 71.2 Hz interharmonic increases the measurement time and sample size 300 times.

To simplify the measurement process and produce repeatable results, IEC 61000-4-7⁶ uses a method based on the concept of grouping. For a 60 Hz system its basis is a Fourier Analysis with a 12 fundamental cycle basis that uses a phase locked loop synchronized with the fundamental frequency. This results in a spectrum with a 5 Hz resolution. Analysis details can be found in the standard.

This analysis produces harmonics at frequencies that are multiples of the fundamental and interharmonics every 5 Hz between the harmonic frequencies. These harmonic and interharmonic components can then be grouped into Harmonic Groups, Interharmonic Groups, Harmonic Subgroups and Interharmonic Subgroups (Figure 3). The magnitude of each group or subgroup is calculated by taking the square root of the sum of the squares of the components of each group or subgroup. According to IEC Standard 61000-4-7 the interharmonic group below the fundamental frequency (subharmonic) is interharmonic 0, the interharmonic group between the fundamental and second harmonic is Interharmonic 1, etc. Not all interharmonic meters follow this convention and instead label the interharmonic group below the fundamental frequency as interharmonic 1, the interharmonic group between the fundamental and second harmonic is Interharmonic 2, etc. The same calculations are used for both voltage and current.

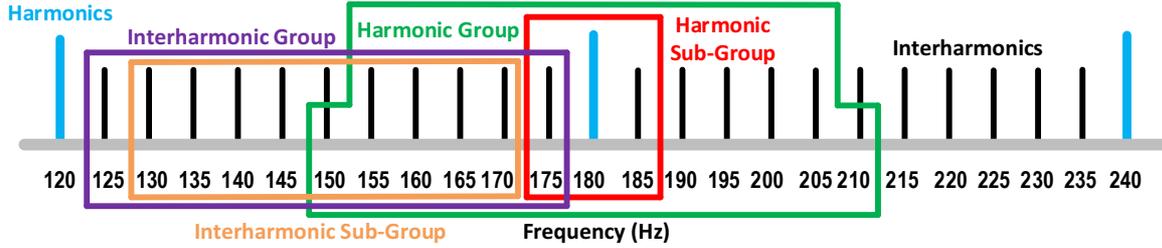


Figure 3: Harmonic and Interharmonic Groups and Subgroups

The magnitude of any Interharmonic Group (IG) is the square root of the sum of the squares of the magnitudes of the interharmonics in that group. For example the magnitude of the second interharmonic group, or more simply the second interharmonic, shown in Figure 3 is the square root of the sum of squares of the magnitudes of the interharmonic components from 125 Hz to 175 Hz. Equation 1 is the equation used to calculate the magnitude of Interharmonic Group N , from the 11 interharmonic component magnitudes (Y) between the N^{th} and $(N+1)^{\text{th}}$ harmonics.

$$IG_N = \sqrt{\sum_{k=1}^{11} Y_{(60Hz*N+5Hz*k)}^2} \quad (\text{Eq. 1})$$

The Interharmonic Subgroup (ISG) magnitude calculation removes the interharmonic components closest to each of the harmonics from the interharmonic group calculation (Equation 2).

$$ISG_N = \sqrt{\sum_{k=2}^{10} Y_{(60Hz*N+5Hz*k)}^2} \quad (\text{Eq. 2})$$

The Harmonic Group (HG) magnitude calculation includes the harmonic frequency and all of the interharmonic components closest to that harmonic frequency. Since the interharmonic components 30 Hz above and 30 Hz below each harmonic are equal distance from each harmonic, half the magnitude of both of these components are included in the calculation (Equation 3).

$$HG_N = \sqrt{\frac{1}{2} Y_{(N*60Hz-30Hz)}^2 + \sum_{k=-5}^5 Y_{(60Hz*N+5Hz*k)}^2 + \frac{1}{2} Y_{(N*60Hz+30Hz)}^2} \quad (\text{Eq. 3})$$

The Harmonic Subgroup (HSG) magnitude calculation includes only the harmonic frequency and the interharmonic components immediately adjacent to the harmonic frequency (Equation 4).

$$HSG_N = \sqrt{\sum_{k=-1}^1 Y_{(60Hz*N+5Hz*k)}^2} \quad (\text{Eq. 4})$$

Total harmonic distortion is calculated as the square root of the sum of the squares of all individual harmonic components of significant value. Similarly, a total interharmonic distortion can be calculated by taking the square root of the sum of the squares of all interharmonic groups of significant value.

INTERHARMONIC STANDARDS, GUIDELINES AND LIMITS

The effects of interharmonics can be divided into three categories: (1) those related to flicker, (2) those similar to harmonics and (3) those affecting power line communications. Because these phenomena are different, the limits required to prevent power system issues because of each of them are also different.

IEEE Standard 519-2014 contains informative interharmonic limits designed to prevent flicker. IEC 61000-2-2: 2002⁷ contains similar “standard compatibility levels” for “interharmonic voltages occurring at a frequency close to the fundamental (50 Hz or 60 Hz), resulting in amplitude modulation of the supply voltage.” Both standards limit the interharmonics of concern for flicker to frequencies below the second harmonic. The IEEE interharmonic voltage informative limits based on flicker are as high as 5% below 16 Hz, above 104 Hz and very close to 60 Hz. There is of course no limit at 60 Hz. The limit is as low as 0.23% at 51 Hz and 69 Hz. These informative interharmonic voltage limits are shown graphically in Figure 4. The limits in 1 Hz increments are included in tabular form in IEEE-519 (Table A-1 in Annex 1). These limits correlate to a short term flicker severity (Pst) of 1.0.

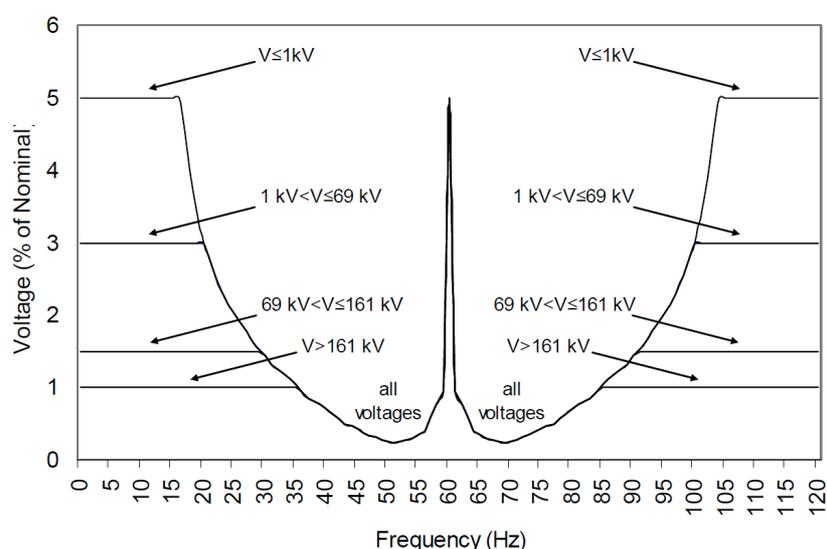


Figure 4: IEEE 519 Informative Interharmonic Voltage Limits Based on Flicker for Frequencies up to 120 Hz for 60 Hz Systems.

Beyond the interharmonic limits based on flicker, IEEE 519 provides little guidance on flicker limitations due to effects similar to those of harmonic distortion or to address power line communication issues. The standard states that “the effects of interharmonics on other equipment and systems such as generator mechanical systems, motors, transformers, signaling and communications systems, and filters” should be given “due consideration” and “appropriate interharmonic current limits should be developed on a case-by-case basis using specific knowledge of the supply system, connected user loads and provisions for future users.”

IEC 6100-2-2 states that there is not enough knowledge of interharmonics on the system for there to be agreement on compatibility limits beyond those for flicker, but provides some discussion on what those limits might look like. For issues similar to those of harmonics they suggest that the limits should be similar to harmonic limits. Specifically, they suggest each interharmonic frequency should have a reference level equal to the compatibility level for the next higher even harmonic. The IEC limits low voltage network 2nd harmonic voltages to 2%, 4th harmonic voltages to 1%, 6th and 8th harmonic voltages to 0.5% and even harmonic voltages from the 10th to 50th to $(0.25 \cdot (10/h) + 0.25)\%$. IEEE 519 low voltage (<1 kV) harmonic voltage limits are 5% for all individual harmonics and 8% for total harmonic distortion. Even harmonic current limits for systems rated 120 V to 69 kV are more complicated; they depend on the ratio of short circuit to load current (I_{SC}/I_L) as well as frequency. These limits range from 0.075% for high frequencies (35th harmonic and above) with low short circuit ratios (<20) to 3.75% for low frequencies (below the 11th harmonic) with high short circuit ratios (>1000).

The IEC standard discusses ripple control receivers as a special case. Receivers can be expected to respond correctly to voltages as low as 0.3% of the supply voltage. Higher response levels are generally avoided, depending on frequency, because they run the risk of causing flicker. The IEC suggests limiting interharmonics near the ripple control frequency to 0.2% of the supply voltage.

An interharmonic voltage limit above 0.2% may be acceptable for wider spectrum communications systems if applied not for a single frequency, but for total interharmonic distortion. This limit would still need to be significantly below harmonic limits. Applying such limits system wide may not be practical in the presence of modern power system equipment that can produce significantly higher interharmonics. Under these circumstances, developing interharmonic limits on a case by case basis is reasonable. Unfortunately, without system wide limits, equipment and system design is difficult.

Above the 50th harmonic, whether or not a frequency is a harmonic or interharmonic has little significance. The IEC suggests limiting any frequency from the 50th harmonic to 9 kHz to 0.2% and any 200 Hz band in this range to 0.3%.

None of these suggested limits are enforceable and there is no consensus as to whether they are too conservative or too liberal. Attempts to design limits that would prevent interharmonics from damaging or causing misoperation of power system and power line communication equipment are in the early stages of development. One thing that is becoming clear is that the limits necessary to allow power line communications could be about an order of magnitude lower than those necessary to prevent flicker or harmonic related issues. The future of interharmonic limits will depend on the benefits interharmonic generating equipment provide the system versus the cost of making other equipment immune to the effects of interharmonics.

INTERHARMONIC MITIGATION

The effects of interharmonic distortion can be mitigated using three methods that are also applicable to harmonic distortion: (1) reducing emission levels, (2) reducing load sensitivity and (3) reducing the coupling between distortion generating equipment and sensitive loads. The wide band nature and variability of the interharmonic distortion emitted from certain types of loads can make all three mitigation methods more difficult for interharmonics than for harmonics.

Reducing interharmonic emission levels is difficult because reducing interharmonics could also reduce the benefits of interharmonic producing equipment such as independent var production or consumption and oscillation damping from devices with electronic controls. Interharmonics from arcing loads and welders cannot be reduced without reducing process efficiency. Similarly, reducing interharmonics from power line communications systems could reduce their effectiveness.

Reducing the sensitivity of loads to interharmonics can, in some cases, be done in ways that are similar to reducing load sensitivity to harmonics. If the additional interharmonic signal makes current overloads or voltage peaks an issue, higher rated equipment can be utilized. Timing issues created by distorted zero crossing or voltage waveforms may be able to be addressed by utilizing equipment that is not synchronized to the power system. Power line communications are more difficult to modify to make them less sensitive to interharmonic distortion. They are usually designed so that their signal strength cannot be significantly increased without risking creating flicker. While single frequency signals can be modified to avoid certain sensitive frequencies, wide spectrum signals, which carry more information, often cannot. Often the most practical solution is to remove wide spectrum communications from the power line.

Reducing the coupling of interharmonic producing devices and sensitive loads is usually done with filters. Filtering can be practical when there is a single, or a minimal number of, interharmonic frequencies of concern. When there are multiple interharmonics of varying frequencies filtering may not be practical. Passive filters use low impedances at targeted interharmonic frequencies to shunt interharmonic currents to ground. Filters, especially lower loss undamped filters, can significantly amplify non-targeted frequencies. When only a limited number of interharmonic frequencies are a concern, these amplified frequencies can be designed to avoid frequencies of concern. This may be practically impossible when a wide range of interharmonics must be filtered.

A major concern when filtering for wide spectrum power line communications is the Mvar size of the filtering necessary. Power line communications require a lower level of interharmonics to function as designed, which means larger (on an Mvar basis) filtering will be necessary. The size of the filters necessary to allow wide spectrum power communications can create unacceptable voltage regulation and cost issues.

CONCLUSIONS

The level of interharmonic distortion on the system is generally low because there are presently few large interharmonic sources on the system. This low level of interharmonics has kept interharmonic related problems relatively rare and the need to measure or mitigate interharmonics uncommon. Interharmonic measurement techniques have been standardized, but there are no mandatory standards for limiting interharmonics. If there were, these limits would likely be similar to existing harmonic and flicker limits, unless they were designed to allow power line communications, in which case they may have to be reduced by approximately an order of magnitude.

Although advances in technology that are increasing the system flexibility are increasing the level of interharmonics on the system, most power system equipment that produces interharmonics produce them at levels significantly below the limits specified for harmonics. This makes it unlikely, at the present time, that interharmonics will cause the problems associated with harmonics on most systems.

Power line communications require lower levels of interharmonics to function properly. These levels can be achieved by filtering for single frequency communications whose frequency can't be changed, but issues with systems that produce wide band interharmonics may only be able to be resolved by eliminating the interharmonic source or removing the communications from the power lines. Wireless communications systems have been used near large interharmonic producing loads, such as industrial arc furnaces, to avoid interharmonic issues.

Today interharmonic issues are resolved on a case-by-case basis. This is reasonable considering the variety and limited number of interharmonic sources and sensitive loads. As the benefits and use of interharmonic generating equipment increases, manufacturers of interharmonic producing equipment and equipment sensitive to interharmonics will need guidelines if they are to design their equipment to be compatible with each other.

BIBLIOGRAPHY

- [1] IEEE Standard 519-2014. "IEEE Recommended Practice and Requirements for Harmonic Control in Electric Power Systems," 2014.
- [2] IEC 61000-2-1:1990, "Electromagnetic Compatibility (EMC) - Part 2: Environment - Section 1: Description of the Environment - Electromagnetic Environment for Low-Frequency Conducted Disturbances and Signalling in Public Power Supply Systems. First Edition May 31, 1990.
- [3] G. T. Heydt, *Electric Power Quality*, West Lafayette, IN: Stars in a Circle Publications, 1991.
- [4] Z. Hanzelka, A. Bien, *Power Quality Application Guide 3.1.1, Harmonics Interharmonics*, Copper Development Association, 2004.
<http://admin.copperalliance.eu/docs/librariesprovider5/power-quality-and-utilisation-guide/311-interharmonics.pdf>
- [5] IEEE Interharmonic Task Force, CIGRE 36.05/CIGRE 2 CC02 Voltage Quality Working Group, Interharmonics in Power Systems, Task Force Working Document, December 1, 1997.
<http://grouper.ieee.org/groups/harmonic/iharm/ihfinal.pdf>
- [6] IEC 61000-4-7:2002 Electromagnetic Compatibility (EMC) Part 4: Testing and Measurement Techniques Section 7: General Guide on Harmonics and Interharmonics Measurements and Instrumentation for Power Supply Systems and Equipment Connected Thereto.
- [7] IEC Standard 61000-2-2:2002 "Electromagnetic Compatibility (ECM) Part 2-2: Environment-Compatibility Levels for Low-frequency Conducted Disturbances and Signaling in Public Low-voltage Power Supply Systems." Second Edition 2002.