ELECTRIC POWER RESEARCH INSTITUTE

PQ TechWatch

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# Understanding
# Harmonics and Interharmonics

November 2011

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## SUMMARY

An interharmonic is a noninteger multiple of the fundamental frequency. Many nonlinear loads that produce harmonics also produce interharmonics, such as variable frequency drives, induction furnaces, cycloconverters, and AC and DC electric arc furnaces. Left unchecked, they can lead to flicker and other system issues.

This *TechWatch* discusses how interharmonics are created and their potential impact on a distribution system. Additionally, application information is presented on how to evaluate harmonic and interharmonic levels and mitigate potential issues that can arise. Accurate measurement data are key in evaluating the potential impacts of harmonic and interharmonic voltage distortion, but these measurements can be difficult to acquire. Several options are discussed for reducing errors from instrument transformers and using advanced signal processing methods to allow for more reliable metering.

Mitigation of harmonics and interharmonics takes the form of either reducing the flow of harmonic or interharmonic current or modifying the impedance that the harmonic or interharmonic current flows through. Capacitor banks or shunt filters are often used successfully to modify the system impedance. Information on the frequency response of each type of filter and how it interacts with the system is delivered here to help in choosing the appropriate harmonic filter design for a particular application.

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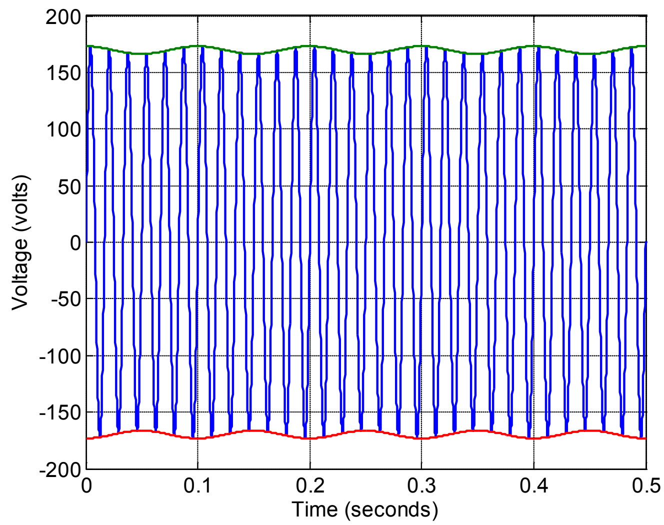
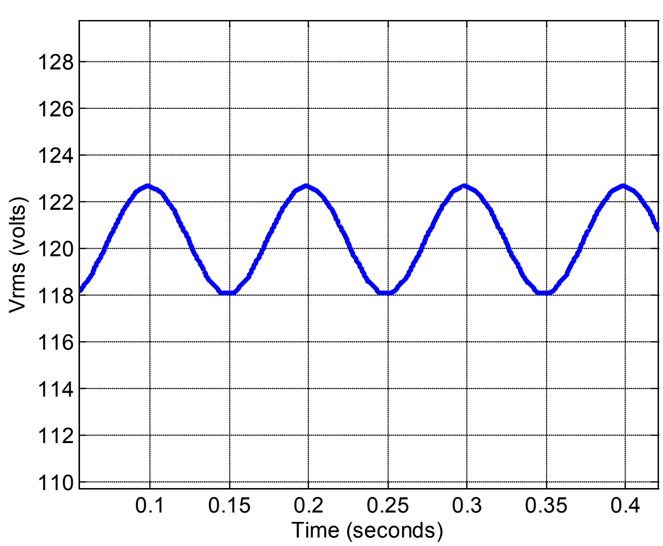
## INTERHARMONICS

The creation of voltage harmonics and the effects harmonics have on distribution systems and end-use equipment have been thoroughly discussed elsewhere,[1] but interharmonics are in need of further attention. Before diving into the subject, a discussion of what interharmonics are and how they are created is appropriate.

### Voltage Waveform with Fundamental and Interharmonic Component




### RMS of Voltage Waveform with Fundamental and Interharmonic Component




### Interharmonics Theory

An interharmonic component is defined in International Electrotechnical Commission (IEC) Report 61000 3-6 as a "component having an interharmonic frequency."[2] For brevity, such components are generally referred to as *interharmonics*. In more simple terms, an interharmonic is a noninteger multiple of the fundamental frequency. For example, a voltage waveform, *v(t)*, containing a fundamental and interharmonic component is described by

$$v(t) = V_m \sin(2\pi 60t) + 0.02 \cdot V_m \sin(2\pi 50t) \qquad (1)$$

where $Vm = \sqrt{2} \cdot 120$. The waveform described by this equation contains a 60Hz fundamental component, and a 50Hz interharmonic component. The waveform is shown graphically in the figure at left. This figure shows that the resulting waveform is amplitude modulated (AM) with a modulation frequency of 10 Hz (60 Hz – 50 Hz). Two interesting features of AM waveforms are: (1) they are aperiodic and (2) their RMS value is time varying. In fact, the RMS value of the waveform described by the equation above varies sinusoidally at a frequency equal to the modulation frequency. To illustrate, the figure at bottom left shows the resulting RMS voltage computed using a one-cycle (16.67 ms) window. As mentioned previously, the resulting RMS voltage varies sinusoidally around 120 V with a period of 0.1 seconds (10 Hz). Consequently, the voltage waveform described by the equation can be problematic if it is a supply source for electric lamps. This phenomenon is referred to as "flicker" and is a common power quality issue.

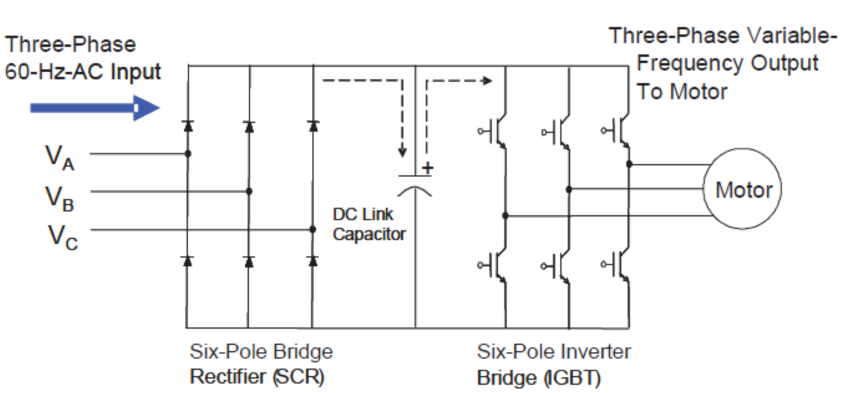
**Unlike with harmonics, not all nonlinear loads generate interharmonics.**

### Interharmonics Generation

Interharmonics are generated by certain nonlinear loads. Unlike with harmonics, not all nonlinear loads generate interharmonics. For example, *n* pulse DC drives do not produce interharmonics. Common nonlinear loads that do generate interharmonics are variable frequency drives (VFDs), induction furnaces, cycloconverters, and AC and DC electric arc furnaces (EAFs). EAFs and induction furnaces are in somewhat of a special category, because they generate randomly varying levels of interharmonics. As will be seen later, induction furnaces (as well as other variable frequency loads) can generate interharmonics whose frequency varies randomly between physical bounds.

In general, power electronic devices that connect two AC systems with different frequencies through a DC link can be an interharmonic source.[3] An example of such a device is a VFD supplying an induction motor, as depicted in the diagram below. The purpose of the VFD is to vary the frequency and magnitude of the motor terminal voltage, thereby modifying the torque-speed curve of the machine and ultimately the shaft speed.

**Circuit Topology of a Typical Variable Frequency Drive**




In general, a frequency converter such as the VFD shown here will generate interharmonics whose frequencies can be described by

$$f_{Ih} = (p_1 m \pm 1) f_1 \pm n p_2 f_0 \quad m = 0, 1, 2, 3, \ldots \quad n = 1, 2, 3, \ldots \qquad (2)$$

where, $p_1$ is the pulse order of the AC-DC converter (rectifier), $f_1$ is the power frequency (50 or 60 Hz), $p_2$ is the pulse order of the DC-AC converter (inverter), and $f_0$ is the operating frequency of the inverter.[4] The interharmonic components described by the equation appear as interharmonic currents at the input terminals of the VFD. The frequencies of these interharmonic currents appear as *side bands* of both the fundamental frequency component and harmonics that are generated by the rectifier. The interharmonics with the largest magnitude are those that appear as side bands of the fundamental frequency component and are described by[5]

$$f_{Ih} = f_1 \pm p_2 f_0 \, . \qquad (3)$$

It is not uncommon for the magnitude of these sidebands to exceed the levels of the characteristic harmonics of the AC-DC converter.[6]

Induction furnaces, such as the one depicted in the figure at the top of the next page, are another application of large frequency conversion devices. The inductance and capacitance shown in this figure form a parallel resonant circuit. The inductance represents the inductance of the scrap metal and induction coil, and is a function of the amount and type of scrap being used as well as the operating temperature. As a result, the "equivalent" inductance varies throughout the melting process. As changes in inductance occur, the output frequency of the inverter is modified appropriately to keep the circuit in resonance; in other words, the output frequency of the inverter is modified in order to maintain the relationship $\omega L = (\omega C)^{-1}$. While in this operating state, the load

**Because interharmonic voltages can cause flicker and other system issues, they should be limited.**

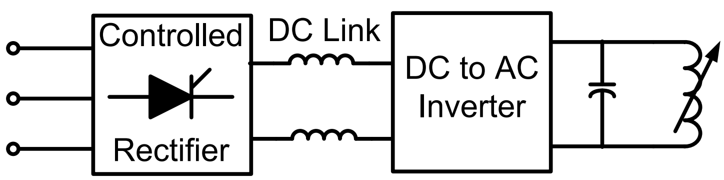
appears purely resistive (resistor representing eddy current loss, etc., not shown in the figure). Therefore, it is advantageous to keep the circuit in resonance.

The typical range of operating frequencies for induction furnaces is 150 to 1200 Hz.[7] Note that because the output frequency of the inverter is constantly changing to maintain a resonant operating condition, the resulting interharmonic spectrum defined in equations 2 and 3 also varies with time. The inverter section of the induction furnace depicted in the circuit diagram is a single-phase current source inverter (CSI). Thus, the pulse number of the inverter is two. According to equation 3, the worst-case interharmonics (those centered around the power frequency) will be of frequencies described by equation 3, where $f_1$ is equal to 60 and $p_2$ is equal to 2:

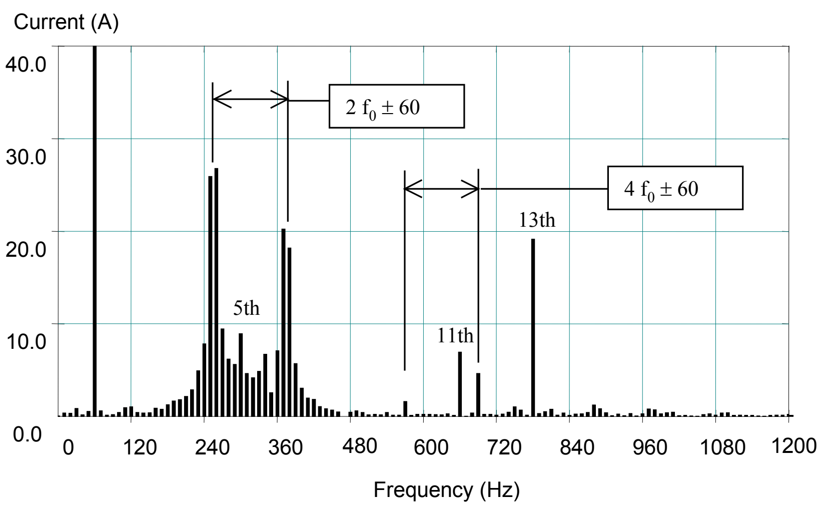
$$f_{Ih} = f_1 \pm p_2 f_0 = 60 \pm 2 f_0 \,. \qquad (4)$$

The figure at bottom left shows the interharmonic current spectrum from a typical induction furnace that is operating at 160 Hz.[8] The interharmonic currents shown are for a single operating frequency. The frequency and magnitude of the interharmonic current spectrum will vary randomly throughout the melt cycle due to changes in operating frequency.

**Circuit Diagram of a Three-Phase Induction Furnace**




**Current Frequency Spectrum of an Induction Furnace Operating at 160 Hz**

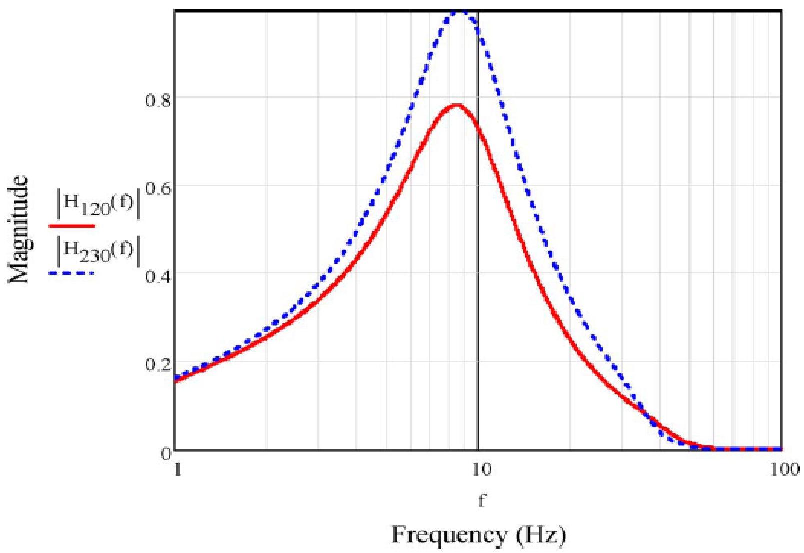



Source: Dugan and Conrad [8].

### Interharmonic Limits

As with harmonics, the flow of interharmonic current through an impedance creates interharmonic voltage. Because interharmonic voltages can cause flicker and other system issues, they should be limited. Similar to their harmonic counterparts, interharmonic limits should be a function of frequency. Although flicker is a subjective phenomenon, the interharmonic frequency is one of the determining factors in whether or not a particular interharmonic voltage will cause visible changes in illumination provided by electric lamps (i.e., flicker). The effect of the lamp-eye-brain response to lamp flicker has been modeled with various transfer functions and is a part of the signal chain of the IEC flickermeter.[9] The overall frequency response of the portion of the IEC flickermeter responsible for modeling the physiological effects of change in illumination on the human eye (Block 3) is provided in the figure on the following page. This frequency response shows the worst-case flicker frequency to be approximately 8.8 Hz,[10] which corresponds to interharmonic voltages of 68.8 Hz and 51.2 Hz.

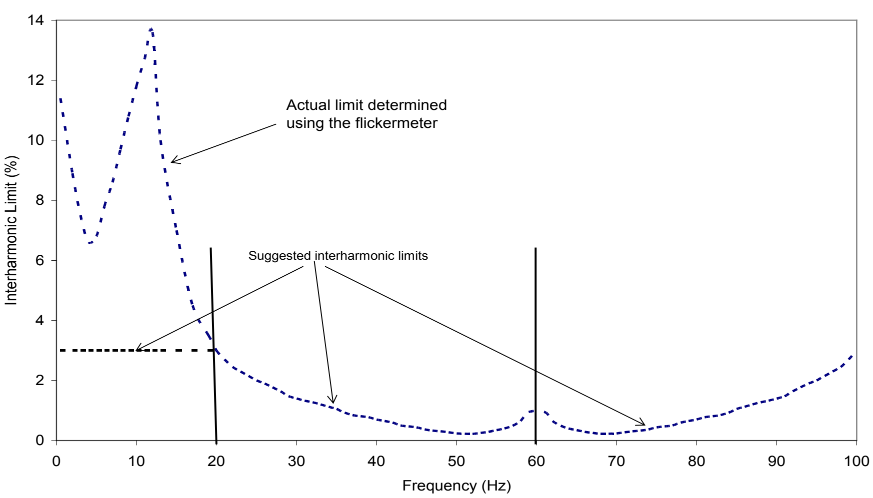
### Overall Frequency Response of IEC Flickermeter Block 3




Source: Horton, Haskew, and Burch [10]

With the concept of frequency dependence in mind, interharmonic voltage limits can be determined.[11] Proposed limits that are currently being evaluated by IEEE Harmonic Task Force (Standard 519) are based on the response of the IEC flickermeter and are shown in the figure below.

### Proposed Interharmonic Limit Curve




Source: Halpin and Singhvi [11]

These suggested limits are based on the level of voltage fluctuation that results in Pst = 1.0. Evaluation of these limits depends on understanding how the IEC flickermeter works. The IEC flickermeter demodulates the input signal and analyzes the modulating signal. The IEC flickermeter then filters the remaining signal (modulating signal) with a bandpass filter that is constructed with a high pass and low pass filter with cut-off frequencies of 0.05 Hz and 42 Hz, respectively. Thus, all input quantities (modulating signals) are band limited from 18 to 102 Hz (60 – 42 Hz and 60 + 42 Hz). Consequently, the flickermeter does not correctly analyze an input signal that has frequency content above 102 Hz. This is a significant limitation since there are documented cases where higher frequency interharmonics have created objectionable flicker. One report provides an example where a 187Hz interharmonic voltage was amplified due to abnormal behavior of a DC electric arc furnace, resulting in objectionable flicker to nearby residential customers.[12]

The concept of interharmonic current limits is also important. Interharmonic current limits for large nonlinear loads such as electric arc furnaces can be derived from interharmonic voltage limits using a reference impedance at the point of common coupling.[13] Such limits can be particularly useful when trying to mitigate the possibility of torsional interaction between an EAF and neighboring steam turbine generators. Interharmonic currents generated by EAFs can excite one or more of the resonant frequencies of nearby steam turbine generators, which can result in damage.[14]

**Depending on the type of instrument transformer being used to perform harmonic and interharmonic voltage measurements, significant errors can occur.**

## MEASUREMENT AND ANALYSIS

Acquiring accurate measurement data is the first step in evaluating the potential impacts of harmonic and interharmonic voltage distortion, and because of the nature of the modern power system, this can sometimes be a daunting task. Assuming that the power quality meter of choice is accurate, two things can make obtaining accurate harmonic and interharmonic data difficult: (1) measurement error associated with instrument transformers and (2) signal processing inaccuracies, with the latter being more related to interharmonics. The following sections describe some of the issues associated with measurement and analysis of harmonic and interharmonic voltages.

### Instrument Transformers

Because of the higher voltages associated with medium voltage (MV) distribution systems and high voltage (HV) and extra-high voltage (EHV) networks, instrument transformers are required to step down primary voltage signals to levels that are usable for metering and protective relaying. Consequently, inaccuracies in the instrument transformers manifest themselves as measurement error. Depending on the type of instrument transformer being used to perform harmonic and interharmonic voltage measurements, significant errors can occur. The following sections briefly describe some of the issues associated with using the various instrument transformers commonly found in MV, HV, and EHV power systems.

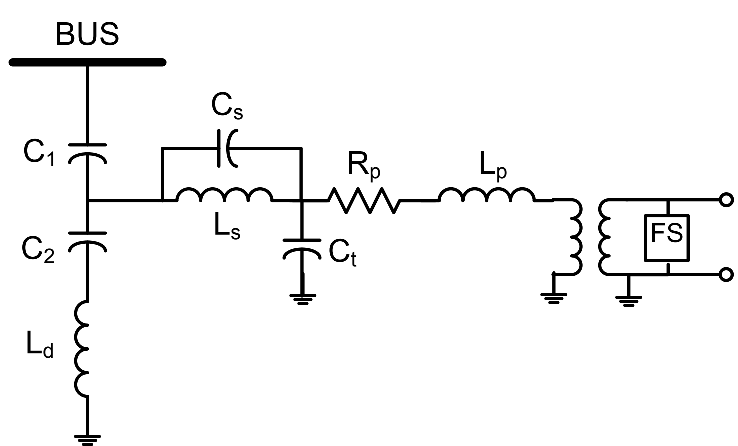
### Capacitively Coupled Voltage Transformers

Capacitively coupled voltage transformers (CCVTs) are commonly used in HV and EHV networks to measure voltage for protective relaying and metering functions. They are far less expensive than wound voltage transformers, and as a result they are used extensively.

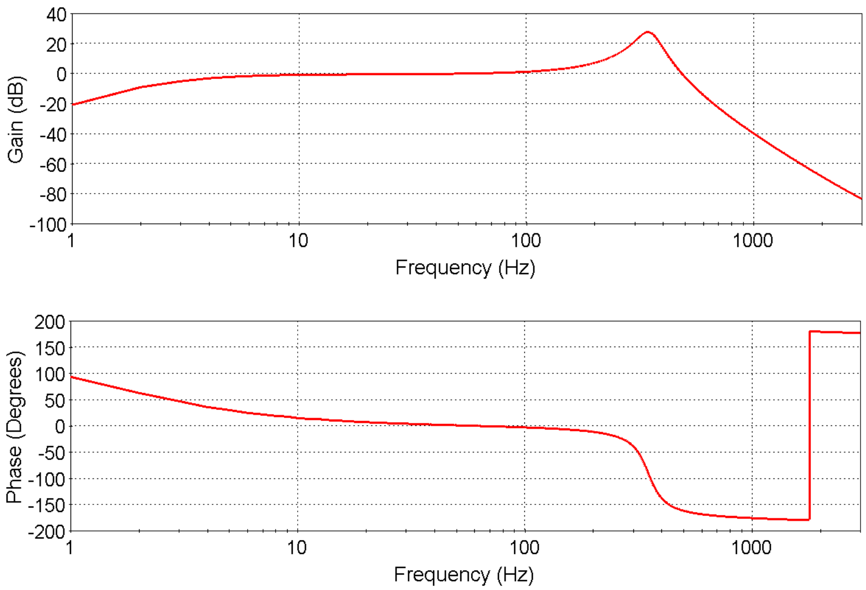
CCVTs are very accurate at nominal frequency; however, they have very poor frequency response at other frequencies, which makes them ill suited for measuring harmonic or interharmonic voltage. This inaccuracy at off-nominal frequency is due to the way in which CCVTs are constructed. To illustrate, an equivalent circuit of a typical CCVT is shown in the figure at left.

In this figure, $C_1$ and $C_2$ are the main capacitances, and $C_s$ and $C_t$ are the stray capacitances of the series reactor and step-down transformer, respectively. $R_p$ and $L_p$ are the resistance and inductance, respectively, of the step-down transformer referred to the high voltage winding. FS corresponds to the ferroresonant suppression circuit and varies among CCVT manufacturers. The combination of these elements results in a very poor frequency response at frequencies other than the fundamental. To illustrate, the figure on the following page shows the frequency response of a typical 242kV CCVT.

**Equivalent Circuit of a Typical Capacitively Coupled Voltage Transformer (CCVT)**



### Frequency Response of a Typical 242kV CCVT




The graphs show the gain is unity (0 dB) and the phase angle is zero at nominal frequency. However, at harmonic and interharmonic frequencies, the per-unit output of the CCVT varies significantly from its input. The table below shows the resulting gain and percent measurement error for several common harmonics.

### Gain and Percent Error for Various Harmonic Frequencies

| Frequency (Hz) | Gain (dB) | % Error |
|---|---|---|
| 60 | 0 | 0.0 |
| 120 | 1.89 | 24.3 |
| 180 | 5.36 | 85.4 |
| 300 | 21.89 | 1143.1 |
| 420 | 12.04 | 299.9 |
| 660 | –19.58 | 89.5 |

These data clearly show that this particular CCVT can not be used to accurately measure harmonics or interharmonic frequency components above 60 Hz. Other CCVTs show similarly poor frequency responses, and as a general rule, CCVTs should not be used to measure harmonic or interharmonic voltages.[15]

### Wound Potential Transformers

Wound potential transformers (PTs) are used less often than CCVTs because of their higher cost. However, they are more accurate, even at nominal frequency, and as a result are sometimes used when metering accuracy is of utmost importance—for example, revenue metering applications. Also, most straight bus applications in HV and EHV networks employ PTs.

The frequency response of a wound PT is more accurate than a CCVT but is limited due to stray capacitances of the transformer. The use of PTs to measure harmonics up to 3 kHz is generally considered acceptable.[16]

### Optical Voltage Transformer and Other Devices

Optical voltage transformers are the most accurate means of measuring harmonic and interharmonic voltages. However, they are more expensive than PTs or CCVTs and require digital-to-analog converters to connect to protective relays and metering equipment. As a result, their use has been limited to date. Some optical voltage transformers have flat frequency response characteristics up to 100s of kHz, making them superior to CCVTs and PTs.

Capacitor voltage dividers and resistance voltage dividers can also be used to accurately measure harmonics. Like optical voltage transformers, they have a flat frequency response characteristic up to 100s of kHz, and in some cases in the MHz range.

## Signal Processing

Understanding the signal processing issues associated with monitoring harmonics and interharmonics is important. Lack of

**Interharmonics do not cause identical distortion in each cycle. Thus, several cycles of data are needed to determine interharmonics.**

understanding can lead to erroneous power quality assessments and conclusions.

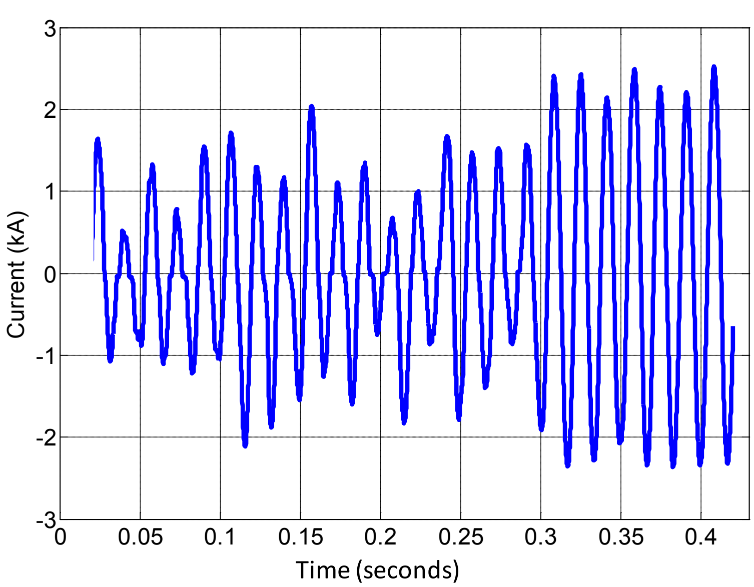
From a signal processing perspective, harmonics are by far easier to determine than interharmonics. As long as the signal is periodic, basic Fourier techniques (e.g., fast Fourier transform [FFT]) with a one-cycle window can be used to determine the harmonic content of the signal with the only limitation being Nyquist's criterion. Nyquist's criterion states that the maximum frequency component to be analyzed should be less than or equal to one-half of the sampling frequency. For example, if a meter is to accurately measure the 7th harmonic (420 Hz assuming fundamental frequency of 60 Hz), the meter must sample at a minimum rate of 840 Hz or 14 samples per 60Hz cycle. Thus, devices that sample at a rate of 16 samples per cycle are generally limited to measuring the 7th harmonic.

As mentioned previously, a one-cycle window can be used to determine harmonics if the signal is periodic. In such cases, the resulting harmonics cause identical distortion in each cycle. Thus, only one cycle of data is required for signal processing. Interharmonics, on the other hand, do not cause identical distortion in each cycle. Thus, several cycles of data are needed to determine interharmonics. The number of cycles required is related to the frequency resolution that is required. The frequency resolution of the FFT algorithm can be determined using the following equation: [17]

$$\Delta f = \frac{f_1}{k} \qquad (5)$$

where $\Delta f$ is the frequency resolution (Hz), $f_1$ is the fundamental frequency (Hz), and $k$ is the number of cycles included in the window. For example, if a frequency resolution of 5 Hz is required (the same resolution required by IEC standards) and the fundamental frequency is 60 Hz, then 12 cycles should be included in the window. Similarly, a 1Hz resolution would require that 60 cycles be included in the window. The problem with using large window sizes is that in some cases the signals are nonstationary, meaning that they vary randomly with time. An example of a nonstationary waveform is provided in the figure below, which shows the measured current at the 34.5kV terminals of an AC EAF transformer during the initial bore-in period.

**Current Waveform of an AC Electric Arc Furnace**



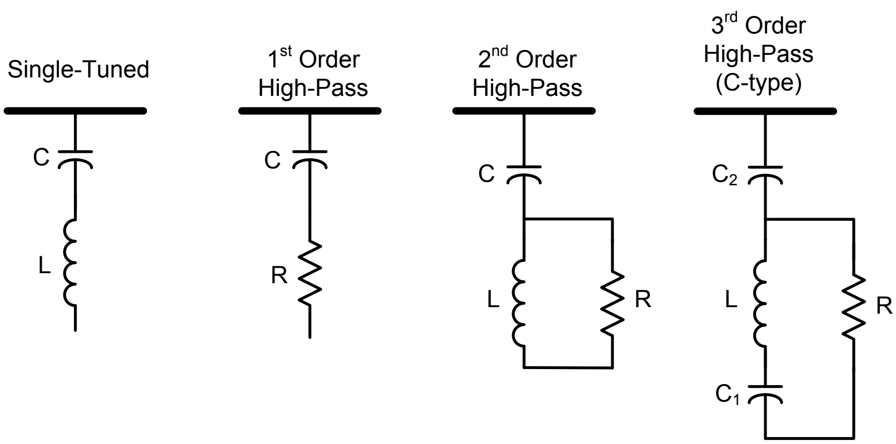

Using a large window to analyze a waveform such as the one shown can result in significant measurement error. More advanced signal-processing methods (such as Prony Method, SVD, MUSIC, etc.) are recommended when analyzing nonstationary waveforms.[18]

## MITIGATION

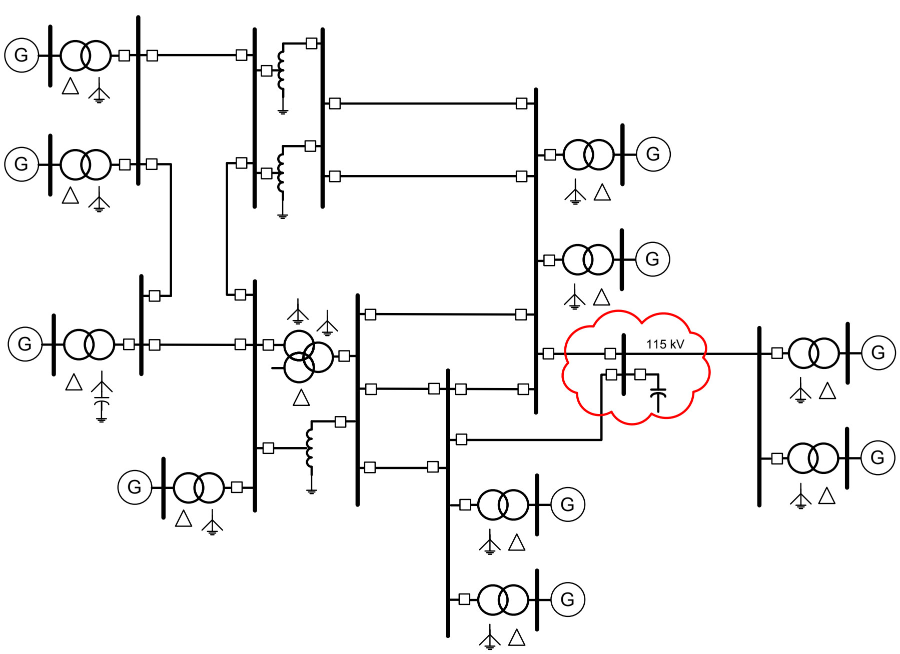
It is well understood that increased harmonic levels can result in problems for utilities and end users alike. Because of the potential problems that can be experienced, harmonic levels should be monitored and limited to satisfactory levels. IEEE Standard 519 provides recommended limits for harmonic levels. Per IEEE 519, utilities are responsible for maintaining harmonic voltage levels to within the specified limits, while end users are responsible for ensuring that their harmonic current emissions are below specified levels.

Harmonic and interharmonic voltages are created by current flow through an impedance. Thus, voltage distortion can be mitigated by either reducing the flow of harmonic current or modifying the impedance that the harmonic or interharmonic current flows through. The system impedance can be modified by the use of capacitor banks or shunt filters. Shunt filters can also be used as a "sink" for harmonic current created by nonlinear loads in order to reduce the amount of harmonic current injected into the system.

**Circuit Topologies of Four Common Types of Shunt Filters**




**Example System in Need of Voltage Improvement**




### Performance of Shunt Compensators

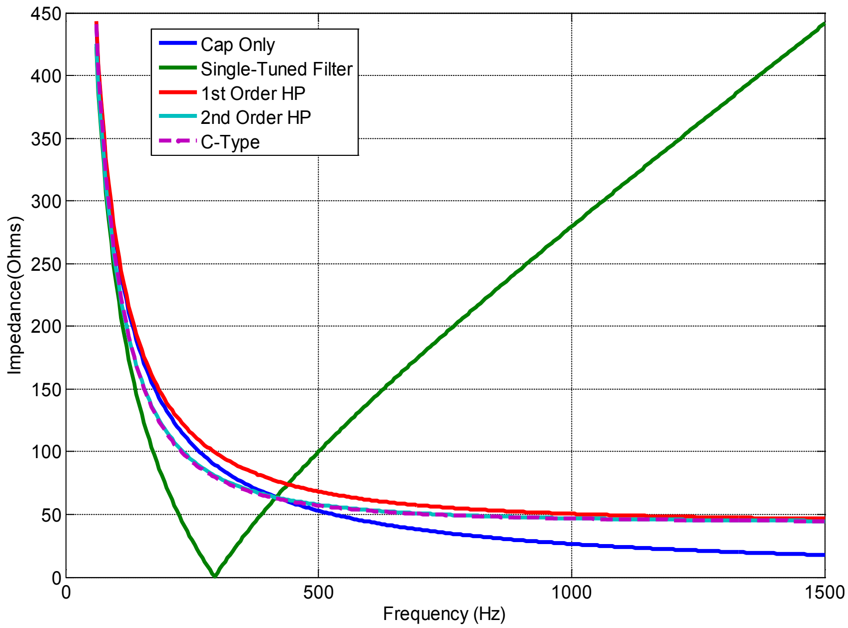
Shunt harmonic filters are typically placed into one of four categories: single-tuned, 1st order high-pass, 2nd order high-pass, or 3rd order high-pass (also referred to as a C-type filter). The figure at left shows the circuit topology associated with each of the four types of shunt filters that are commonly employed.

The most common of the four types of shunt filters are the single-tuned filter and the 3rd order high-pass (C-type) filter, with the latter being more common in transmission applications[19] and low-order harmonic filters for industrial applications and static volt-ampere-reactive compensators.

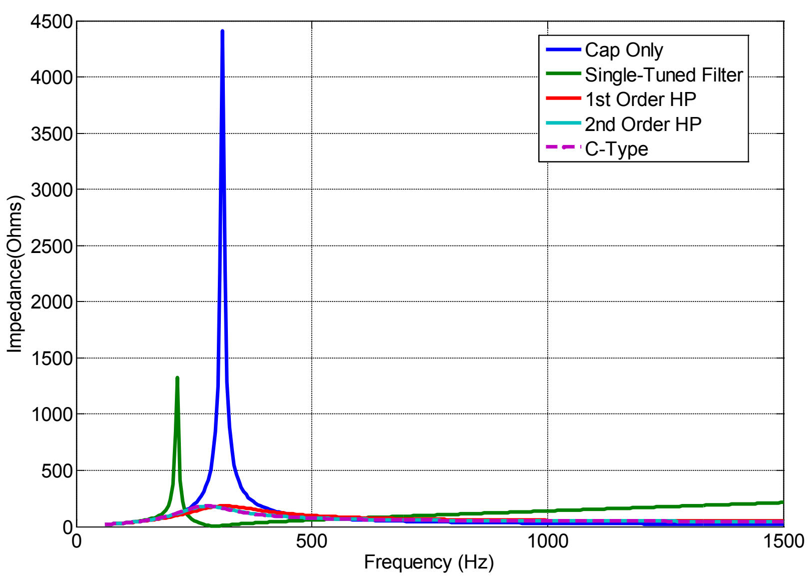
When choosing the appropriate harmonic filter design for a particular application, it is important to understand the frequency response of each type of filter and how it interacts with the system. This is best illustrated by example. The figure at left shows an example system that is in need of voltage improvement.

Assume that 30 MVAR of shunt compensation is required at the highlighted 115kV bus. The figure at the top of the following page shows the terminal frequency response (impedance magnitude vs. frequency looking into the terminals of the shunt device with the device disconnected from the network) for various types of shunt filters and a standard shunt capacitor bank. For this example, the tuned frequency for all shunt filters was chosen to be 294 Hz ($h = 2.9$).

### Terminal Frequency Response of Various Filter Types




### Driving Point Impedance at 115kV Application Bus

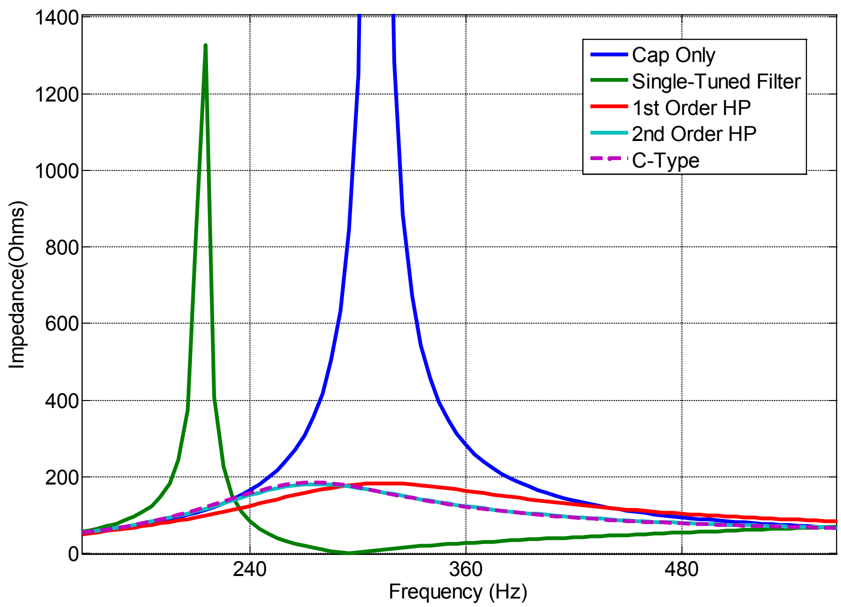



The graph shows that the input frequency responses of all of the filters are essentially the same with the exception of the single-tuned filter. All high-pass filters provide a low impedance path for harmonics over a broad frequency range, whereas the single-tuned filter appears as a short circuit to harmonic current at its tuning frequency with increasing impedance at frequencies higher or lower than the tuning frequency. If one were to solely analyze this graph to assess the performance of each of the filter types, a very erroneous conclusion would be drawn.

Whenever a shunt filter is connected in the system, it interacts with the system impedance, and in some cases, in an extreme way. Consider our example system. Assume that the available short circuit level at the 115kV bus is 800 MVA with X/R of 10. The bottom figure shows the resulting frequency responses of the various shunt devices including the effects of the frequency-dependent system impedance ($R_{sys} + j\omega L_{sys}$). Results provided show that two of the shunt compensators (shunt capacitor and single-tuned filter) create parallel resonances (sharp peaks).The figure on the next page provides a closer view near the area of interest.

When a shunt capacitor is connected to a power system bus, the Thevenin equivalent impedance "looking" into the bus (also referred to as "driving point impedance") is modified significantly by the application of the compensator. In the example here, a parallel resonance was created near 310 Hz. Parallel resonant frequencies near the characteristic harmonics of many common nonlinear loads will likely result in significant increases in harmonic voltage. An increase in harmonic voltage can also lead to substantial increases in harmonic current flow in the capacitor, which can result in loss of life or even damage in extreme cases.

**Driving Point Impedance at 115kV Application Bus (Close-Up View)**




**Mitigation options for radial systems generally focus on minimizing the amount of distorting current that is injected into the system by nonlinear loads.**

Shunt filters also interact with the system impedance. The single-tuned filter presents a very low impedance path at the tuning frequency, but it also creates a parallel resonance. In this example, the parallel resonance occurred near 210 Hz, which is an interharmonic of 60 Hz and one that can be generated by many nonlinear loads such as VFDs, EAFs, and induction furnaces. If a nearby nonlinear load were to inject interharmonic current at 210 Hz, a substantial interharmonic voltage would result that could lead to damaging overvoltages for filter components.

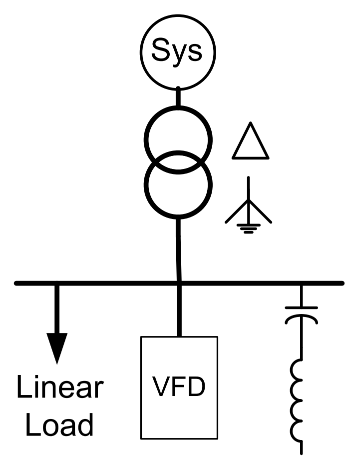
As seen in close-up view, the high-pass filters do not suffer from the same limitations as the capacitor bank or single-tuned filter. However, they do not provide the same low impedance path to currents near the tuning frequency as does the single-tuned filter. There are trade-offs between the filter types, and oftentimes the system type (radial or network) will be a deciding factor in determining the necessary filter type.

## Filter Application in Radial Systems

In radial systems, limiting the harmonic or interharmonic current flow will, in general, reduce the resulting harmonic or interharmonic voltage. Therefore, mitigation options for radial systems generally focus on minimizing the amount of distorting current that is injected into the system by nonlinear loads. The most common method of minimizing the harmonic or interharmonic current injection of nonlinear loads is by the application of single-tuned harmonic filters. The figure below shows a typical example in which a shunt filter is used to reduce the amount of harmonic current injected into the utility system by the nonlinear load (VFD).

A harmonic filter such as the one shown is typically tuned to the lowest characteristic harmonic produced by the nonlinear load.[20] Generally, the filter is tuned slightly below this lowest characteristic frequency to allow for drift in values of filter component. The frequency response of the resulting filter and system is evaluated to ensure that a parallel resonance is not created at a harmonic or interharmonic frequency that is generated by nearby nonlinear loads. Filter ratings are computed using filter Mvar rating, size of nearby nonlinear loads, and background harmonic voltage levels.

**Example Radial System**



**Harmonic filters designed for radial power systems should be designed to accommodate loadings associated with background harmonic voltage levels that are compliant with IEEE 519 standards.**

**Since the overall harmonic current injection of nearby nonlinear loads is unknown in a network power system, the concept of voltage gain must be used to determine the resulting effects on the system.**

The design of a harmonic filter bank applied in a system such as the one depicted in this diagram must be carefully evaluated to ensure that all components are designed adequately. The short circuit impedance at the bus where the filter is connected is typically controlled by the step-down transformer. Thus, large variations in system impedance are typically not an issue for filter applications in radial systems. However, in some situations utility capacitor banks can impact the frequency response of the bus, which in turn affects the loading of the filter. Background harmonic voltage levels should also be evaluated to ensure that filter ratings are determined correctly. Harmonic filters designed for radial power systems such as the one shown in this example should, at a minimum, be designed to accommodate loadings associated with background harmonic voltage levels that are compliant with IEEE 519 standards.

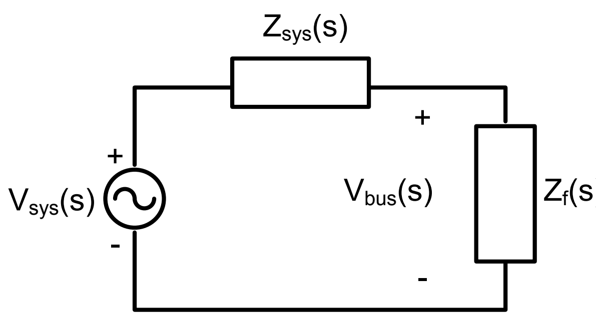
### Filter Application in Network Systems

Although the concept of harmonic filters is rather simple, designing harmonic filters that are to be installed in HV or EHV networks such as the one depicted can be a daunting task. Unlike industrial applications, such as the example radial system depicted here, the harmonic current injected by a particular load or aggregate of several loads is not known nor can it be readily estimated. Such information is simply unknown in a networked power system. Additionally, in a radial power system, the current injection follows a radial path, whereas in a network power system, it is divided among the numerous paths of the network. Consequently, estimated or measured background harmonic voltage levels must be used to determine filter component values and ratings.

Another difficulty that arises in network applications is the existence of shunt capacitor banks that are already in the network. For years, many utilities have been using unfiltered shunt capacitor banks as a means of reactive power support of the HV and EHV network. The existence of shunt capacitor banks tends to create parallel resonances that can cause additional loading of filter components, and as a result, any application of harmonic filters in an HV or EHV network must consider the effects of existing shunt capacitor banks.

Since the overall harmonic current injection of nearby nonlinear loads is unknown in a network power system, a simple application of Ohm's law can not be used to determine the resulting harmonic voltage. Consequently, the concept of voltage gain must be used to determine the resulting effects on the system. The circuit shown below can be used to determine the resulting voltage gain at the point of application, where $Z_{sys}(s)$ represents the frequency-dependent source impedance and $Z_f(s)$ represents the frequency-dependent impedance of the shunt filter or capacitor bank.

**Equivalent Circuit Used to Determine Voltage Gain**




The resulting bus voltage, $V_{bus}(s)$, can be determined using

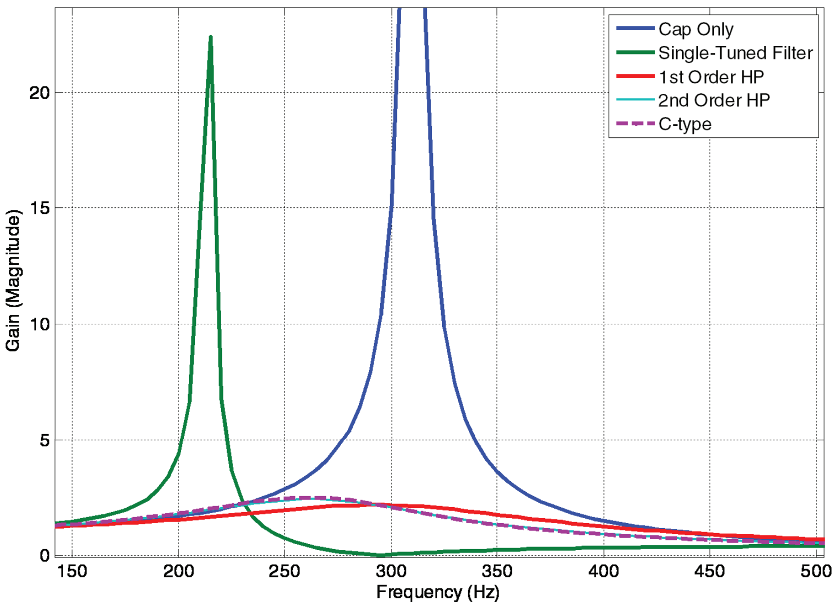
$$V_{bus}(s) = \frac{Z_f(s)}{Z_f(s) + Z_{sys}(s)} V_{sys}(s) \quad (6)$$

Using this equation, the voltage gain is therefore defined as

$$Gain = \left| \frac{V_{bus}(s)}{V_{sys}(s)} \right| = \left| \frac{Z_f(s)}{Z_f(s) + Z_{sys}(s)} \right|. \quad (7)$$

Equation 7 can be used to determine the relative increase or decrease in harmonic voltage that will result from the application of a shunt compensator. This can be illustrated using the previous example system. The figure below shows the resulting voltage gain at the point of application for the various shunt compensators.

### Voltage Gain from Application of Shunt Compensator




An important feature of this figure is to show the relative change of various frequency components; however, to truly evaluate the effects of the shunt device, either measured or estimated background harmonic voltage data must be available. The table below shows the background harmonic voltage levels, resulting harmonic voltage (Vh) levels, and percentage of total harmonic voltage distortion (%Vthd), once a particular shunt compensator is connected to the 115kV bus.

Results in the table indicate that the addition of a shunt capacitor bank would cause the resulting harmonic voltage levels to far exceed the recommended levels specified in IEEE 519. All other filters maintain acceptable levels of harmonic voltage distortion. The question then becomes, which of the filters is best suited for the environment in which it is placed? The single-tuned filter is adequate for radial power systems, but it is susceptible to detuning caused by variations in system impedance when applied in network power systems; thus, it has limited use in HV or EHV networks. First and second order high-pass filters perform adequately; however, they are very lossy and, consequently, are not

### Harmonic Voltage Data

| h | Vh (%) | Cap Only (%) | Single-Tuned Filter (%) | 1st Order High-Pass (%) | 2nd Order High-Pass (%) | C-type (%) |
|---|---|---|---|---|---|---|
| 2 | 0.50 | 0.59 | 0.61 | 0.58 | 0.60 | 0.60 |
| 3 | 0.50 | 0.75 | 1.08 | 0.71 | 0.79 | 0.80 |
| 5 | 0.50 | 7.57 | 0.02 | 1.09 | 1.04 | 1.04 |
| 7 | 0.50 | 0.60 | 0.18 | 0.55 | 0.41 | 0.40 |
| 11 | 0.50 | 0.14 | 0.24 | 0.20 | 0.17 | 0.16 |
| 13 | 0.50 | 0.09 | 0.24 | 0.15 | 0.13 | 0.13 |
| Vthd% | 1.22 | 7.65 | 1.30 | 1.55 | 1.51 | 1.51 |

preferred. The C-type filter performs adequately over a broad frequency range and has very low loss at 60 Hz. Therefore, it is the preferred filter configuration for HV and EHV applications.

## NOTES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