Review

Interharmonics: basic concepts and techniques for their detection and measurement

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Abstract

The term interharmonics refer to those frequencies that are not integral harmonics of the supply fundamental frequency. Although international organizations defined the terminology and proposed measurement guidelines, difficulties still exist in its detection and measurement with acceptable accuracy. When interharmonic components appear in a spectrum, it is still debatable if they really exist and, if the answer is yes, what are the actual frequencies and magnitudes of the components. This paper reviews the mathematical basis of the interharmonics and discusses the difficulties in detecting and measuring interharmonics. A few practical rules are proposed to assist the measurement of interharmonics. Simulations, laboratory experiment and field test results are provided to illustrate the difficulties in interharmonics analysis.
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1. Introduction

Lots of work has been done in the field of interharmonics. This terminology has been officially defined by IEC-1000-2-1 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' [1]. A recent IEC-61000-2-2 draft re-defines interharmonic as 'Any frequency which is not an integer multiple of the fundamental frequency' [2]. IEEE Interharmonic Task Force adopted IEC definition and recommended inclusion of interharmonics for next IEEE 519 revision [3]. Large mount of work has been published on subjects such as interharmonic sources, impacts, measurement, limit values and mitigation [4–7]. However, the difficulties in finding accurate interharmonic frequency and magnitude still keep this field with many questions.

Interharmonic is a non-integral order component. Therefore it is necessary to use a long window to obtain adequate resolution for interharmonics detection. How-

ever, power system signals are seldom stationary. The non-stationary nature of waveforms could corrupt the spectrum analysis results. This is one of the main difficulties interharmonic analysis faces. In this paper, we will address such problems by using mathematical analysis, simulations and field measurements. The paper reviews the mathematical basis of interharmonics at first. A few real interharmonic sources are then presented and the difficulties in finding the interharmonic components are discussed. The paper also lists several loads that could be wrongly considered as interharmonic sources. Finally, this paper proposes some practical rules for interharmonic measurement and detection. The pros and cons of IEC/IEEE recommended interharmonic measurement standards are commented in the last part of the paper.

2. Mathematical basis of interharmonics—a review of Fourier transformation

The harmonic concept is based on Fourier analysis whose motivation is to reconstruct non-sinusoidal periodical waveshape by a series of sinusoidal components. If $x(t)$ is a continuous periodical signal with period of T and it satisfies Dirichlet condition, we can

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represent it by a Fourier series of:

$$x(t) = \sum_{k=-\infty}^{\infty} X(k\Omega_0)e^{jk\Omega_0 t} \tag{1}$$

where $\Omega_0 = 2\pi/T$ is called fundamental frequency, $X(k\Omega_0)$ is the Fourier coefficient at the kth harmonic.

This implies that a non-sinusoidal periodical signal can be separated into a series of sinusoidal components with frequencies which are integral multiples of the fundamental frequency. Note for the Fourier series, both the time and frequency domain signals have infinite length.

In order to implement Fourier analysis in computer, the signal in both time and frequency domain must be discrete and have finite length. Discrete Fourier transform (DFT) is then introduced:

Assume $x(t)$ is sampled with a rate of N points per cycle, i.e., $T_s = T/N$, its DFT will be:

$$X(\omega_k) = \sum_{n=0}^{N-1} x(n)e^{-j(2\pi/N)nk}, \quad k = 0, 1, \ldots, N-1 \tag{2}$$

where $\omega_k = (2\pi/(T_sN))k = (2\pi/T)k$, $X(\omega_k)$ is the so-called spectrum of $x(n)$. Here $x(n)$ is assumed to be one cycle of a periodical signal, in another word, the signal is supposed to precisely repeat itself for every N point. The angular frequency resolution of the spectrum is determined by the length of the signal as:

$$\Delta\omega = \frac{2\pi}{T} \tag{3}$$

Thus, if T is selected as one period of $x(n)$, the outcome spectrum will only have components that are integral multiple of the fundamental frequency, they are defined as harmonics. If the data length is selected as p cycles ($p > 1$) of the fundamental, however, the frequency resolution will change as;

$$\Lambda\omega = \frac{2\pi}{pT} = \frac{\omega_1}{p} \tag{4}$$

This implies that once we use more than one fundamental cycle to perform DFT, it becomes possible to get a component whose frequency is not integral multiple of the fundamental. These non-integral order components, according to IEC definition, are called interharmonics. In summary, a necessary condition for interharmonic detection is that the sampled data for DFT operation must cover multiple fundamental cycles. For example, if we select five 60 Hz cycles for DFT, the frequency resolution will be: $\Delta f = 60/5 = 12$ Hz, then it will be possible to get non-zero bins at frequencies of 12, 24, 36 Hz,... These components, whatever the cause is, are defined as interharmonics.

There are various causes that could lead to the above defined interharmonic components. One example is a signal that actually contains a component whose frequency is non-integral multiple of the fundamental frequency. If the sampling window is selected properly so that there are exactly integral cycles of that component in the window, we can find it at the right frequency. These are genuine interharmonics. For example, assuming a signal consists of two frequencies: $x(t) = \sin(2\pi60t) + 0.5\sin(2\pi90t)$, the 90 Hz component lies between the fundamental frequency and the 2nd order harmonic and is a genuine interharmonic. The signal will repeat itself every two 60 Hz cycles (33.3 ms). So if we perform DFT on this signal with a window size of 33.3 ms, the aforementioned assumption for DFT, the windowed waveform repeats itself, can be satisfied. The frequency resolution will be $60/2 = 30$ Hz, consequently we can find the 60 Hz component at the 3rd bin and the 90 Hz at the 4th bin as shown in Fig. 1. This is the case of genuine interharmonics where the spectrum represents actual signal components.

There are cases, however, where the inter-harmonic components are produced by spectrum leakage or picket-fence effect of the DFT. The leakage effects can 'create' new interharmonic components in the spectrum even though such components do not exist at all. For instance, if the frequency of the non-integer harmonic component is changed to 100 Hz in last example and we still select window size of 33.3 ms, the window will contains 3.33 cycles of 100 Hz component. Since DFT assumes the windowed waveform will repeat itself outside the window, the repetition of the 100 Hz component is therefore incomplete. The waveform 'seen' by the DFT is different from the actual waveform, as shown in Fig. 2. This leads to the creation of additional spectral components. The picket-fence effect is a phenomenon where the resolution of the spectrum is such that certain frequencies are not visible or available. For example, a 33.3 ms window length give a frequency resolution of 30
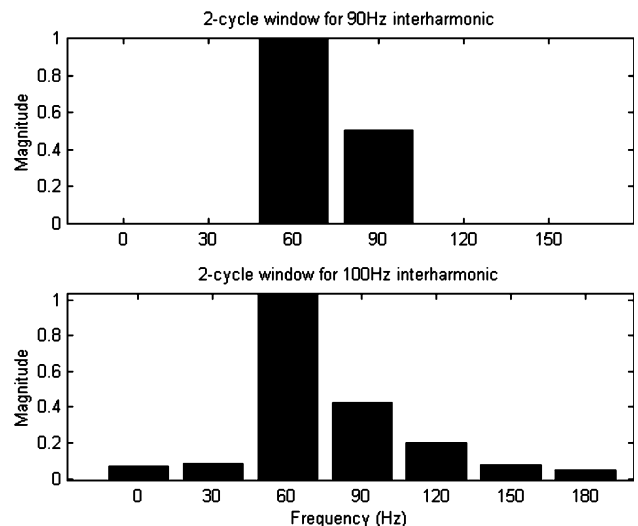

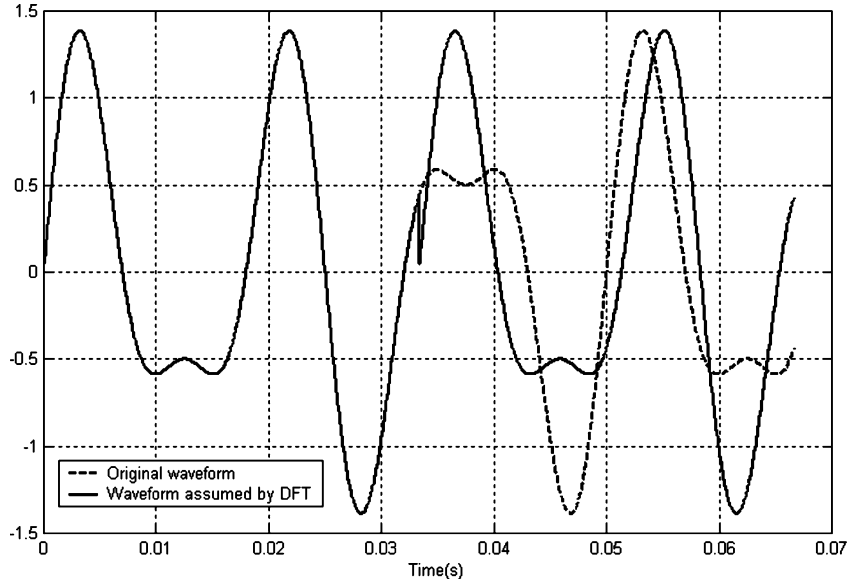Fig. 1. Different interpretation of 90 Hz spectrum.

Fig. 2. Effect of non-integral cycle truncation.

Hz. In other words, the DFT only provides components at 30, 60, 90 Hz etc. If we apply this window to the example signal, the 100 Hz component cannot be seen. Instead, we will see a non-zero component at the 90 Hz (Fig. 1).

The second cause that can give misleading interharmonic results is related to the non-stationary nature of power system voltages and currents. Since multi-cycle window is needed to find interharmonics, the non-stationary characteristic of a signal could corrupt DFT results more easily. This problem will be discussed in detail later. In summary, interharmonics are resulted from the use of multi-cycle windowed DFT. We should not take it for granted that 'interharmonic' components calculated from the DFT really exist in the original signal.

3. Genuine interharmonics sources

There are some types of loads that indeed introduce interharmonics. This section will list some examples.

3.1. Interharmonic sources

As an example of interharmonic sources, cycloconverter gains the most consensus. The current harmonics introduced by cycloconverter are thoroughly documented in [8] as:

$$f_i = (p_1 m \pm 1)f \pm p_2 n f_0 \qquad (5)$$

where p_1: pulse number of the rectifier section; p_2: pulse number of the output section; m, n: integers; f: power frequency; f_0: output frequency of the cycloconverter.

It is not difficult to understand the interharmonic injections by cycloconverter since it directly connects two different frequencies. More generally, power electronic equipment that connects two AC systems with different frequencies through a DC link can be an interharmonic source. Variable speed drives, HVDC and other static frequency converter are typical examples of this class of sources. Their common features are that they contain a AC–DC rectifier and a DC–AC inverter, the rectifier and inverter are coupled through a reactor or capacitor. If the reactor or capacitor has infinite value, there will be no any ripple on the DC side. As a result, an ideal rectifier will only generate characteristic harmonics of:

$$f_h = (pn \pm 1)f \qquad (6)$$

where p is the pulse number of the rectifier, f is the power frequency.

In practical, however, the DC side has finite reactor or capacitor value and, consequently, ripples at DC side are inevitable. The converter's AC side will be modulated by the DC ripple and interharmonics could be produced. For example, for a six-pulse rectifier, its characteristic frequencies are 60, 300, 420 Hz... If its DC side has a ripple of $f_r = 177$ Hz, the AC side current will be modulated as 177 ± 60, 300 ± 177, 420 ± 177 Hz,... These are interharmonic components. In general, the DC side ripple frequency can consist of a series of components determined by the inverter pulse number, control method and the inverter output frequency. If the pulse number of the inverter is p_2 and the output frequency is f_0, the DC ripple will contain frequencies of

$$f_r = n p_2 f_0 \qquad (7)$$

where n is an integral number. These frequencies will

modulate with the rectifier's characteristic harmonics in Eq. (6), so the AC side total output will be in the form of Eq. (5) as the cycloconverter. In fact, cycloconverter can be regarded as a special frequency converter without DC link.

Another group of interharmonic sources is the periodically varying load, such as arc furnaces. The frequency at which the load varies will determine the frequencies of interharmonics. Assuming the system voltage is $V(t) = \sin \omega t$ and a load has a characteristic of $R(t) = 1 - r \sin \omega_m t$, where $r < 1$ and ω_m is the load varying frequency, then the load current can be found as:

$$I(t) = \frac{V(t)}{R(t)} = \frac{\sin \omega t}{1 - r \sin \omega_m t} = \sin \omega t (1 + r \sin \omega_m t + r^2 \sin^2 \omega_m t + r^3 \sin^3 \omega_m t + \cdots) \qquad (8)$$

Further mathematical operation on the above equation can show that $I(t)$ contains components of $\omega \pm \omega_m$, $\omega \pm 2\omega_m$, $\omega \pm 3\omega_m \ldots$ As a result, interharmonics will appear in the current spectrum as long as ω_m is asynchronous with ω. Fig. 3 shows an example when $\omega_m = 8$ Hz and $r = 0.5$. It can be seen that the current waveform is modulated by a 8 Hz component. Interharmonic components of 36, 44, 52, 60, 68, 76, 84 Hz are visible in the spectrum, which are consistent with the predicted 60 ± 8, 60 ± 16, 60 ± 24 Hz. The window size used for spectrum analysis is 15 cycles, which has resolution of the maximum common divider of all components, 4 Hz. This size ensures exactly integral cycles are covered in the window for all components hence leakage effect can be eliminated. It is important to note that this kind of low frequency fluctuation is usually a source of light flicker. In this example the flicker frequency will be 8 Hz, which is very sensitive to human's vision. The interharmonics are at low frequency around 60 Hz in this example. In fact, any interharmonic components can be generated in a similar way as long as the load can vary fast enough. Fig. 4 gives another example when ω_m is changed to 172 Hz. The current signal is still modulated at 8 Hz, the visible spectrum components are consistent with the theoretical prediction. The interharmonics are located at higher frequency band, but they can also cause flicker for some types of lamps [3].

3.2. Interharmonics and flicker

Eq. (8) has revealed that a modulated signal may contain interharmonic. It is equally interesting to investigate the reverse of the above phenomena, that is, if there are interharmonics in the signal, will flicker or modulation occur? The answer is YES, as long as the interharmonic is close to a harmonic (or fundamental) frequency. As widely known, the harmonics are always in synchronous with the fundamental. A signal will have same RMS and peak values for each fundamental cycle if it contains harmonics only. The interharmonics, however, is asynchronous with fundamental and harmonics. As a result, the peak value and RMS value of the total signal will vary cycle by cycle if interharmonic exists. If a signal contains an interharmonic component
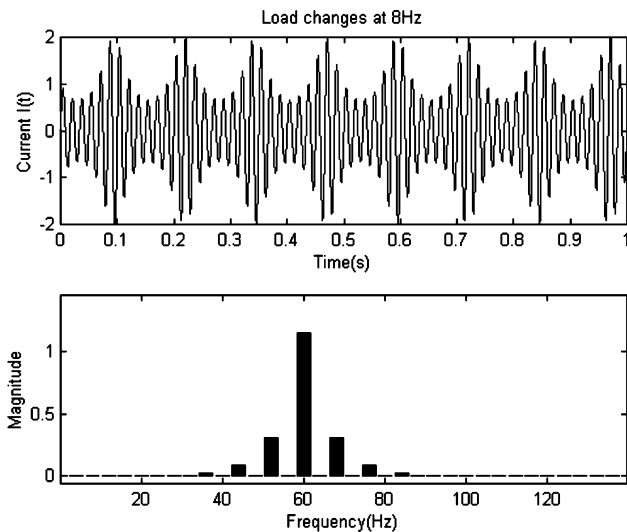
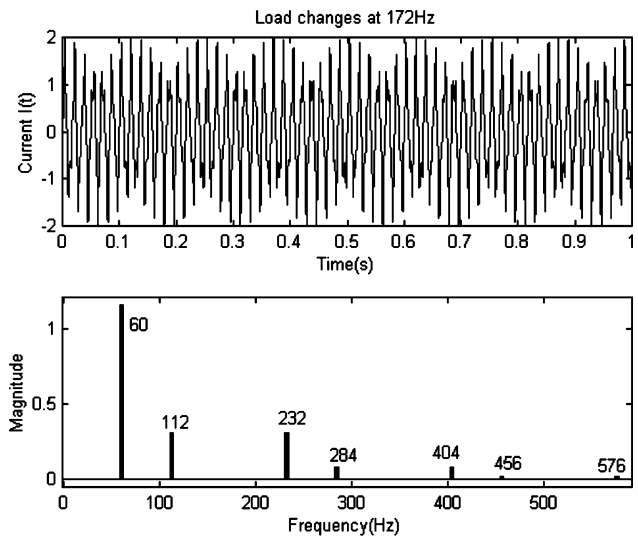Fig. 3. Low frequency interharmonics introduced by load varying.

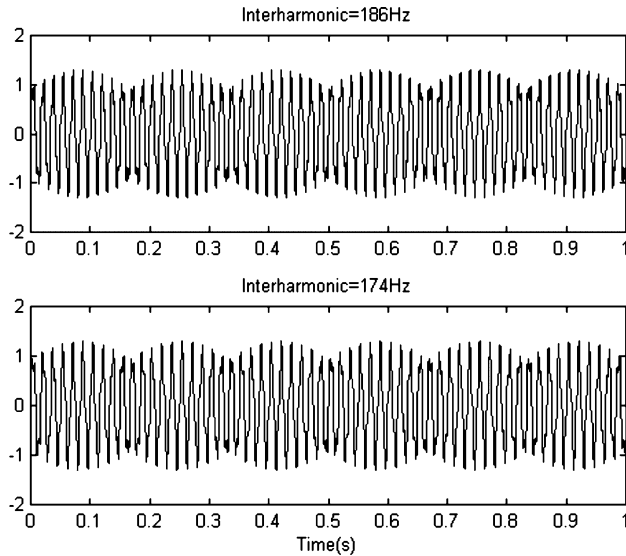Fig. 4. High frequency interharmonics introduced by load varying.

Fig. 5. Flicker caused by interharmonic.

with frequency of ω_i, its envelop will fluctuate at frequency of ω_f which is determined by:

$$\omega_f = |\omega_i - \omega_k| \qquad (9)$$

where ω_k is frequency of the harmonic that is closest to ω_i [9]. Since human eyes are most sensitive to light flicker at frequency around 8 Hz, interharmonics at this distance to a harmonic may cause significant vision disturbance. As an example, Fig. 5 shows the waveform of a signal $\sin(2\pi 60 t) + a\,\sin(2\pi f_i t)$, where $a = 0.3$, f_i is 186 and 174 Hz, respectively. It can be seen that the envelops of the waveforms display an obvious 6 Hz fluctuations, which may cause flicker if the light load is sensitive to such peak value variations [3].

4. Fake interharmonic sources

Due to the limitation of the DFT based spectrum analysis, it is possible that some waveforms can be wrongly interpreted as containing interharmonics. In this section, we discuss two such cases.

The first case involves non-stationary signal. Power system inherently has many variations, such as load change, that can result in non-stationary waveforms. Harmonics and interharmonics, however, are defined on the basis of stationary signals, that is, the waveform to be analyzed is supposed to repeat itself periodically. When we apply DFT on non-stationary signals, this basic assumption is violated. There will be no certainty that each spectral component generated by DFT really exists. Fig. 6 shows a laboratory measured transformer inrush current, which can be considered as an extreme example of non-stationary signal. Fig. 7 plots its spectra when the first 12 and 60 cycles are used for rectangle-windowed DFT, respectively. The DC and fundamental

component are omitted for better readability. The charts in the right hand side plot spectra around the 6th and 7th harmonics to show the effect of non-stationary characteristics on spectrum analysis. It can be seen if 12 cycles are used, there are two distinct peaks at 360 and 420 Hz. One can state that the system contains 6th and 7th order harmonics. If the window size is extended to 60 cycles as shown at the bottom right, however, the 360 and 420 Hz components appear as valleys. Their adjacent components, 353–359 Hz, 361–371 Hz, 414–419 Hz and 421–425 Hz have higher amplitude. The conclusion is therefore significantly affected by the length of sampling window. This ambiguity is inherently caused by the non-stationary nature of inrush current.

The second case of fake interharmonic source is the integral cycle control (ICC) load that is used in ovens, furnaces or other heating applications. ICC operates by chopping the voltage to zero in increments of some integral cycles in a periodic fashion. Fig. 8 illustrates the waveform of such a load and its spectrum, where the voltage is chopped to zero for one cycle periodically after every three-cycle normal operation. Rich non-integral harmonic bins can be found from this figure, but we must be very careful to label them as inter-harmonics. For example, the spectrum shows components of 30 and 90 Hz. Are they real interharmonics? As we know, if a signal really contains 30 and 90 Hz components, it can always be detected by using any window with size of two fundamental cycles because the resolution 30 Hz is their common divider. But for the ICC waveform in Fig. 8, it is obvious that we can have only one 60 Hz bin if we select the first two cycles for spectrum analysis. This fact denies the existence of 30 and 90 Hz components.

5. Detection and measurement of interharmonics

There are two problems need to be addressed in interharmonics analysis: firstly one needs to confirm if the fractional order components calculated from DFT do exist. Secondly one needs to determine the magnitudes and frequencies of the interharmonics with acceptable accuracy. The difficulties in these problems, as aforementioned, are mainly due to leakage and picket-fence effects. A thorough solution for these effects is to select window width as exact integral multiple of all signal periods. That is, select frequency resolution as a common divider of the frequencies of all components in signal. This is called synchronization in some literature [6]. However, synchronizing to inter-harmonics is practically infeasible because the frequencies of interhamonics are usually unpredictable or the ideal window size is too large. The interharmonics analysis, therefore, inherently encounters difficulties introduced by spectral leakage and picket-fence effects.
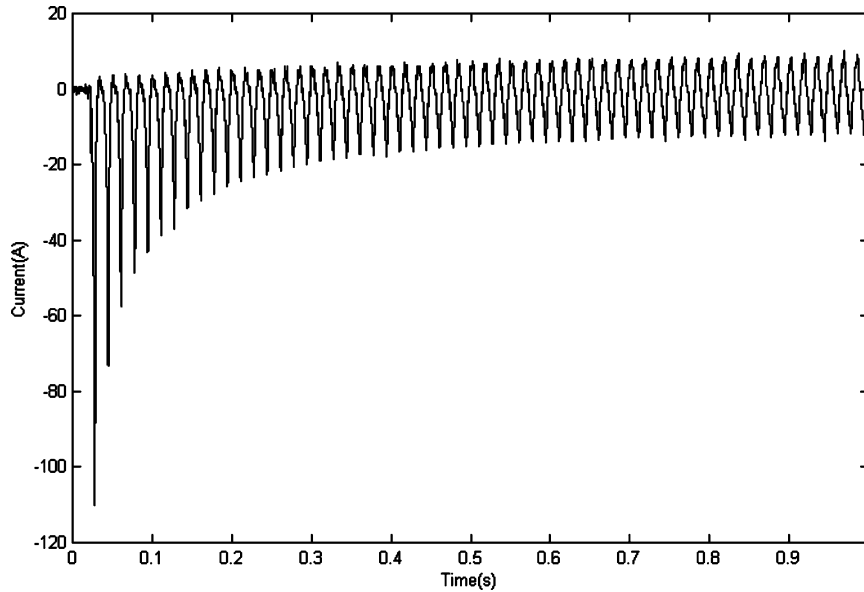
Fig. 6. Transformer inrush current.

There are huge amount of literatures presenting signal processing techniques to reduce these effects. In this paper, however, we propose the following practical guidelines for interharmonic detection and measurement.

5.1. Practical methods for interharmonic detection

Engineering experiences and judgements can play an important role in detecting interharmonics. Here we will use a field test example to demonstrate this point. Fig. 9 shows a system we monitored, where the 4.16 kV bus supplies a variable speed drive. The rectifier's pulse

number of the VSD is 12, the inverter's is 6. Current and voltage waveforms at the measurement point are shown in Fig. 10 when VSD output is set at 30 Hz. Ripples can be seen from the waveform envelope, light flicker was reported at that site before the measurement. We have used the following practical methods to diagnose this interharmonic caused problem.

Rule 1. If the magnitude of a signal appears modulated, it is very likely that the signal contains interharmonics.

An interharmonic can beat with a certain harmonic component (or fundamental), which result in that, as we
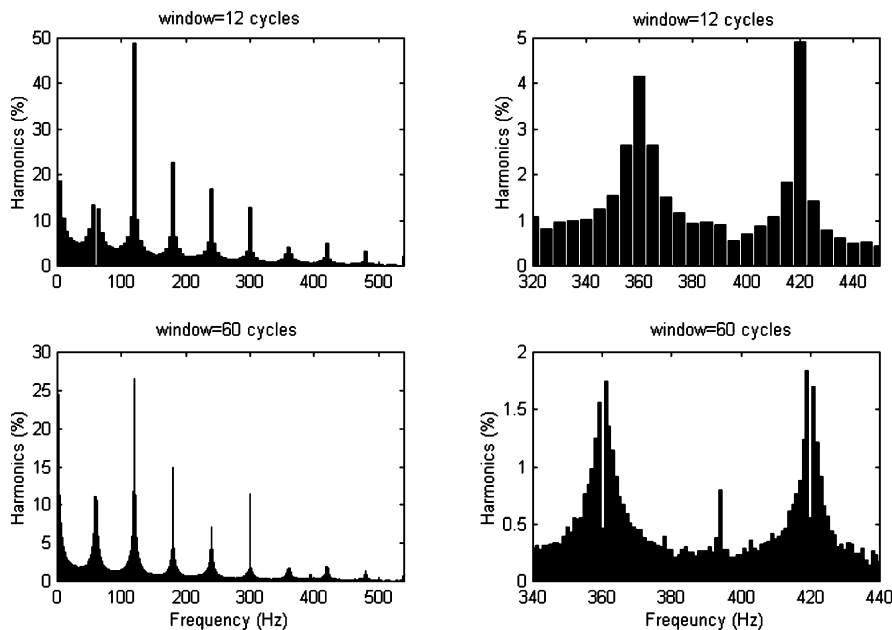

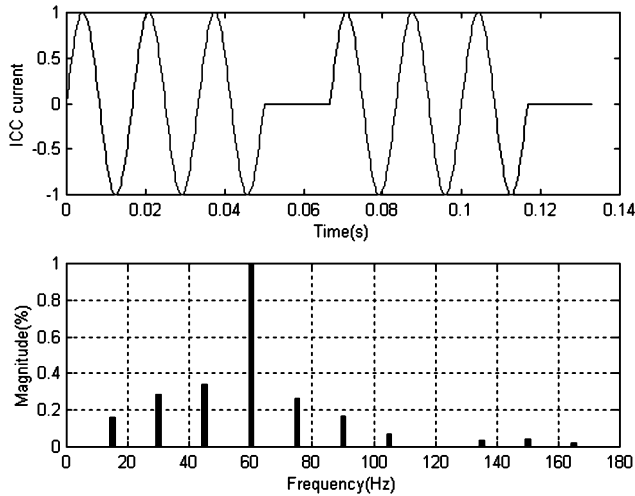Fig. 7. Spectrum of the inrush current for different window sizes.
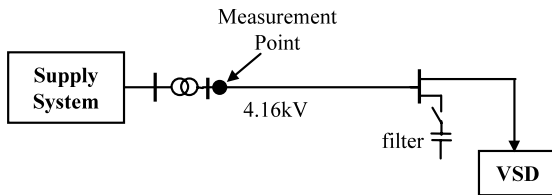
Fig. 8. ICC waveform and its spectrum.

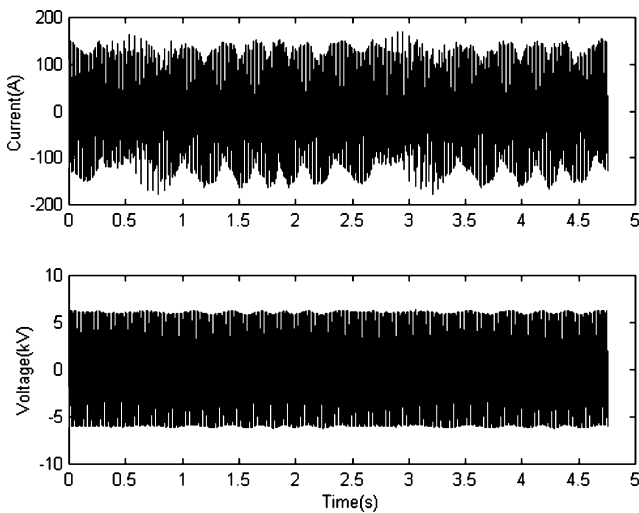Fig. 9. Diagram of the field measurement system.

Fig. 10. Waveform at the measurement point.

illustrated in Section 3, the envelop of waveform may have obvious ripples. Inversely if such ripples are observed as in Fig. 10, it is reasonable to guess interharmonics exist in the signal. In order to verify this assertion, Fig. 11 shows the current and voltage spectra of the waveforms in Fig. 10 when 12- and 60-cycle windows are used, respectively. It can be seen that there is a component of 235 Hz (window size = 12 cycles) or 236 Hz (window size = 60 cycles) in both current and voltage spectra. There is also a component
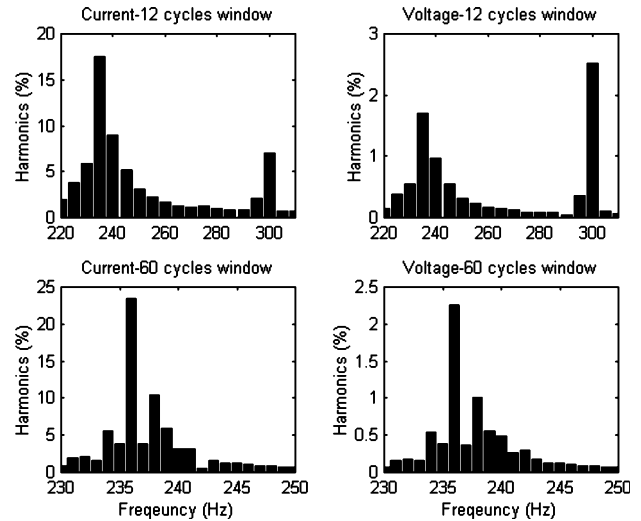

Fig. 11. Current and voltage spectra with different window sizes.

of 115 (window size = 12 cycles) or 116 Hz (window size = 60 cycles) in the spectrum which is not shown in the figure. The correlation of the current and voltage spectra encourages us to believe the interharmonics do exist. This interharmonic component (235 or 236 Hz) is close to a harmonic (4th), therefore, it intends to cause flicker. The existence of these two components can be well explained by Eq. (5). Here reference of f_0 is set as 30, $p_2 = 6$, $p_1 = 12$. If the inverter output frequency has a minor deviation from 30 Hz, for example, 29.4 Hz, the DC link reactor will has ripple frequency of $6 \times 29.4 = 176$ Hz. This ripple will beat with fundamental and consequently $60 + 176 = 236$ Hz and $176 - 60 = 116$ Hz interharmonics will be generated.

Rule 2. If interharmonics do exist, the voltage and current spectra should show correlation.

A genuine interharmonic injection will generate voltage drop along system impedance. Therefore both
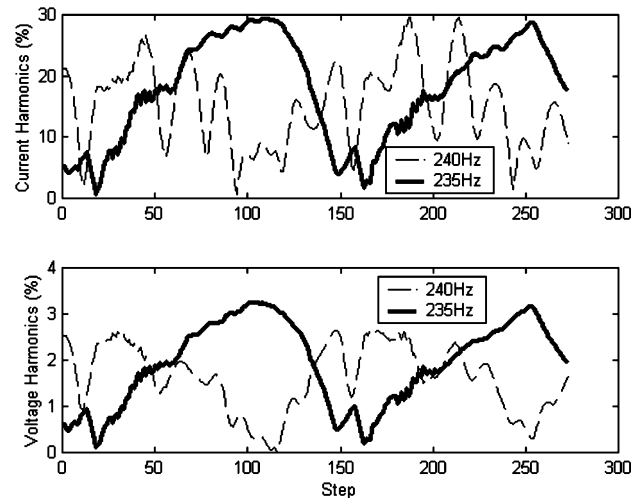

Fig. 12. Current and voltage trends comparison.

the voltage and current spectra should display similar trends at that frequency. In another word, they should be correlated. Fig. 12 plots 235 and 240 Hz component trends when 12 cycles window is applied. The window slides at a step of one cycle. Clearly the 235 Hz current and voltage trends have similar shape, indicating correlation between them. This is helpful to confirm the existence of that interharmonic. The 4th harmonic component, however, shows no correlation between voltage and current, which implies that the bin at 240 Hz is very likely leakage from other component.

Rule 3. Interharmonics usually coexist with harmonics.

As aforementioned, the major interharmonic sources are power electronic based devices, which usually introduce rich harmonics too. Real interharmonics components, therefore, are reasonably expected to be accompanied by rich harmonics. Otherwise we should check the non-integral bins carefully to confirm their real cause. The ICC spectrum shown in Section 4 is a typical example of non-coexist of harmonics and interharmonics, from which it can be concluded the fractional order components are fake interharmonics.

Rule 4. Use long window size if applicable.

Another practical method is to use longer window size if applicable. If the signal is almost stationary and enough data are available, longer window size can improve frequency resolution and help to locate the interharmonic more accurately. Fig. 11 has shown that 60-cycle window size result is more convincing than the 12-cycle one for confirming the existence and location of interharmonic. Of course, if the signal is significantly non-stationary, long window should be avoided.

5.2. Use zero-padding to locate interharmonic frequency

'Picket fence' effect is an important factor which may deteriorate interharmonics measurement. When only limited data length is available, the spectrum we obtained is like observing the true spectrum through a 'picket fence'. The result could be misleading since some significant details may hide behind the fence. Fig. 1 is such an example. An improved technique to observe the true spectrum through limited 'fences' is zero-padding, which appends dummy samples with value of zero to the end of effective data. Zero-padding smoothens the spectrum thus helps to get a better idea of the true spectrum. Fig. 13 illustrates spectrum readability improvement where the example in Fig. 1 is reanalyzed by applying zero-padding. The window size is still selected as two cycles but different lengths of zeros are concatenated to its end. From the original spectrum, it is hard to tell which bins are from actual components and how many components exist in the signal. By using zero-
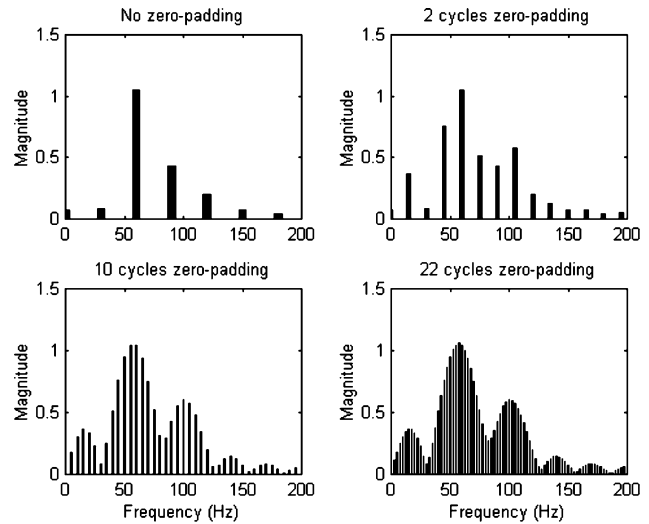

Fig. 13. Effectiveness of zero-padding.

padding, two components at 60 and 100 Hz appear obviously. The other small peaks are due to leakage from side lobes. Zero-padding is helpful in interpreting the spectrum, but we should also bear in mind that it cannot improve frequency resolution. The effective data are still the original ones, there is no any new information introduced by adding zeros to a signal.

5.3. International standards on interharmonics measurement

IEEE Interharmonic Task Force is an active interharmonic research organization. A series of working documents have been released and interharmonic inclusion has been recommended for IEEE 519 standard revision [3]. Basically they adopt IEC standard for interharmonic definition, measurement and limitation. In IEC61000-4-7, 5 Hz resolution is standardized for harmonic and interharmonic measurement. Harmonic and interharmonic groups or subgroups are defined for measurement report. Subgroup is recommended to use if interharmonics are concerned. A harmonic subgroup includes one harmonic bin and two bins adjacent to the central harmonic. For example, {175, 180, 185 Hz} is the 3rd harmonic group. All the other bins between two adjacent harmonic subgroups form interharmonic group. For instance, {130, 135,…, 165, 170 Hz} is interharmonic subgroup between the 2nd and 3rd harmonics. This concept obviously intends to address the leakage problem. The performance of grouping measurement can be found in [6]. This standard, however, should be used carefully when the purpose of measurement is interharmonic related troubleshooting. Some limitations of this standard should be kept in mind. Firstly, interharmonic frequencies could not be found accurately under this framework. In this standard, the central frequency of interharmonic group is

defined as the group frequency, no exact interharmonic frequency information is available from measurement. The defined group frequency could be far from the actual component when an interharmonic is located close to fundamental or a certain harmonic. Secondly and more importantly, those interharmonics close to fundamental or harmonics could not be detected properly. As we have proven in Section 3, it is the interharmonics close to harmonic or fundamental that cause significant flicker.

Therefore, detecting those interharmonics for flicker troubleshooting is highly desirable. But since the standard includes the bins adjacent to harmonic into harmonic subgroup, the possibility of detecting flicker-causing interharmonics will be significantly decreased. The 5 Hz resolution degrades interharmonic identification further. Fig. 11 is an example to show the disadvantage of grouping interharmonic measurement. If a 12-cycle window is used, the 235 and 245 Hz components will be included into 4th harmonic subgroup, even though the 240 Hz bin has much smaller magnitude. There is little possibility to find the real interharmonic which is about 235 Hz. The significance of this error is that the harmonic analysis result cannot reconstruct the modulated waveforms shown in Fig. 10. As a result, the link between 235 Hz interharmonic and flicker could not be detected, which is useful for flicker troubleshooting. In order to detect those interharmonics near fundamental or harmonics, other improved methods should be considered.

6. Conclusions

The definition and measurement of interharmonics are still debatable. In order to measure genuine interharmonics, multiple-cycle window must be selected for Fourier analysis. However, long window is susceptive to errors due to the non-stationary nature of waveforms. This paper has analyzed the problems in interharmonic definition, detection and measurement. It has provided several practical recommendations for interharmonic analysis. The key points of this paper can be summarized as:

- There are some genuine interharmonic sources. When AC–DC–AC type device connects two different frequencies, it may introduce interharmonics. The frequencies of interharmonics are determined by the topology of the converter (pulse number) and the output frequency. When waveform appears modulated, there is good chance that interharmonics exist.
- Interharmonics near fundamental or harmonics could cause light flicker. But these components are not easy to detect due to leakage or resolution limit.

- Non-stationary signal is a major source producing non-integral bins, but they are not real interharmonics. They are attributed to the violation of basic DFT assumption: stationary and periodical.
- In order to identify interharmonics correctly, the window size should be selected to ensure the frequency resolution is the common divider of all components in the signal.
- Engineering experiences and judgements, such as voltage–current correlation, wave-shape check or interharmonic–harmonic coexistence, may help to recognize if the non-integral components are real interharmonics.
- Zero-padding is helpful for spectrum readability improvement. It can be used to locate the interharmonic frequency.
- The 5 Hz resolution and group harmonic/interharmonic concept as recommended by the IEC and IEEE might not be sufficient for interharmonic detection. Especially for those interharmonics that cause flickers.

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