TOWARDS A STANDARDIZED MEASUREMENT METHOD FOR VOLTAGE AND CURRENT DISTORTION IN THE FREQUENCY RANGE 2 TO 150 KHZ

Anders LARSSON
LTU – Sweden
anders.larsson@ltu.se

Math BOLLEN
LTU and STRI– Sweden
math.bollen@stri.se

ABSTRACT

Compared with other frequency ranges, the range between 2 and 150 kHz has not been so well investigated and there is a general lack of standards as well. This is about to change and this paper presents a proposal on a standardized measurement method for this range. The method is mostly based upon our experience from performing measurements in this range in the LV grid.

INTRODUCTION

The frequency range between 2 and 150 kHz has long suffered from a lack of attention in the standard-setting world, but recently this has started to change. Activities towards standardization in this frequency range are ongoing in at least four IEC working groups and in one CENELEC working group. These activities include the development of standardized measurement methods and the setting of emission limits, immunity limits and compatibility levels.

This paper proposes a number of standardized methods for the measurement of voltage and frequency distortion in this frequency range. Such methods could be part of a future version of the IEC standard on power-quality measurements, IEC 61000-4-30.

Before discussing measurement methods, it is important to define what is included in that. The scope of this paper is similar to the scope of IEC 61000-4-30. The aim of the described measurements includes measurement in the a.c. power supply system but it can also be used in measurement of separate equipment. The paper does also not cover the voltage and current transducers used to transform the actual voltages and currents in the grid to signals that are fed into the measurement device. Especially for the higher frequencies that are discussed here, the choice of transducers is very important.

COMPONENTS IN THE RANGE 2 TO 150 KHZ

Over the years we have conducted a number of different measurements on separate equipment and in different buildings in this frequency range on the LV network. The majority of these measurements are though conducted in Sweden with the Swedish network as a source. However most of the devices studied here are more international since these are produced for an international market.

Sources of frequency components

From our viewpoint the majority sources of emission in this frequency range are power electronics and power line communication (PLC).

The emission from power electronics are mainly remains from the switching within the equipment since the EMC filter is not ideal. Also other components are emitted that most likely are due to resonances between the EMC filter and the grid [1].

PLC is also typically found in the LV grid. Our experience is that this is, at least in Sweden, most commonly used for transmitting data from the revenue meter but also other sources can be found where PLC is used to control e.g. radiators, car heaters etc.

There is however other sources that can be expected to emit emission in this frequency range like the commutation of e.g. arc-furnaces, welding equipment and asynchronous machines.

Characteristics of frequency components

The characteristics of the components found in this frequency range can at least be divided into:

- Narrowband components
- Broadband components
- Recurrent oscillations

Narrowband component is typically defined as signal with bandwidth less than 5 kHz. These components can either be continuous or discontinuous. Broadband components can be somewhat more difficult to define. These can either be continuous, discontinuous or even show up as a narrowband component that shifts frequency over time. The recurrent oscillations are often showing up as a damped oscillation that repeats every 10 ms, synchronized with the power system frequency. Typically the frequency of these oscillations is in the lower kHz range [1].

Why standardized methods

The presence of standardized methods for the measurement of waveform distortion in this frequency range, will allow a more systematic measurement of voltage and current quality including higher frequencies.

It further allows for a comparison of the results obtained by different measurement devices and therewith makes it easier to exchange knowledge and experience. Standardized measurement methods will also encourage manufacturers of measurement equipment to include this frequency range in their devices without running a big risk that their equipment will be outdated soon. This in turn makes it easier to perform measurements and gather data resulting in a further growth of information about this frequency range.

THE MEASUREMENT

Voltages and Currents

Depending upon the reason of measurements it may be important to get as much information about distortion in this frequency range as possible. Disturbances may occur as common mode, differential mode or both. We therefor propose to consider measurements of voltages between phase-to-phase, phase-to-neutral and even neutral-to-ground. For currents, the phase current, the neutral current and the current through the protective earth should be measured. It is however not always possible to perform all these measurements due to several reasons; which measurements to be taken should be decided case by case. Note that it may be needed to use different analyses and presentation methods for these different measurements.

Filtering

Signal components in frequency range 2 to 150 kHz have much lower amplitude compared with the fundamental at 50 or 60 Hz than components below 2 kHz. The fundamental component should either be removed by using an analogue filter; or a sufficiently high number of bits should be used. The standard should prescribe a maximum level of quantization noise of the unattenuated pass-band and a maximum amplitude range. It should be up to the equipment manufacturer to decide which method to use to achieve this. Based upon our experience the maximum quantification noise should be at most 10 mV or 200 μA.

In the case when a filter is used to remove frequency components below 2 kHz, the maximum range should be somewhere around ±50 V and in the case without filter the range should be sufficient to include the 230 V fundamental component.

An anti-aliasing filter should also be defined. Our proposal is to shift the requirements in the informative annex with IEC 61000-4-7 from 9 kHz to 150 kHz.

Basic Measurement Window

The calculation of voltage-quality indices for waveform distortion in the frequency range up to 2 kHz is defined in IEC 61000-4-30 and IEC 61000-4-7. The use of a basic measurement window with a length of 10 or 12 cycles of the power-system frequency is prescribed by these documents (10 cycles in a 50-Hz system or 12 cycles in a 60-Hz system; in both cases corresponding to about 200 ms). The informative annex with IEC 61000-4-7 contains a method for calculating indices for waveform distortion in the frequency range from 2 to 9 kHz. Here the use of a 200-ms window is proposed.

Since the amount of data and the processing time is a lesser problem today our proposal is to use the same 200-ms window for the whole frequency range from 2 to 150 kHz. This window can be synchronized to the power-system frequency or synchronized to an independent clock. In the frequency range from 2 to 150 kHz, there is no need for the measurement window to be synchronized, but some equipment manufacturers may want to use the same recording for analyse both below and above 2 kHz. In that case the indices for the higher frequency range will be obtained from a synchronized window.

Time aggregation

According to IEC 61000-4-30, class A instruments, in the frequency range up to 2 kHz the basic measurement windows shall be gapless continuous to determine harmonics. The 40 grouped harmonic components are obtained from 10/12 cycles which results in about 200 harmonic values every second. The standard defines two levels of time aggregation: from 10/12 cycles to 150/180 cycles, about 3 seconds, and from 10/12 cycles to 10 minutes. The time aggregation of each harmonic component gained from the 10/12 cycle window shall be performed using the square root of the arithmetic mean of the squared input values as:

$$h_n = \sqrt{\frac{1}{N}\sum_{n=1}^{N} h_n^2}$$

Gapless continuous measurements appear non-practical for the frequency range 2 to 150 kHz because of the much higher sampling rate. The DFT should be applied over at least 60 000 samples instead of 800 samples for harmonics up to 2 kHz.

To be as consistent as possible with the time aggregation for lower frequencies it is proposed to obtain one basic measurement window every 3 seconds or every 150/180 cycles. This should be up to the equipment manufacturer to decide. The spectra from all the basic measurement windows (200 or about 200) during a 10-minute time window are aggregated into one spectrum in the same way as in IEC 61000-4-30 for lower frequencies. Our proposal is thus to take the rms value over all 200 values within the 10-minute window in case of a non-synchronized measurement, or the rms value over the approximately 200 values within the 10-minute window in case of a synchronized measurement.

FREQUENCY DOMAIN

Frequency Aggregation

Applying the discrete Fourier transform algorithms to the basic measurement window of 200-ms length results in 5 Hz separation between frequency values. That gives 400 frequency values up to 2 kHz. These are aggregated into harmonic and interharmonic groups and subgroups according to IEC 61000-4-7 when a filter is not used. IEC 61000-4-30 prescribes the use of harmonic and interharmonic subgroups for quantifying voltage disturbance.

In the frequency range from 2 to 9 kHz, applying the discrete Fourier transform gives 1400 values. According to the informative annex with IEC 61000-4-7 these are aggregated into 200-Hz bands according to

$$G_b = \sqrt{\sum_{f=b-95Hz}^{b+100Hz} C_f^2}$$

where the frequency bands b are centre frequencies at 2100, 2300, 2500… 8900 Hz.

To align with CISPR 16 our proposal is to use the same aggregation into 200-Hz bands for the whole frequency range from 2 to 150 kHz, either synchronized or non-synchronized.

Indices for Narrow Band Components

The frequency aggregation method described in the previous section is appropriate for broadband frequency components, as are common in this frequency band. However due to increased use of power-line communication, narrow-band components may become more common. Narrow-band components are also emitted by some power-electronic devices. To obtain a better insight in the presence of those components, it may be necessary to develop an alternative way of frequency aggregation. A possibility is the use of a signal-processing technique to detect the dominant narrow-band signals, like ESPRIT[2]. These so-called model-based methods do not take the complete spectrum but estimate the dominant narrow-band components immediately. Such a method has been used in [3] to detect time-varying interharmonics. Further research and development is needed here.

TIME DOMAIN

High Frequency Peak Voltages and Currents

The character of the distortion in the frequency range above 2 kHz is however different from the character of the distortion in the frequency range below 2 kHz. Therefore time-domain indices are proposed next to the frequency-domain indices defined in the previous section.

For the calculation of the time-domain indices, the low-frequency part of the signal is removed by means of an analogue or digital high-pass filter. The earlier requirements on quantization noise also hold here. Further studies are needed to determine to which extent the choice of high-pass filter impacts the resulting values of the indices. If the impact turns out to be big, requirements on the filer will have to be part of the standard.

The highest voltage in absolute value during the basic measurement window is used as a basic index. The measurement and the calculation are repeated every 3 seconds or every 150/180 cycles. The basic measurement windows are the same for the calculation of time-domain and for the calculation of frequency-domain indices. Over each 10-minute window the following indices are calculated

- ✓ The 95% value of the highest absolute values from each measurement window. This value is referred to as the “10-minute 95% high-frequency peak voltage”
- ✓ The rms value of the highest absolute values from each measurement window. This value is referred to as the “10-minute rms high-frequency peak voltage”
- ✓ The average value of the highest absolute values from each measurement window. This value is referred to as the “10-minute average high-frequency peak voltage”

Oscillations

From our experience some of the signals present in the grid in this frequency range appear as damped oscillations that reoccur with the fundamental frequency as described above. Fig. 1 shows an example of the damped oscillation created by active PFC in the high frequency ballast powering a fluorescent lamp. The current shows an oscillation close to the zero crossing. In this case it is only a single device connected and any effect on the voltage is not visible. However a larger number of devices connected would result in distortion of the voltage.

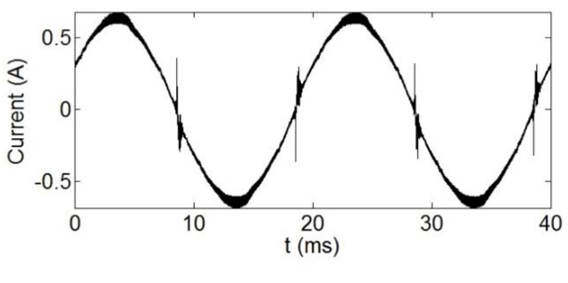

Fig. 1 Measurement of current feeding a fluorescent lamp.

Since these oscillations are strongly damped the DFT is not a suitable tool to analyze these. For the highest peak we would like to know the oscillation frequency, damping, etc. We have so far used the peak value of the time-domain values with different types of band pass filters to get quantitative data of the amplitude. ESPRIT (Estimation of Signal Parameters via Rotational Invariance) has been used to quantify the damping and frequency of these oscillations but researchers and developers are recommended to come with appropriate algorithms.

TIME-FREQUENCY DOMAIN

The time-frequency domain is introduced in [1][3] as an alternative next to the time domain and the frequency domain for presenting voltage and current distortion in the frequency range 2 to 150 kHz. The use of time-frequency domain has shown being a useful tool to get a better understanding of the signal characteristics, especially if the signal is changing frequency over time as described above.

The STFT algorithm divides the measured time window into smaller subwindows and applies the Discrete Fourier Transform (DFT) to each subwindow [2]. The spectra are combined again in the time domain as a matrix to display either in an intensity graph or in a 3-dimensional plot. The resulting matrix is represented in our work with time on the horizontal axis, frequency on the vertical axis and the amplitude by a color coded intensity. The benefit is that one can retrieve information about non-stationary signals within the measured window, e.g., if a signal is modulated with another frequency or if the occurrence of a signal is synchronized with signals at other frequencies.

The maximum frequency that is achieved from the DFT depends on the sampling rate, which is the same for each subwindow. But since the time length of subwindow is smaller than of the total measurement window, the frequency resolution is affected. A higher time resolution corresponds to a lower frequency resolution and vice versa, with their product being constant.

In the frequency range from 2 to 150 a frequency separation of 1 kHz and a time separation of 1 ms is revealing.

Other algorithm like the wavelet or ESPRIT with a sliding window can also be deployed to achieve time-frequency data [3]. The standard should formulate requirements so these methods can be used.

SITE INDICES

The following site indices are proposed, to be obtained from the 3-second and 10-minute aggregated values of the 200-Hz values:

- ✓ The 95-percentile of the 10-minute values over one week
- ✓ The 99-percentile of the 10-minute values over one week
- ✓ The 95-percentile of the 3-second or 150/180-cycle values over one week
- ✓ The 99-percentile of the 3-second or 150/180-cycle values over one week
- ✓ The maximum of the 10-minute values over one week

Similar site indices should be defined in the future for narrow-band indices and for time-domain indices.

CONCLUSIONS

This paper presents some guidance for the development of standardized methods for measuring and quantifying voltage and current distortion in the frequency range 2 to 150 kHz. The straightforward method is to define 200-Hz values and treat these in a similar way as the harmonic and interharmonic subgroups below 2 kHz. Such an approach will however leave out a lot of information that is specific to this frequency range and that is needed for a better understanding of the causes and consequences of the emission in this range.

Recommendations are given how to proceed towards the development of standard methods for quantifying narrow-band emission, distortion in time domain, recurrent oscillations and emission in time-frequency domain. On all these areas further research and development is needed.

Acknowledgments

The material presented in this paper was gained from a number of research projects over time. Funding for these projects was mainly obtained from Skellefteå Kraft and the Swedish Energy Authority.

REFERENCES

[1] Larsson, A 2011, *On high-frequency distortion in low-voltage power systems*. Luleå tekniska universitet, Luleå. Doctoral thesis / Luleå University of Technology

[2] M.H.J. Bollen and I.Y.H. Gu, Signal processing of power-quality disturbances, Wiley, 2006

[3] I.Y.H. Gu, M.H.J. Bollen, Estimating interharmonics by using sliding-window esprit, IEEE Transactions on Power Delivery, Vol.23, No.1 (January 2008).

[4] E.O.A. Larsson, M.H.J. Bollen, M.G. Wahlberg, C.M. Lundmark, and S.K. Rönnberg, Measurements of high-frequency (2–150 kHz) distortion in low-voltage networks, IEEE Transactions on Power Delivery, Vol.25, No.3 (July 2010), pp.1749-1757.