Comparison of Measurement Methods for the Frequency Range 2-150 kHz (Supraharmonics) Based on the Present Standards Framework

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\textbf{ABSTRACT} Advances in power electronics, increasing share of renewables in the energy system and e-mobility cause an increase of disturbances in the frequency range 2-150 kHz, also known as supraharmonics. A rigorous, credible and agreed measurement framework is essential to evaluate electromagnetic compatibility (EMC) in this frequency range. While a normative method exists for measuring equipment emission in the laboratory, no normative method exists yet for the measurement of supraharmonic disturbance levels in the grid. The aim of this research is a detailed comparison of potential measurement methods derived from existing standards IEC 61000-4-7, IEC 61000-4-30, CISPR 16-1-1 and a critical assessment of their suitability for disturbance measurements in grid applications. Based on a comprehensive set of synthetic signals and real measurements from laboratory and field, this article studies the ability of the methods to assess the typical characteristics of supraharmonic emission with relevance to EMC coordination. It presents the benefits and drawbacks of the existing measurement methods and discusses the suitability of possible modifications for grid compliance assessment. The results and recommendations intend to be an input for the present activities of IEC SC 77A WG 9 to define a normative method for the measurement of supraharmonic disturbance levels to be included in the next edition of IEC 61000-4-30.

\textbf{INDEX TERMS} Distortion measurement, electromagnetic compatibility, measurement standards, power quality, supraharmonics, frequency domain analysis.

\section{I. INTRODUCTION}

Due to the increasing use of renewables and electric vehicle (EV) chargers as well as the continuous rise of energy efficiency in modern mass-market appliances, a tendency in shifting emission from lower to higher frequencies is observed. While the low order harmonic distortion is usually significantly reduced, end-users and network operators facing an increase in emission in the frequency range 2-150 kHz, which is also commonly referred to as supraharmonic emission [1], [2].

An essential part of the Electromagnetic Compatibility (EMC) coordination is a credible and agreed framework for the measurement of emission and disturbance levels in this frequency range. At present, a normative method (mandatory for compliance with a standard) is defined only for the measurement of device emission under laboratory conditions to assess compliance with equipment limits.

A standardization framework for the measurement of disturbance levels in the grid, e.g. to compare them with compatibility levels, is still lacking but urgently required.

Presently, there are several methods proposed by different working groups at IEC SC 77A for the frequency range 2-9 kHz and 9-150 kHz. They are introduced as informative annexes in the standards IEC 61000-4-7 [3] and IEC 61000-4-30 [4]. Due to its informative character, these methods are considered as optional requirements, but are not mandatory for compliance with the respective
standards. Since the compatibility levels in the frequency range 9-150 kHz, which has recently been introduced in IEC 61000-2-2 [5], are defined based on the laboratory measurement method specified in CISPR 16-1-1 [6], an adoption of this method for grid disturbance measurements has also to be considered.

Following the increasing demand of network operators and other stakeholders to measure disturbance levels in the grid, instrument manufacturers have already implemented supraharmonic measurement methods in their instruments. Due to the lack of a normative method, these implementations differ from each other, which makes measurements taken with different instruments incomparable and emphasizes the urgent need for a normative method.

Several studies dealing with the comparison of measurement methods for the supraharmonic frequency range have been conducted in recent years. A review of existing methods can be found in [7]–[10], where different aspects of their implementation such as choice of the measurement interval, frequency bandwidth, and filter technique are discussed. The first attempts to compare the results of the different measurement methods are presented in [10]–[12] but considering only IEC 61000-4-7 and IEC 61000-4-30. Moreover, papers [10]–[12] identify parameters of the methods with an impact on the measurement results, but they do not consider their ability to reflect the specific characteristics of supraharmonic disturbances in the field. Thus, the suitability of the methods for the measurement of grid disturbance levels is not comprehensively addressed yet.

This research continues and extends the existing studies by providing a detailed comparison of all relevant methods described in present standards, including the method in CISPR 16-1-1. Besides the standard implementations, possible modifications for the improvement of their suitability for grid compliance assessment according to the standard IEC 61000-2-2 are also studied. The results aim to provide reliable support to IEC SC 77A WG 9 for their decision on a future normative method. The performance of the different methods is compared by introducing a comprehensive set of synthetic signals as well as real signals from laboratory and field measurements, which represent the typical characteristic of supraharmonic disturbances. The study is intentionally limited to potential methods taken from existing standards, as these are already widely accepted in the community.

The article starts with a brief description of the measurement methods including the considered modifications and specifies the parameters of their implementation for this study. Next, the comparison framework is introduced, which provides an overview of test signals and metrics used for comparison. This is followed by a detailed discussion of the results distinguishing between synthetic and measured signals. The computational complexity of the methods is compared before a summarizing discussion and conclusions are presented.

II. MEASUREMENT METHODS

In this section, the measurement methods and their modifications for potential improvement are introduced. All methods are based on the frequency domain. Section VI provides a brief discussion of the benefits and drawbacks of frequency-domain methods compared to alternative approaches (e.g. in the time domain).

This article distinguishes between the terms “analysis interval” and “measurement interval”. The measurement interval corresponds to the time interval for which a signal is sampled and directly processed by a Discrete Fourier Transform (DFT). The analysis interval is the shortest interval for which a measurement value has to be reported according to the definition in the standards. A single measurement interval is always shorter or equal to the analysis interval. One analysis interval can also consist of multiple measurement intervals. In this case, the length of the sum of all measurement intervals used to obtain the values for one analysis interval can be shorter (gaps, no overlaps), equal (no gaps, no overlaps) or longer (no gaps, with overlaps) than the analysis interval.

Fig. 1 illustrates the measurement intervals for one analysis interval (200 ms) and Fig. 2 the resulting frequency bands for the three standard methods, which are considered in the article and described in detail in the next subsections. The gray ticks indicate times/frequencies for which an individual value is (internally) calculated by the method. The figures show already significant qualitative differences between the methods. Method B has significant gaps in time, whereas method C has considerable overlaps in frequency and time.

Converting a waveform from time domain to frequency domain results in a frequency spectrum consisting of

![FIGURE 1. Measurement and analysis intervals for the considered methods (A: IEC 61000-4-7; B: IEC 61000-4-30; C: CISPR 16-1-1; fB – start time of the analysis interval).](image1)

![FIGURE 2. Frequency bands provided for the considered methods (A: IEC 61000-4-7; B: IEC 61000-4-30; C: CISPR 16-1-1; fB – start frequency of frequency band).](image2)
magnitude and phase angle for each spectral component. This article considers only the magnitude expressed as Root Mean Square (RMS) value, which is commonly used in present grid applications.

A. IEC 61000-4-7 (METHOD A)
In its normative part, this standard deals with measurement methods for harmonics and interharmonics. A method for measuring emission in the frequency range 2-9 kHz is specified in informative Annex B. Even if the standard is intended for measuring equipment emission, it is also widely accepted and applied for the measurement of grid disturbance levels.

The method in Annex B specifies a measurement interval of 200 ms (rectangular window) independent of the nominal frequency (50/60 Hz). This results in a discrete spectrum with 5 Hz resolution. The spectral components $Y_{C,i}$ are grouped in 200 Hz bands using the Root Sum Square (RSS).

The 200-Hz-band was introduced to make the method comparable with the Band A (9-150 kHz) definition in CISPR 16-1-1. The analysis interval equals the measurement interval. The method is gapless and not overlapping in frequency and time (cf. Fig. 1 and 2).

To obtain the required 200-Hz-bands, also shorter measurement intervals are possible (cf. Table 1), which could reduce the computational complexity and the memory requirements of the method significantly. In order to cover the analysis interval of 200 ms gapless, multiple shorter measurement intervals are required, which have to be aggregated in time in order to obtain one measurement value at the end of the analysis interval.

### TABLE 1. Possible modifications of the length of measurement intervals for method A (IEC 61000-4-7).

| Measurement interval, ms | Frequency resolution, Hz | Number of spectral components to be grouped | Number of measurement intervals to be aggregated |
|--------------------------|--------------------------|--------------------------------------------|-----------------------------------------------|
| 100                      | 10                       | 20                                         | 2                                             |
| 50                       | 20                       | 10                                         | 4                                             |
| 20                       | 50                       | 4                                          | 10                                            |
| 5                        | 200                      | -                                          | 40                                            |

Previous research [11] shows that shorter measurement intervals are also better able to reflect the variation of supraharmonic emission in time, corresponding to improved detection of minimum and maximum values. However, the results depend on the starting point of the measurement interval within the power cycle, which affects the reproducibility of the method significantly.

This paper considers for method A only the gapless implementation of the two most different measurement intervals (200 ms and 5 ms) using a sampling rate of 1 MHz. The 200 ms measurement interval equals the analysis interval and provides therefore already the final magnitude values of the spectral components without requiring aggregation in time, which are subsequently grouped to the 200-Hz-bands. The gapless implementation of the 5 ms measurement interval requires an additional aggregation of 40 consecutive measurement intervals, but no further grouping (cf. Table 1). For each analysis interval (200 ms), the minimum, maximum and RMS values of these 40 magnitudes are calculated.

B. IEC 61000-4-30 (METHOD B)
This standard defines methods for measuring voltage disturbance and current emission levels in electricity networks and is the most important standard with regard to the measurement of grid disturbance levels. It describes the measurement of distortion in the frequency range 2-9 kHz and 9-150 kHz in informative Annex C and recommends the method described in IEC 61000-4-7 for the frequency range 2-9 kHz. For the frequency range 9-150 kHz, a method with a sampling frequency of 1024 kHz and a high pass filter for damping the components below 9 kHz is proposed. The analysis interval is 10 cycles for 50-Hz-networks and 12 cycles for 60-Hz-networks respectively. For each analysis interval, 32 measurement intervals of 512 samples shall be equally distributed over the analysis interval and analyzed using a Fast Fourier Transform (FFT). Each measurement interval has a duration of 0.5 ms resulting in a frequency resolution of 2 kHz. In order to obtain the final values for the analysis interval, the magnitudes of the 32 measurement intervals are aggregated in time. Similar to the aggregation procedure explained in the previous subsection, minimum, maximum and RMS values are calculated for each analysis interval.

There are several issues in the application of this method. Firstly, the method has considerable gaps in time and covers only 8% of the analysis interval (cf. Fig. 1, method B). As the length of the individual gaps is not specified in the standard, their distribution and consequently the obtained results can differ significantly, which results in a poor reproducibility of the method [11]. Another important drawback of method B is the low frequency resolution of 2 kHz, which does not correspond to the CISPR 16-1-1 requirements of 200 Hz for the frequency range 9-150 kHz (CISPR band A). Under certain conditions, the different bandwidth of methods A and B can result in significantly different results.

This article implements for method B only the variant with 32, equally distributed measurement intervals (equidistant gaps), which is described in the standard. No modifications are considered.

C. CISPR 16-1-1 (METHOD C)
This standard defines a method to measure equipment emission in the frequency above 9 kHz under laboratory conditions, including the CISPR Band A (9-150 kHz).

The measurement method is based on the principle of a heterodyne spectrum analyzer, whose output is processed with a quasi-peak-detector provided a weighted peak value of the envelope of the signal as the final measurement result.

Originally, this method could only measure one frequency at a time and was consequently not gapless in time. This is of minor importance for equipment emission measurements, but a significant issue for grid compliance assessment.
Since 2010, the standard allows digital DFT-based implementations of the method, which enables the parallel measurement at multiple frequencies at the same time. The standard requires a frequency resolution of 100 Hz or higher and an overlap in time of 75% or higher (cf. Fig. 1 and Fig. 2, method C).

This overlap complicates the calculation of integral values comparable to the THD for harmonics. Integral values have no importance in the emission assessment according to CISPR 16 but are useful in grid disturbance assessment. Further, the quasi-peak detector has been introduced decades ago to quantify the disturbance of radio transmission by clicking noise caused by peaks in the emission. Today, radio transmission at frequencies below 150 kHz is rarely used and its interference is virtually irrelevant. However, other interference phenomena in the considered frequency range (e.g. between Power Line Communication (PLC) and other electronic equipment) significantly increased in importance, which questions the suitability of the quasi-peak detector in the frequency range 2-150 kHz in the future. This issue has to be further discussed in the relevant working groups at IEC SC 77A and CISPR.

The implementation of method C used in this study complies with the requirements of CISPR 16-1-1 and follows the recommendations given in [13]. A Gaussian window (α = 5.8) is used to ensure the −6 dB bandwidth of 200 Hz. Measurement intervals of 20 ms are chosen with an overlap of 90%, which results in a measurement value per frequency provided at each 1.9 ms. The frequency resolution is set to 50 Hz. In addition to the quasi-peak detector, this study also considers the RMS detector and the peak detector, because RMS and peak values are common indices to quantify signal characteristics in grid disturbance assessment. RMS and peak detectors calculate the respective values over detector dwell time (similar to analysis interval). The implementation of the quasi-peak detector is more complex and follows the principle of a digital model introduced in [14].

III. COMPARISON FRAMEWORK
The comparison of the measurement methods is based on a comprehensive set of test signals, which include synthetic and measured signals.

A. SYNTHETIC SIGNALS
The synthetic signals are derived from the typical characteristics of supraharmonic emission [15], which considers two signal features: frequency content and magnitude variation within the power cycle. Regarding frequency content, narrowband emission (distinct individual frequency component, smaller than the smallest considered frequency band of 200 Hz) and broadband emission (multiple adjacent frequency components, wider than 200 Hz) are distinguished [1]. Multiple adjacent frequency components can be caused either by emission at multiple components constant in frequency or by frequency variation of a single component. Magnitude variation within the power cycle is classified into constant, varying and transient behavior [16]. Considering these characteristics, the following synthetic signals are derived:

1) constant in magnitude and frequency,
2) constant in frequency with variation in magnitude,
3) constant in magnitude with variation in frequency,
4) variation in magnitude and frequency;

The standard requires a frequency resolution of 100 Hz or higher and an overlap in time of 75% or higher (cf. Fig. 1 and Fig. 2, method C).
The actual frequencies of the signal components, always equal to center frequencies of the frequency bands used in methods A and C, are listed in Table 2. The reference values for method B are calculated by grouping these values into 2-kHz-bands.

The signal with variation in magnitude and frequency (S4) is observed for circuit topologies using a PFC with a boost converter (e.g. in LED lamps) is shown in Fig. 3 (c). This signal is generated using the same ten frequencies as for the signal with varying frequency and constant magnitude, but the magnitude of the different signal components is varied using a sinusoidal characteristic. The power cycle RMS values increase quadratically from 25 kHz to 15 kHz and are listed in Table 2.

**TABLE 2.** Reference values for synthetic signals varying in frequency.

| Signal | Reference values | f, kHz | V_{min}, V | V_{max}, V |
|--------|------------------|--------|------------|------------|
| S3     |                  | 14.9   | 2.18       | 6.90       |
|        |                  | 15.5   | 2.18       | 6.90       |
|        |                  | 16.1   | 2.18       | 6.90       |
|        |                  | 16.7   | 2.18       | 6.90       |
|        |                  | 17.7   | 2.18       | 6.90       |
|        |                  | 18.9   | 2.18       | 6.90       |
|        |                  | 20.1   | 2.18       | 6.90       |
|        |                  | 21.5   | 2.18       | 6.90       |
|        |                  | 23.1   | 2.18       | 6.90       |
|        |                  | 24.9   | 2.18       | 6.90       |
| S4     |                  | 1.68   | 6.90       | 6.90       |
|        |                  | 1.66   | 6.90       | 6.90       |
|        |                  | 1.64   | 6.90       | 6.90       |
|        |                  | 1.61   | 6.90       | 6.90       |
|        |                  | 1.58   | 6.90       | 6.90       |
|        |                  | 1.54   | 6.90       | 6.90       |
|        |                  | 1.49   | 6.90       | 6.90       |
|        |                  | 1.45   | 6.90       | 6.90       |
|        |                  | 1.40   | 6.90       | 6.90       |
|        |                  | 1.35   | 6.90       | 6.90       |

**B. MEASURED SIGNALS**

The synthetic signals are complemented by two real measured signals. While these signals represent realistic emission behavior, the “true” emission content of these signals and consequently a reference value are unknown. Furthermore, the measurement noise and grid frequency deviations have an impact on the results, especially for the field measurement.

The measurements were taken with a sampling rate of 1 MHz. The total length of each signal needed for the analysis with the different measurement methods amounts 2 s and is determined by the dwell time of the quasi-peak detector of method C. Each signal begins at a positive zero crossing of the supply voltage.

As shown in [10], a high-pass filter to suppress the fundamental component and low order distortion to avoid unwanted leakage is essential for the analysis with the methods A and B. For these purposes, a software implementation of an elliptical high-pass filter is used [17].

The laboratory measurement is performed with an almost perfect sinusoidal supply voltage and an EV with an on-board charger connected to it. The switching frequency of the EV charger at around 27 kHz and its 2nd harmonic at 54 kHz are clearly identifiable in the spectrogram of supraharmonic voltage in Fig. 4.

The field measurement is performed at the terminal of a customer with a photovoltaic (PV) installation. A PLC system is used in the network for the meter reading. The switching frequency of the PV inverter at frequency around 20 kHz and the emission of the PLC in the range 35-90 kHz can be seen in Fig. 5.

**C. ASSESSMENT METRICS**

In order to compare the results of the different measurement methods, a set of indices is defined. It reflects the ability of the individual methods to catch certain characteristics of
supraharmonic emission. The following sections describe the indices and how the performance of the methods is assessed.

1) ASSESSMENT INDICES

The indices to characterize supraharmonic emission in this study are derived from the most common interference mechanisms in this frequency range. Three main indices are considered in this article, which are related to the immunity of electrical appliances to supraharmonic emission. Further details can be found in [16].

Any distortion in the supply voltage causes additional thermal stress for shunt capacitances and can reduce their lifespan significantly. As an example, reference [18] analyzes the additional thermal stress on DC link capacitors in mass-market equipment caused by supraharmonic disturbances. This additional stress can be linked to the long-term power cycle RMS value in the supraharmonic spectrum. In case emission occurs at multiple frequencies at the same time, an integral value is commonly used to represent the total signal power (or disturbing power) and the total additional thermal stress for a device. Therefore, similar to the total harmonic voltage (THV) for the harmonic range, a total thermal stress for a device. This aspect is an important issue that has to be addressed in future studies and is further discussed in section VI.

The red, rectangular windows of method A do not overlap and provide one single value at the center frequency $f_0$ of the band b in steps of 200 Hz. Method C provides 4 times more values (step size of 50 Hz), which results in a better frequency resolution, but significantly overlaps between adjacent windows (blue/gray windows in Fig. 6). The calculation of the correction factor is not in the scope of this article and as a first approximation, only each fourth signal component of method C, corresponding to the center frequency of the 200-Hz-bands according to method A is used to calculate the integral values. This can miss some emission, especially if it is located between two consecutive windows.

A second interference mechanism is the sensitivity of electronic equipment or PLC communication against high disturbance magnitudes. In case of too high maximum magnitudes for certain signal components, perceptible malfunctions or unwanted audible noise [19] or saturation of input transducers (e.g. in smart meters) can occur. Since the variation in magnitude is a typical feature of supraharmonic emission, the maximum magnitude can usually not be properly represented by the power cycle RMS value and, consequently, an additional index, namely the maximum magnitude is introduced.

2) PERFORMANCE CRITERIA

The performance of the methods is assessed using different approaches for synthetic and measured signals.

For the synthetic signals, the power cycle RMS values of the frequency components used to generate the signal are used as reference values. The respective signal components are referred to as expected components in the further text. The deviation between the results and these reference values determines the accuracy of the method. Since all considered methods include a DFT, the appearance of unexpected components in the frequency spectrum (e.g. due to leakage) is considered as another performance criterion. Therefore, an integral value of all signal components not including those for generating the respective synthetic signals is calculated using the RSS. For method C similar to the TSHV only each fourth signal component except those corresponding to the expected signal components are used to calculate the RSS of the unexpected signal components.

For the measured signals, frequencies of supraharmonic emission are only approximately identified from the signal spectrum. No reference values for magnitudes are available, because the “true” emission magnitudes in the signals are unknown. Consequently, no distinction between expected and unexpected signal components as for the synthetic signals is possible. Since the definition of compatibility levels in IEC 61000-2-2 refers to CISPR 16-1-1, the results of method C with the quasi-peak detector are used as a reference. It should explicitly be noted that using method C as reference does not imply that this method is suitable to reflect the interference mechanisms in the supraharmonic range adequately. This aspect is an important issue that has to be addressed in future studies and is further discussed in section VI.

IV. RESULTS OF COMPARISON

This section provides the results for the analysis of synthetic and measured signals with the different measurement methods: IEC 61000-4-7 (method A), IEC 61000-4-30 (method B) and CISPR 16-1-1 (method C). Besides the reference implementation of these methods as described in the standards, the modifications introduced in section II are also considered.

Table 3 presents a summary of the studied variants and the used abbreviations. The cell containing the reference variant (always V1) of the respective standard is highlighted in gray.
TABLE 3. Overview of considered modifications of standard methods (reference variants highlighted in gray).

| Measurement | Number of | Detector |
|-------------|-----------|----------|
| A: IEC 61000-4-7 | 200 ms | V: 1 |
| B: IEC 61000-4-30 | 5 ms | V: 2 |
| C: CISPR 16 | 32 | B: V1 |

TABLE 4. Relative error for expected signal components in %.

| Index | Reference | Variant |
|-------|-----------|---------|
| f: kHz | U, V | A:V1 | A:V2 | B:V1 | C:V1 | C:V2 | C:V3 |
| RMS | 19.9 | 6.9 | 0 | 0 | 0 | 0 | 0 |

TABLE 5. Magnitude of unexpected signal components.

| Variant | A:V1 | A:V2 | B:V1 | C:V1 | C:V2 | C:V3 |
|---------|------|------|------|------|------|------|
| Unexpected components, V | 0 | 0 | 0.2 | 0.9 | 0.9 | 0.9 |

TABLE 6. Relative error for integral values in %.

| Index | Reference | Variant |
|-------|-----------|---------|
| TSHV | 6.9 V | A:V1 | A:V2 | B:V1 | C:V1 | C:V2 | C:V3 |
| RMS | 15.25 | 2.1 | -67.. | -73.. | -54.. | -52.. | -68.. | -70.. | -60.. |
| RMS | 6.9 | -85.. | -77.. | -26.. | -85.. | -87.. | -75.. |

TABLE 7. Relative error for expected signal components in %.

| Index | Reference | Variant |
|-------|-----------|---------|
| f: kHz | U, V | A:V1 | A:V2 | B:V1 | C:V1 | C:V2 | C:V3 |
| RMS | 19.9 | 5.1 | -6 | -11 | 0 | -5 | -8 | 21 |
| RMS | 19.9 | 6.9 | -30 | -33 | 0 | -29 | -31 | -10 |

TABLE 8. Magnitude of unexpected signal components.

| Variant | A:V1 | A:V2 | B:V1 | C:V1 | C:V2 | C:V3 |
|---------|------|------|------|------|------|------|
| Unexpected components, V | 1.7 | 2.3 | 0.2 | 1.6 | 1.5 | 2.1 |

TABLE 9. Relative error for integral values in %.

| Index | Reference | Variant |
|-------|-----------|---------|
| RMS | 6.9 | A:V1 | A:V2 | B:V1 | C:V1 | C:V2 | C:V3 |
| RMS | 6.9 | 5.1 | 0 | 0 | 0 | -3 | 28 |

TABLE 10. Range of relative errors for expected signal components in %.

| Index | Reference | Variant |
|-------|-----------|---------|
| f: kHz | U, V | A:V1 | A:V2 | B:V1 | C:V1 | C:V2 | C:V3 |
| RMS | 15.25 | 2.1 | -67.. | -73.. | -54.. | -52.. | -68.. | -70.. | -60.. |
| RMS | 15.25 | 6.9 | -85.. | -77.. | -26.. | -85.. | -87.. | -75.. |

A. SYNTHETIC SIGNALS

Since the emission content of synthetic signals is known, the results are reported as percentage errors related to the corresponding reference values. For each signal firstly the expected signal components, secondly the unexpected signal components and finally the TSHV value are discussed.

The results for signal constant in magnitude and frequency (S1) are presented in Tables 4-6.

All methods provide precise results for the expected frequency component. The different modifications do not affect the results.

Method A has no and method B only very low unexpected components. For method C, the overlap in the frequency domain leads to additional emission in the individual neighboring bands with magnitudes of 0.67 V (10 % of the reference value), which sum up to the total value of 0.9 V.

Regarding the integral values methods A and B match the reference value, while method C provides slightly overestimated results.

The results for signal constant in frequency with variation in magnitude (S2) are presented in Tables 7-9.

Method A underestimates the results for the expected signal component due to the leakage caused by the magnitude variation within the measurement interval. The relative error for the RMS value is higher for variant A:V2 compared to the reference variant A:V1. Similar behavior, but with higher deviations is observed for the maximum value.

Method B shows the best performance for both RMS and maximum values, which results from the very short measurement intervals properly representing the signal component variation.

The results for method C strongly depend on the type of detector. Regarding the RMS value, quasi-peak (C:V1) and RMS (C:V2) detectors underestimate the reference value and provide results comparable to method A. The peak detector (C:V3) better suits for the estimation of maximum values, but clearly overestimates the RMS value.

Methods A and C show moderate levels of unexpected components compared to method B, which presents the best performance. For method C, this level depends on the detector type and is highest for the peak detector.

Regarding integral values, methods A and B provide precise results. For method C, the quasi-peak detector matches the reference value, while the RMS detector shows slight underestimation. Contrary, the peak detector overestimates the integral value of total supraharmonic emission.

The results for signal constant in magnitude with variation in frequency (S3) are shown in Tables 10-12 and Fig. 7 (only reference variants A:V1, B:V1, C:V1). The RMS spectra are presented as absolute values in dB/\mu V, as this is the common representation in CISPR for frequencies above 9 kHz. For the sake of consistency, it is also used for 2-9 kHz.

Table 10 presents the minimum and maximum error observed for the ten individual signal components. A rather poor representation with significant variation of error is
TABLE 11. Magnitude of unexpected signal components.

| Variant | A:V1 | A:V2 | B:V1 | C:V1 | C:V2 | C:V3 |
|---------|------|------|------|------|------|------|
| Unexpected components, V | 6.3  | 6.2  | 2.3  | 6.0  | 5.7  | 8.8  |

TABLE 12. Relative error for integral values in %.

| Index | Ref. | A:V1 | A:V2 | B:V1 | C:V1 | C:V2 | C:V3 |
|-------|------|------|------|------|------|------|------|
| TSHV  |      | -2   | -4   | -5   | -7   | -11  | 39   |
| PSHV_{15-25 kHz} |       | -6   | -8   | -3   | -10  | -16  | 89   |

FIGURE 7. RMS spectra of the signal constant in magnitude with variation in frequency (blue – A:V1, red – B:V1, yellow – C:V1, green – reference).

noticeable for all variants due to the considerable leakage. Methods A and C both tend to underestimate the resulting values, while method B provides partly higher results due to lower frequency resolution. No relationship exist between the level of error and frequency of the signal component, which means that minimum error does not necessarily correspond to the signal component with the lowest and the maximum error to the signal component with the highest frequency.

Due to the very short occurrence of the individual signal components, the results for the maximum value largely deviate from the reference values even for method B.

Method A and C show a higher level of unexpected components compared to method B. This difference originates mainly from the different frequency resolutions. Methods A and C cover the frequency range between 15 and 25 kHz with 50 bins at 200 Hz, while only 10 bins contain expected signal components. Contrary, method B requires only six 2-kHz-bins with each bin containing expected signal components and therefore not counting as unexpected components.

Methods A and B perfectly represent the reference value of total supraharmonic voltage, but show some deviation for the specific frequency range of 15-25 kHz. For method C, quasi-peak and RMS detectors provide underestimations for both the total and partial supraharmonic voltage, while the peak detector overestimates them.

The results for signal with variation in magnitude and frequency (S4) are presented in Tables 13-15 and Fig. 8 (only reference variants A:V1, B:V1, C:V1). The additional variation in magnitude does not result in a qualitatively different impact on the error compared to the signal with constant magnitude and varying frequency.

Table 13 presents the minimum and maximum error observed for the ten individual signal components. The performance with regard to the RMS values of expected signal components is rather poor, and the range of the relative errors is broader compared to the signal with constant magnitude and varying frequency. Accuracy for individual frequency components tends to be more accurate for methods with shorter measurement intervals. Variant A:V2 (5 ms) shows lower relative error compared to A:V1 (200 ms). Results of method B (0.5 ms) tend to have the lowest error, which is mainly caused by the lower frequency resolution. Similar to the signal with constant magnitude and varying frequency no relationship exists between the level of error and frequency of the signal component.

Similar to the analysis of the signal with constant in magnitude with variation in frequency, methods A and C have the highest level, while method B has the lowest level.
TABLE 16. Comparison of individual frequency bands.

| f_0, kHz | Variant | A:V1 | A:V2 | B:V1 | C:V1 | C:V2 | C:V3 |
|---------|---------|------|------|------|------|------|------|
| 27      | U_{RMS} | 0.4  | 0.7  | -0.2 | Ref. | -0.2 | 2.6  |
|         | U_{max} | 0.4  | 1.7  | 2.7  |      |      |      |
| 54      | U_{RMS} | -0.6 | 0.2  | 2.9  | Ref. | -0.4 | 2.9  |
|         | U_{max} | -0.6 | 1.0  | 7.0  |      |      |      |
| 108     | U_{RMS} | 0    | 2.0  | 2.7  | Ref. | -0.2 | 2.2  |
|         | U_{max} | 0    | 2.9  | 6.8  |      |      |      |

TABLE 17. Comparison of integral values.

| Variant | A:V1 | A:V2 | B:V1 | C:V1 | C:V2 | C:V3 |
|---------|------|------|------|------|------|------|
| TSHV, dBµV | 117.9 | 117.9 | 117.8 | 117.5 | 117.1 | 120.6 |

TABLE 18. Comparison of individual frequency bands.

| f_0, kHz | Variant | A:V1 | A:V2 | B:V1 | C:V1 | C:V2 | C:V3 |
|---------|---------|------|------|------|------|------|------|
| 20      | U_{RMS} | -0.6 | 0.7  | 2.2  | Ref. | -1.7 | 4.6  |
|         | U_{max} | 1.0  | 6.5  | 9.3  |      |      |      |
| 54      | U_{RMS} | -4.1 | -3.9 | 5.2  | Ref. | -4.8 | 5.9  |
|         | U_{max} | -1.8 | 4.8  | 7.8  |      |      |      |

TABLE 19. Comparison of integral values.

| Variant | A:V1 | A:V2 | B:V1 | C:V1 | C:V2 | C:V3 |
|---------|------|------|------|------|------|------|
| TSHV, dBµV | 111.7 | 111.8 | 113.2 | 115.0 | 110.9 | 121.1 |
| PSHV, dBµV | 109.5 | 109.5 | 109.5 | 113.5 | 108.6 | 120.1 |

of unexpected components. The reasons are similar as it is explained above.

Regarding integral values of supraharmonic emission, methods A and B again accurately reflect the reference value of emission in the entire supraharmonic range. For method C, quasi-peak and peak detectors overestimate, while the RMS detector underestimates integral values of supraharmonic emission. The difference from results presented in Table 12 can be explained by a broader range of relative errors for expected signal components (i.e. RMS values) for the signal with variation in magnitude and frequency.

B. MEASURED SIGNALS

This subsection discusses the results obtained for the measured signals. Since the true emission content of these signals is unknown, the frequencies selected for the performance comparison (e.g. switching frequency of EV charger or frequency range of PLC) have been manually identified in a preliminary analysis of the signal spectra. Due to the absence of reference values, the results are referred to the results of method C:V1 (CISPR 16-1-1 with the quasi-peak detector), which is at present the reference method for assessing emission limits and definition of compatibility levels in IEC 61000-2-2 (see section III.C.2 for further details) for the frequency range 9-150 kHz.

The results for the signal from the laboratory measurements are presented in Tables 16 and 17. Fig. 9 shows the RMS spectra for the reference variants A:V1, B:V1, C:V1. Emission at frequencies 27, 54 and 108 kHz was identified in the preliminary analysis of the signal spectra. For the proper interpretation of results, it should be noted that methods, which do not overlap in frequency can, but not necessarily do, split the energy content of a considered emission between two adjacent frequency bands. For instance, variant A:V2 detects the emission at 27 kHz only in the 26.9 kHz frequency band, whereas variants A:V1 and C:V1-V3 detect the emission in the frequency bands 26.9 and 27.1 kHz. As can be seen in Fig. 12, the same also applies to method B. In case of a “band splitting”, only the value of the frequency band to which the detected frequency belongs according to the definition in IEC 61000-4-7 (e.g. the 26.9 kHz band for the 27 kHz emission) is compared and reported in Table 16. Only for the emission at 54 kHz all variants detect emission in one single frequency band.

The RMS value of both variants of method A show in general a good comparability with method C:V1. The higher values of variant A:V2 compared to A:V1, especially at 108 kHz, are caused by the higher susceptibility of variant A:V2 to leakage due to the shorter measurement interval. Method B provides comparable results at 27 kHz due to the “band splitting”, but considerably higher values compared to variant C:V1 at 54 kHz and 108 kHz, mostly as consequence of higher leakage and noise level (cf. Fig. 9). While leakage results from the short measurement interval, the higher noise is caused by the lower frequency resolution. The higher noise level can even cause that individual components, which can be identified by methods A and C (e.g. at 81 kHz in Fig. 9) are not anymore identifiable with method B.

For method C, the RMS detector (C:V2) provides slightly lower results than the quasi-peak detector (C:V1), while the values provided by the peak detector (C:V3) are significantly higher. It is worth noting that the results with RMS detector, which is more suitable to represent the thermal impact on devices, are almost similar to the results of method A:V1.

Both methods A and B provide similar integral values, which are slightly higher than the results obtained with the quasi-peak detector of method C.
FIGURE 10. RMS spectra of the signal from field measurement (blue – A:V1, red – B:V1, yellow – C:V1).

The results for the signal from the field measurement are presented in Tables 18 and 19. RMS spectra measured for the reference variants A:V1, B:V1, and C:V1 are presented in Fig. 10.

Emission at a frequency of 20 kHz and in the range 35-90 kHz was identified in the preliminary analysis of the signal spectra. For the assessment of results it should be taken into account that variants A:V1 and C:V1-V3 split energy content of emission at 20 kHz between two adjacent frequency bands.

Method A shows again a good comparability to results of method C:V1 regarding RMS values of narrowband emission at 20 kHz. Conversely, method A results in about $-4\text{dB}$ lower values then variant C:V1 in case of the short and distinct emission caused by PLC. This deviation in the RMS-values can be linked to the behavior of the quasi-peak detector.

Similar to the laboratory signal, the results of method B are generally higher compared to the results of C:V1. This applies especially for the broadband emission at 54 kHz, where the signal energy in the 2-kHz-band is inherently much higher than for an individual 200-Hz-bin of methods A and C. The low-frequency resolution of method B compared to methods A and C results also in the highest noise level. Consequently, method B is not able to identify emission components at some individual frequencies (e.g. 108 kHz in Fig. 10), which are detected by methods A and C.

The integral values are calculated for the entire supraharmonic range (TSHV) and the limited frequency range 35-90 kHz of the PLC system (PSHV). Regarding the entire frequency range, method A provides lower results than the quasi-peak detector. The results of the PSHV$_{35-90\text{kHz}}$ suggest that this is caused by the broadband emission of the PLC-signal. Method B underestimate the PSHV$_{35-90\text{kHz}}$ of emission in the same way like method A, as due to the large frequency range considered in the integral values the individual frequency resolution of the methods has no significant impact.

V. COMPUTATIONAL COMPLEXITY

Besides the performance of the measurement methods related to the accuracy, their computational complexity is of crucial importance as it significantly determines the final costs of the measurement instrument. The complexity of an algorithm can be assessed by the number of required Floating Point Operations (FLOP) and the required amount of memory for the processing of each measurement interval.

FLOP represents the total number of mathematical operations to obtain the measurement values from the sample data for each analysis interval. The digital implementation of the measurement methods includes four main stages: signal filtering, FFT computation, post processing and aggregation. The most dominating and diverse impact on the total number of FLOP has the FFT stage, which can be calculated based on the number of sample points according to [12].

The total number of FLOP for each variant of the methods is calculated based on the minimum sampling rate and number of FFTs required to obtain the measurement values for one analysis interval (200 ms). The results are summarized in Table 20. For the calculation of memory requirements, it is assumed that the sample values of the original signal and the result of the FFT have to be stored at the same time using 32-bit floating point format.

Method C has by far the highest computational complexity. As the FFT stage is independent of the detector used in the post-processing, the number of FLOP for each of the variants C:V1, C:V2 and C:V3 is virtually equal. Method A requires about 31,500 times less FLOP compared to method C. Method B:V1 has about 6 times lower computational complexity than method A, but has significant gaps in time and uses the lower resolution of 2 kHz instead of 200 Hz for methods A and C. If method B would be implemented gapless, 400 instead of 32 FFTs are required for the 200 ms analysis interval. In this case, the method would require slightly more FLOP than both variants of method A (ratio to reference C:V1: $5.5\times$).

With regard to memory, method C has the highest requirements due to the parallel DFTs, whereas method B the lowest. Even if the computational complexity of method A:V1 and A:V2 is comparable, the memory requirements for method A:V2 are significantly less compared to

| Variant  | A:V1     | A:V2     | B:V1     | C:Vx     |
|----------|----------|----------|----------|----------|
| Single FFT | 327.68 kHz | 409.6 kHz | 1024 kHz | 409.6 kHz |
| Single FFT FLOP | 1048576 | 22528 | 4608 | 106496 |
| Single FFT memory | 512 kB | 16 kB | 4 kB | 8 kB(*2960) |
| Number of required FFTs | 1 | 40 | 32 | 310800 |
| Total FLOP for all FFTs | 1048576 | 901120 | 147456 | 33181911578 |
| Ratio to reference C:V1 | 3.2 % | 2.7 % | 0.44 % | 100 % |
VI. DISCUSSION

In section V, the performance of three measurement methods for the frequency range 2-150 kHz taken from present standards is compared with regard to their application to measure grid disturbance levels. In addition, three modifications with the capability to improve the standard methods have been included in the comparison (cf. Table 3). This section briefly summarizes the results with regard to the suitability to quantify typical characteristics of supraharmonic disturbances, the similarity to the CISPR 16-1-1 method with the quasi-peak detector (C:V1), which is the present reference in IEC 61000-2-2, and computational complexity.

Both variants of method A (IEC 61000-4-7) are gapless implementations without overlap in time and frequency, which ensures good reproducibility of results. The frequency resolution is comparable to the method C. Individual signal components, which are narrow compared to the frequency resolution of 200 Hz and which do not significantly vary within the measurement interval are quantified with high accuracy. In the case of signal components with varying magnitude and/or frequency, the RMS values are usually underestimated due to the increasing leakage. In many cases, the results are comparable with the CISPR 16-1-1 with quasi-peak and RMS detectors. Integral values for method A properly reflect the signal energy virtually independent of the signal characteristics, which is an important feature for the assessment of thermal impact on devices. The computational complexity is much lower compared to the method C. As a possible trade-off between implementation costs and comparability with method C:V1, method A:V2 could be considered as a potential candidate for a future method.

Method B has significant gaps in time (only 8% signal coverage), which limits the reproducibility but results in the lowest computational complexity. Method B uses a ten times lower frequency resolution than methods A and C. This results in a significantly higher noise floor. Therefore, signal components with low magnitudes, which are still detectable with method A and C, can disappear in the noise. The short measurement interval provides a much better time resolution of the method, which offers the best performance for RMS and maximum values in case of varying signal components. In case the emission covers less than 200 Hz in each 2-kHz-bin (narrowband emission), the results are comparable with method A. In case of broadband emission (emission covers more than 200 Hz in a single 2-kHz-bin), the results differ by up to 8 dB, because the signal energy multiple 200-Hz-bins are combined in the respective 2-kHz-bin. This issue is also a major drawback of method B related to the grid compliance assessment (comparison of measurement values with compatibility levels), which is based on 200-Hz-bins. One possible solution could be a grouping of the compatibility levels to comparable 2-kHz-bands. If this is acceptable, especially by IEC SC 77A WG 8, and the method is extended to become gapless, it might also be considered as a possible candidate for a normative method in the future.

Method C has a very high computational complexity compared to methods A and B. The limitation in the accurate representation of integral values due to the considerable overlaps in frequency is another drawback of the method. This might be solved by developing respective (window-depending) correction factors. An even more general question related to method C is the suitability of the method itself to reflect the relevant interference mechanisms in the considered frequency range, which is a basic requirement for successful EMC coordination in the future. Despite the high computational complexity, the comparison with methods A and B suggests that quasi-peak and RMS detectors seems to be more suitable to reflect RMS values, while the peak detector is better representing maximum values in the signal. If strict comparability with CISPR 16-1-1 is required for grid measurements, method C seems to be the only possible candidate for a future normative method, but further adaptions (e.g. with regard to the implementation of the commonly used 3-second- and 10-minute-aggregation) are still required. However, the good comparability of results between methods A and C should be noted. If method C has to be used for class A instruments, method A would be suitable for class S instruments according to IEC 61000-4-30. All these aspects should be carefully discussed and decided jointly by IEC SC 77A WG 8 and WG 9, as this will considerably affect the costs of future measurement instruments.

The responsibility for the frequency range 2-150 kHz is divided in IEC for administrative reasons between SC77A (below 9 kHz) and CISPR (above 9 kHz). Therefore, in addition to a possible distinction between methods for class A and class S instruments, also a distinction in the measurement methods below and above 9 kHz is under discussion. In order to ensure a general applicability of this article, all methods, originally introduced for different frequency ranges, are discussed for the whole frequency range. One intention of this article is to explore, if a single method might be suitable for the whole frequency range with regard to the assessment of grid disturbance levels. In particular a possible extension of the IEC 61000-4-7 method to frequencies above 9 kHz is therefore considered, as this would simplify the application for end-users and would require much less computational power compared to the CISPR16-1-1 implementation.

All methods and their modifications studied in this article are based on the frequency domain analysis. This naturally implies that they have a rather poor performance in representing the instantaneous characteristics of a signal, i.e. its variation in magnitude and frequency. This could be solved by introducing additional indices derived in different domains, like the depth of commutation notches, which is a time-domain index. Some examples of new indices for supraharmonic emission in time-domain and time-frequency domain are introduced and discussed in [16]. The final decision about the future need for new indices has to be closely linked to the interference mechanism, which is not
adequately covered by existing indices. Such additional indices might also influence the decision about future developments towards a normative measurement method. One example is the (supraharmonic) phase angle, which would be required to extend power definitions in the frequency domain to the supraharmonic frequency range. Furthermore, the proper preservation of the time characteristic of the supraharmonic content and accurate determination of the supraharmonic phase angle might require the specification of additional filter requirements with regard to its phase response [20].

VII. CONCLUSION

The paper compares different frequency-domain methods for the measurement of supraharmonic emission with the objective of their application for measuring grid disturbance levels. The selected methods are based on the specifications in present standards IEC 61000-4-7 (ininformative), IEC 61000-4-30 (informative) and CISPR 16-1-1 (normative). The presented results shall contribute to the ongoing discussion towards a normative measurement method for the frequency range 2-150 kHz for the next edition of IEC 61000-4-30. The comparison is based on a comprehensive set of synthetic and measured signals, which represents the typical characteristics of supraharmonic emission of modern power electronic equipment.

The comparison has shown that all concerning methods have difficulties in case of signals containing components varying in frequency and/or magnitude. This is typical for frequency domain methods and could be overcome by introducing additional indices based on time- or time-frequency domain analysis.

A clear recommendation of one specific method is not possible, as all methods have their individual benefits and drawbacks. In many situations, especially the method according to IEC 61000-4-7 provides a good comparability with CISPR 16-1-1. It finally depends on the priorities of the responsible standardization committees, which method is most eligible to become a normative method.

Despite of the fact that the signals used for the comparison in this paper are derived from the most recent knowledge, further effort towards the characterization of supraharmonic emission, in particular from grid measurements, is needed. Future research is also required on describing the most relevant interference mechanism in the supraharmonic frequency range, as this should be the main driver for defining compatibility levels, emission and immunity limits and respective normative measurement methods.

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