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On the feasibility on RM-A method for extended RMS measurements in the 9-500 kHz range

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Abstract. The conducted emissions in the 2-500 kHz range are widely known for prematurely age certain components of devices connected to the low-voltage (LV) distribution grid. The method described in IEC 61000-4-7 for the 2-9 kHz range is the only standardized technique that provides valid RMS results to assess the energy of the emissions, which is related to this phenomenon. Recently, the RM-A have been presented as an adaptation of the IEC 61000-4-7 to the 9-150 kHz band.
This paper analyzes the suitability of the extension of the RM-A method to the 9-500 kHz range and for 10 min measurements intervals. This work compares the performance of the RM-A method with respect to the IEC 61000-4-7 method, analyzing the deviations on the output spectral values and the execution performance of both methods. In this study, 30 recordings of 10 min length, taken in the LV grid, are processed with both methods to perform a statistical analysis of the deviations. The study shows that the RM-A method provides comparable RMS outputs to the IEC 61000-4-7, but requiring less computational burden and memory resources. Moreover, the RM-A spectra provides higher time and frequency resolution than the IEC 61000-4-7 due to its configuration.

Key words. Electromagnetic interference, measurement methods, power quality, power line communications, supraharmonic emissions.

1. Introduction

In the last decades, several new technologies have been developed in the electrical grid in order to achieve the decarbonization of the economy. The electric vehicle charging station (EVCS) are gaining more and more presence in the low-voltage (LV) distribution grid due to the promotion of the e-mobility. These devices implementing inverter- and rectifier-based components are widely known for the injection of conducted disturbances in the LV grid [1],[2]. Conducted emissions in the 2-500 kHz range, also known as the supraharmonic region, are related to the switched-mode power supplies, switching frequency of high-power semiconductor components, and the pulse width modulation implemented in power electronics [3],[4].

The conducted emissions in the 2-500 kHz range are known for being an interference phenomenon in the grid; interfering power line communications (PLC) [5] and adding thermal stress to the devices connected to the grid [6]. The additional heat that the conducted emissions generate in the electronic components can reduce the lifetime of the electrical equipment. For instance, the built-in capacitors for voltage smoothing in electronic mass-market equipment may be aged prematurely due to conducted disturbances [7],[8].

In order to assess the possible contribution of the conducted emissions to the thermal stress of the devices connected to the grid, the energy of the conducted emissions in the 2-500 kHz is measured. The root-mean-square (RMS) values in the frequency domain are computed to quantify the energy of the conducted emissions. Additionally, the maximum amplitude value of the spectra are computed in this study, which is related to the malfunction that equipment connected to the grid may suffer [6].

Currently, several measurement methods to assess the level of the conducted emissions in the frequency domain are defined in standards and in research publications. IEC 61000-4-30 Ed.3 [9] standard, in its Annex C, contains the measurement methods to characterize conducted emissions in the 2-150 kHz. For the 2-9 kHz range, the measurement method described in IEC 61000-4-7 – Annex B [10] is suggested; while for the 9-150 kHz band, three measurement approaches are proposed: the CISPR 16 receiver [11], the extension of the IEC 61000-4-7 method to this frequency range [10], and an alternative method described in the own IEC 61000-4-30 standard [9]. Nonetheless, only the IEC 61000-4-7 method is able to provide RMS values continuously over the entire measurement interval to quantify the energy of the conducted emissions [12]. The CISPR 16 standard series do not define a RMS detector, but RMS-average and average detectors that do not reflect the effective value of the level of the emissions, since they are based on the charge and discharge process of a critically damped meter followed by a peak indicator [11]. In addition, the alternative method described in IEC 61000-4-30 Ed.3 is not valid to estimate the energy of the disturbances, since the 92% of the measurement interval is not processed, in order to reduce the computational burden [9]. Therefore, the unique standardized method to assess the RMS spectra of the conducted disturbances continuously is the IEC 61000-4-7 – Annex B method. Nevertheless, the IEC 61000-4-30 – Annex C does not provide any guidance on how to extend the IEC 61000-4-7 to frequencies above 9 kHz. Furthermore, the direct implementation of the method to the 9-500 kHz band would imply a high computational burden, due to the extension to a bandwidth 50 times larger than the one specified in the standard. In addition, the windowing of 200 ms is too long for the characterization of emissions at 9-500 kHz band, and impulsive phenomena may be hidden in the Fourier analysis.

Recently, an adaptation of the IEC 61000-4-7 method to the 9-150 kHz band has been published [13]. This research method, labelled as RM-A method, adapts some parameters of the configuration of the IEC 61000-4-7 method, such as the window length and the frequency grouping, to characterize the conducted emissions in the 9-150 kHz band. In [13], the application of the RM-A method to measurements intervals of 3 s in the 9-150 kHz band is defined to obtain RMS and peak readings. Nonetheless, its application up to 500 kHz and for extended measurement has not been defined.

This contribution studies the feasibility of extending the configuration of the RM-A method to the 9-500 kHz range and for the evaluation of measurement intervals of 10 min.

2. Objectives

This contribution aims to extend the measurement configuration of the RM-A method up to 500 kHz and prove its feasibility to obtain RMS values in measurement intervals of 10 min for the 9-500 kHz. In order to achieve the main objective of this work, the temporal aggregation strategy of the output values of RM-A method is defined.. To prove the feasibility of the RM-A method, a statistical study of the deviations in the output of the RM-A with respect to IEC 61000-4-7 technique is performed, as well as a study of the computational burden.

3. Measurement methods

This section describes the measurement methods to be compared in this contribution.

A. IEC 61000-4-7 – Annex B

The method described in IEC 61000-4-7 [10] standard was originally defined for the 2-9 kHz range, in order to assess the conducted emissions above the harmonic range. This method is based on a two-step process (see Fig. 1). Firstly, the spectral values of the conducted emissions every 200 ms are computed, and secondly, the spectral values obtained every 200 ms are aggregated in the aggregation intervals defined in power-quality standards (3 s, 10 min, etc.) [9].

In the first step, the frequency analysis is applied, by means of a short-time Fourier transform (STFT) and non-overlapped rectangular windows of 200 ms length. The output values, whose resolution bandwidth (RBW) and

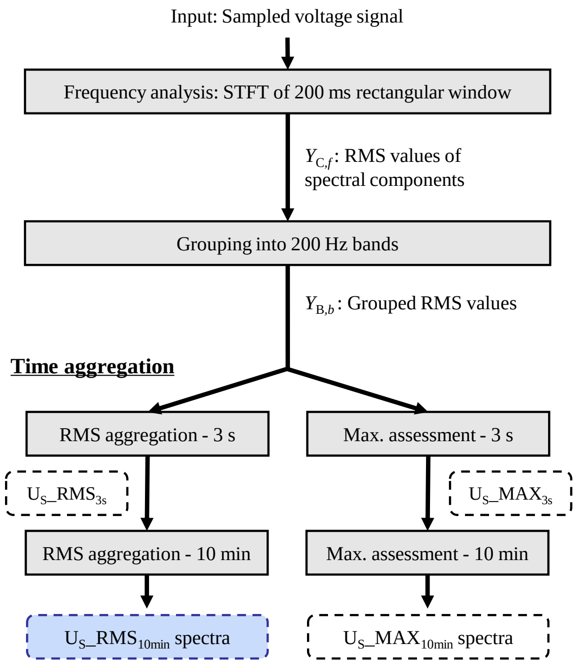

Fig. 1. Schematic overview of IEC 61000-4-7 Annex B measurement method.

frequency-step-size (FSS) is of 5 Hz, are grouped to obtain spectral samples with a RBW and a FSS of 200 Hz. In the second step, the grouped values are subsequentially aggregated in 3 s and 10 min measurement intervals to obtain representative information of the level of the conducted emissions. The aggregation is performed by means of a cascade of RMS and peak detectors to assess the RMS and maximum value of the conducted emissions in the defined measurement intervals (see Fig. 1).

The IEC 61000-4-7 method provides the following metrics (see Fig. 1):

- $Y_{B,b}$: The spectral grouped values provided by the method every 200 ms.
- U_S_RMS_{3s}: The RMS spectra obtained every 3 s.
- U_S_MAX_{3s}: Peak values obtained every 3 s.
- U_S_RMS_{10min}: The RMS spectra aggregated in 10 min measurement intervals.
- U_S_MAX_{10min}: Peak values obtained every 3 s.

B. RM-A method

The RM-A [13] is the adaptation of the IEC 61000-4-7 method for the 9-150 kHz band, in which the window length and the frequency grouping has been changed to characterize more precisely the interference phenomenon in this frequency range. This technique is also defined as a two-step process, involving both frequency analysis and spectral aggregation (see Fig. 2).

The spectral analysis block is composed of a STFT which implements non-overlapped rectangular windows of 20 ms length (instead of 200 ms). The spectral components obtained every 20 ms, whose RBW and FSS is of 50 Hz (instead of 5 Hz), are then grouped applying the 'symmetrical grouping' defined in [13]. This grouping provides spectral values with a RBW of 200 Hz and a FSS of 100 Hz. This grouping, together with a 10 times smaller windowing, provides results with higher frequency resolution (100 Hz instead of 200 Hz) and time resolution (20 ms instead of 200 ms) than the IEC 61000-4-7 method.

Regarding the aggregation stage, in [13] the process to obtain spectral values every 3 s is defined; firstly, aggregating the grouped values ($Y'_{B,b}$ in Fig. 2) every 200 ms ($U_R\_XX_{200ms}$ in Fig. 2), and then, aggregating them in 3 s measurement intervals by means of peak and RMS detectors ($U_R\_XX_{3s}$ in Fig. 2).

This contribution proposes to extend the aggregation process up to 10 min ($U_R\_XX_{10min}$ in Fig. 2), in order to assess the level of the conduced emissions with extended measurements.

The extension of the RM-A method provides the following metrics (see Fig. 2):

- $Y'_{B,b}$: The spectral grouped values obtained at the output of the 'symmetrical grouping' every 20 ms.
- $U_R\_RMS_{200ms}$: The RMS spectra aggregated every 200 ms.
- $U_R\_MAX_{200ms}$: Peak values assessed every 200 ms.
- $U_R\_RMS_{3s}$: The RMS spectra obtained every 3 s.
- $U_R\_MAX_{3s}$: Peak values obtained every 3 s.
- $U_R\_RMS_{10min}$: The RMS spectra aggregated in 10 min measurement intervals.
- $U_R\_MAX_{10min}$: Peak values obtained every 10 min.

Even though the RM-A was defined to characterize conducted emissions in the 9-150 kHz band, this work proposes and evaluates its application up to 500 kHz extending the configuration described in [13] without requiring additional processing techniques.

4. Methodology

This section contains the methodology followed in this contribution to assess the feasibility of RM-A method to characterize conducted emissions in the 9-500 kHz range for measurement intervals of 10 min. This section contains, firstly, the information about the grid recording used to evaluate the results provided by the RM-A method against the output values of IEC 61000-4-7; and secondly, the comparison procedure for the detailed analysis.

A. Grid recordings

In this study, 30 recordings of 10 min length containing conducted emissions generated by 9 electric vehicles are processed to compare the outputs of RM-A and IEC 61000-4-7 methods. The recordings were taken in the point-of-connections of different EVCS to the LV grid in 3 measurement campaigns.

The acquisition system used to record the measurements is composed of a voltage probe, a digital oscilloscope, and a laptop [14],[15]. The voltage probe implements a bandpass filter to get rid of the conducted emissions outside the 2-500 kHz range the fundamental of the grid (50/60 Hz) and the harmonic components. In addition, it implements a galvanic isolation to prevent over-voltage surges and spikes. The digital oscilloscope digitizes the signal filtered by the probe with a resolution of 16 bits and a sampling frequency of 8.92 MS/s. Finally, the laptop automatizes the measurements and stores the acquired data.

B. Comparison procedure

The performance of RM-A and IEC 61000-4-7 methods are compared in this contribution for 10 min measurements

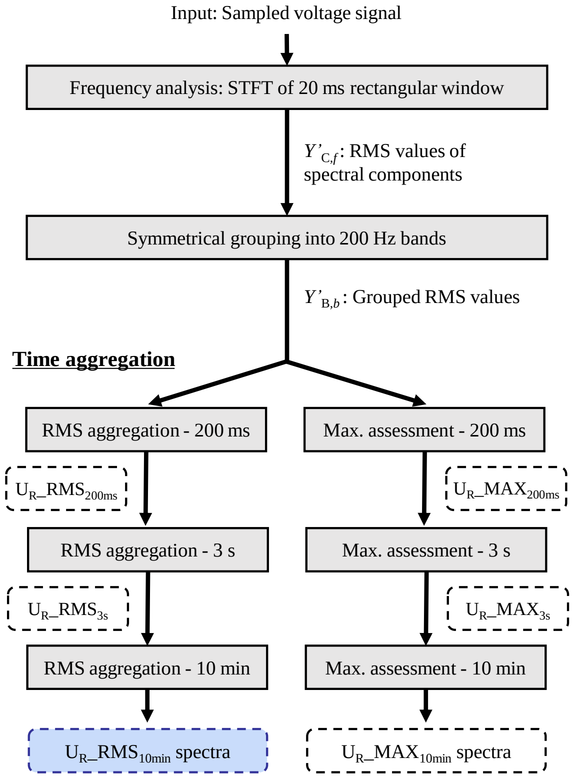

Fig. 2. Schematic overview of RM-A measurement method.

in the 9-500 kHz range. For this purpose, the 10 min RMS spectra of 30 recordings obtained with both methods ($U_S\_RMS_{10min}$ and $U_R\_RMS_{10min}$ in Fig. 1 and Fig. 2, respectively) are compared by means of a statistical analysis. The 300 minutes of measurements used to evaluate both methods provides a comprehensive evaluation of the performance of both methods.. This in-depth analysis is based on several metrics that assesses the differences in the results, such as, the median, the 95th percentile, and the 80% of the range (the difference between 90th and 10th percentiles) of the absolute differences. In addition, the median value and the 95th percentile of relative differences, and the percentage of spectral samples with a difference in results below 10% are computed.

The computational burden of both methods is also studied in this contribution. The execution time and the memory resources needed by the methods to process 10 min measurement intervals is computed in this work to assess their computational complexity. This analysis is performed on the same platform for both methods (Windows 10, CPU Intel i7-1265U 2.68 GHz, RAM 16 GB 3200 MHz), evaluating the performance of the digital versions of both methods implemented in Matlab, to ensure a comparable framework.

5. Results

This section contains the results of the comparison between the two methods, where the performance of the methods is evaluated in terms of computational cost and the deviations of the output data.

A. Analysis of execution resources

The results of the analysis evaluating the execution performance of the methods is contained in Table I. The methods studied in this work require different number of discrete Fourier transforms (DFTs) to process a 10 min measurement interval. The IEC 61000-4-7 method requires 3000 DFTs, while the RM-A method requires 30,000 DFTs since the windowing is 10 times smaller (20 ms length for RM-A and 200 ms length for IEC 61000-4-7).

Regarding the memory resources, RM-A method requires 3 times less storage than the IEC 61000-4-7 method (see Table I). The main contribution to this metric is the raw voltage data that must be stored by each method to fill a DFT window. The implementation in RM-A method of 10 times smaller windows with respect to the standardized method results in reduced memory requirements. This memory is utilized for storing the additional aggregation step (from 20 ms to 200 ms) defined in this method. For the execution time, the RM-A requires 15% less real clock time and almost 40% CPU time to process a 10 min measurement than the IEC 61000-4-7 method. Although it may seem that a higher number of DFTs could indicate a higher complexity of the RM-A method, in this particular scenario, the size of the DFT window plays a more decisive role (see Table I), and this is the reason because the RM-A method demands less memory resources, shorter computational time and lower computational requirements.

B. Comparison of methods outputs

The outputs provided by the RM-A method are compared with respect to the values obtained with IEC 61000-4-7 in this section.

In Fig. 3 and Fig. 4, the spectra obtained with both methods for two LV grid recordings are represented. The RMS outputs (U_S_RMS$_{10min}$ and U_R_RMS$_{10min}$ in Fig. 3 and Fig. 4) are nearly overlapped in the entire spectrum, while the peak values (U_S_MAX$_{10min}$ and U_R_MAX$_{10min}$ in Fig. 3 and Fig. 4) differ considerably, providing differences of up to 10 dB (see Fig. 3). As the RM-A method implements windows 10 times shorter than the IEC 61000-4-7 (20 ms instead of 200 ms), the RM-A method is able to detect impulsive emissions more precisely when the peak detector is applied, detecting with more detail fast amplitude fluctuations. The rectangular window of 200 ms length implemented in IEC 61000-4-7 causes impulsive emissions to be hidden during the DFT calculation process. In addtion, the RM-A method provides results with higher time granularity (20 ms instead of 200 ms) and frequency resolution (100 Hz instead of 200 Hz) than the standardized IEC 61000-4-7 method. Nonetheless, the shorter rectangular window (20 ms instead of 200 ms one of IEC 61000-4-7) implemented by RM-A increases the spectral leakage. This effect is generated since the energy of the adjacent emissions is sneaked into the frequency bins where waveforms have lower amplitude, resulting in an overestimation of the amplitude of the frequency components under study.

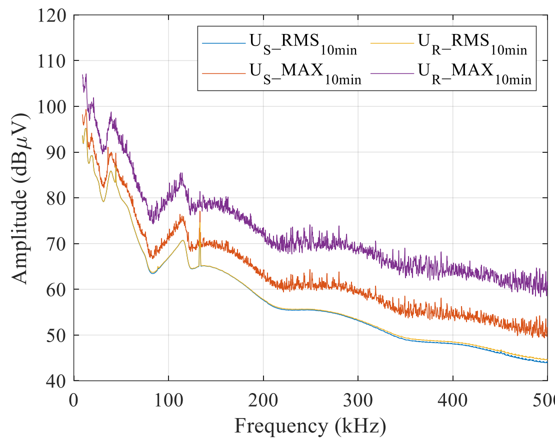

Fig. 3. Output values for a 10 min length recording processed with the IEC 61000-4-7 and RM-A methods.

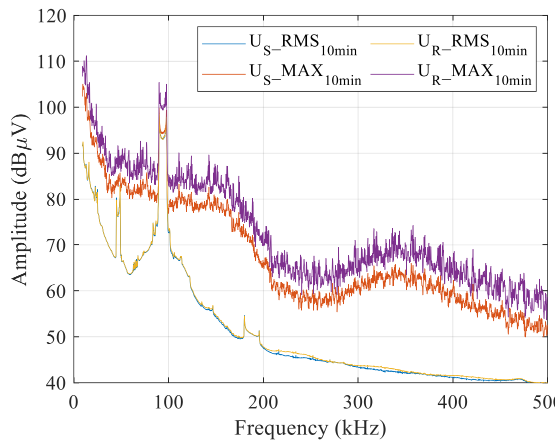

Fig. 4. Output values for a 10 min length recording processed with the IEC 61000-4-7 and RM-A methods.

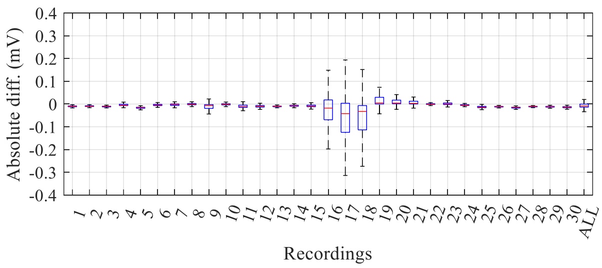

Fig. 5. Boxplot of the absolute differences between the outputs provided by the RM-A and IEC 61000-4-7 for the 30 recordings of the dataset (individual and overall results).

Table II shows the results of the statistical analysis performed over the spectral RMS outputs for the 10 minutes length recordings of the dataset. The results contained in Table II show that the median, the 95th percentile and the range of 80% of absolute differences are below few tens of microvolts. Fig. 5 shows that the dispersion of the absolute differences is within ±0.4 mV.

TABLE I

COMPUTATIONAL REQUIREMENTS OF IEC 61000-4-7 AND RM-A METHODS FOR 10 MINUTES MEASUREMENTS

Method	Time step	Number of DFT	Memory	Elapsed real time	CPU processing time
IEC 61000-4-7	200 ms	3000	35.31 MB	384.95 s	1769.83 s
RM-A	20 ms	30,000	11.18 MB	330.68 s	1113.85 s

TABLE II

COMPARISON OF RM-A RESULTS AGAINST IEC 61000-4-7 OUTPUTS

Spectra	Absolute value of differences			Relative differences		
	Median	95^{th}	Range of 80 % (90^{th} -10^{th})	Median	95^{th}	Perc. of diff. ≤10 %
U_S_RMS_{10min}–U_R_RMS_{10min}	-0.008 mV	0.060 mV	0.046 mV	1.54 %	9.68 %	95.56 %

Regarding the relative differences, the median value shows that the 50% of the spectral samples provide a deviation of around 1.5%, while the 95^{th} percentile demonstrates that the 95% of the spectral bins provide a deviation lower than 9.7% (see Table II). Additionally, the percentage of spectral samples providing deviation lower than the 10 % has been calculated, showing that the 95.5% of values are below that threshold.

To sum up, the RM-A method provide similar results to the IEC 61000-4-7, but requiring less memory and computational resources.

6. Conclusions

Due to the proliferation of equipment implementing inverters and rectifiers, such as EVCS, conducted emissions in the 2-500kHz band are becoming more and more an abundant interference mechanism on the LV distribution grid. The effective energy of these emissions is directly related to the premature aging of certain components of the grid-connected devices. Therefore, the quantification of the RMS spectra of the conducted emissions in the 9-500 kHz is crucial.

Recently, the adaptation of the IEC 61000-4-7 – Annex B to the 9-150 kHz band, which was originally defined for the 2-9 kHz range, has been published under the name of RM-A method. This work proposes and validates the extension of the novel measurement method up to 500 kHz and for measurement intervals of 10 min length.

This contribution analyzes the feasibility of the extension the RM-A method comparing, by means of statistical analyses, the output level values and the execution performance of the novel method against the standardized IEC 61000-4-7 method.

The results obtained by processing 30 recordings of 10 min length taken in the LV distribution grid show that the deviation in the amplitude output between both methods are below 0.4 mV and the median of the relative differences is around 1.5%. Moreover, the RM-A method computes spectral values with a FSS of 100 Hz, resulting in twice the frequency resolution compared to IEC 61000-4-7. Furthermore, the RM-A method computes spectral values every 20 ms, providing a temporal granularity 10 times higher than IEC 61000-4-7. Regarding the computational burden, the RM-A method requires 3 times less memory and 40% less CPU execution time than the IEC 61000-4-7.

To sum up, the RM-A method provides comparable results to the standardized IEC 61000-4-7 in the 9-500 kHz range for 10 min measurement intervals providing higher time and frequency resolution, but requiring less memory resources and computational burden.

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