

Article

Aggregated Conducted Electromagnetic Interference Generated by DC/DC Converters with Deterministic and Random Modulation

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Abstract: The assessment of electromagnetic compatibility (EMC) is important for both technical and legal reasons. This manuscript addresses specific issues that should be taken into account for proper EMC assessment of energy systems that use power electronic interfaces. The standardized EMC measuring techniques have been used in a laboratory setup consisting in two identical DC/DC converters with deterministic and random modulations. Measuring difficulties caused by the low frequency envelopes, resulting from frequency beating accompanying aggregation of harmonic components of similar frequencies, were indicated as a phenomenon that might lead to significant problems during the EMC assessment using currently binding standards. The experimental results describing deterministic and random modulated converters might be useful for practitioners implementing power interfaces in microgrids and power systems as well as for researchers involved in EMC assurance of power systems consisting in multiple power electronic interfaces.

Keywords: conducted electromagnetic interference; electromagnetic compatibility; aggregated electromagnetic interference; power electronic interfaces; frequency beat

1. Introduction

Electromagnetic compatibility (EMC) assessment is demanded for technical as well as legal reasons. EMC evaluation is usually based on the use of the dedicated standards, which determine the permissible limit values for electromagnetic interference (EMI), measurement methods, test equipment and provide classification of products according to their characteristics and electromagnetic environment where they are intended to be used [1]. The shape of conducted EMI depends on the source of the interference as well as complex phenomena accompanying the flow of interference in circuits, including parasitic couplings. In the subject matter literature, some papers emphasize the necessity for assurance of reliable operation of complex energy systems and the need for EMC assurance [2–8]. Furthermore, some papers highlight how approaches concerning deterministic modulation (DetM) and random modulation (RanM), based on the parameters' control of fundamental switching frequency (f_{sw}) and duty cycle (d), may contribute to achieving EMC requirements [9–20]. Indeed, the RanM has been widely used since the 1980s [21]. From the practical viewpoint, beyond the reduction in the maximum level of voltage or current harmonics, the choice for RanM has been considered in order to provide, for instance, reduced of burdensome acoustic noise related to switching frequency [10]. However, some manuscripts have shown that the aggregation of interference in the case

of deterministic modulation might be accompanied by low frequency envelopes. This phenomenon may lead to misinterpretations during the EMC assessment [22–25].

According to requirements of the EMC Directive [26] “where apparatus is capable of taking different configurations, the electromagnetic compatibility assessment should confirm whether the apparatus meets the essential requirements in the configurations foreseeable by the manufacturer as representative of normal use in the intended applications”. Moreover, the EMC Directive defines responsibility of standard organizations in this context: “The European standardisation organisations should take due account of that objective (including the cumulative effects of the relevant types of electromagnetic phenomena) when developing harmonised standards”. Taking into account a global approach to standardization, the issues presented in this paper, concerning aggregation of the conducted electromagnetic interference introduced by power electronic converters with deterministic [27] and random modulation, might constitute a contribution to the elaboration of relevant standards as well as practical information for engineers dealing with assurance of EMC in systems consisting power electronic converters.

As mentioned above, random modulation might contribute to a reduction of maximum levels of EMI spectrum due to more even dispersion of interference over frequency range in comparison with deterministic modulation. Figure 1 shows the EMI measurement of one buck converter topology, with the $f_{sw} = 60$ kHz, $d = 0.5$ and with both switch control strategies, DetM and RanM. The EMI measurement presented by Figure 1 was carried out based on the FPGA-based system proposed in [20].

The detailed standard requirements concerning conducted EMI can be found in CISPR 16. Standardized conducted EMI measurements consider the frequency range from 9 kHz to 30 MHz, where the Intermediate Frequency Band Width (IFBW) equal to 200 Hz is applied for the range from 9 kHz to 150 kHz (CISPR A) and IFBW = 9 kHz is applied for the range from 150 kHz to 30 MHz (CISPR B). Since the core concept of the DetM is to provide a f_{sw} constant under the time. The power spectral density is concentrated for frequencies equal to the harmonics of the switching frequency. On the other hand, RanM provides the spreading of interference over frequency range, thus the reduction of maximum observed values is obtained.

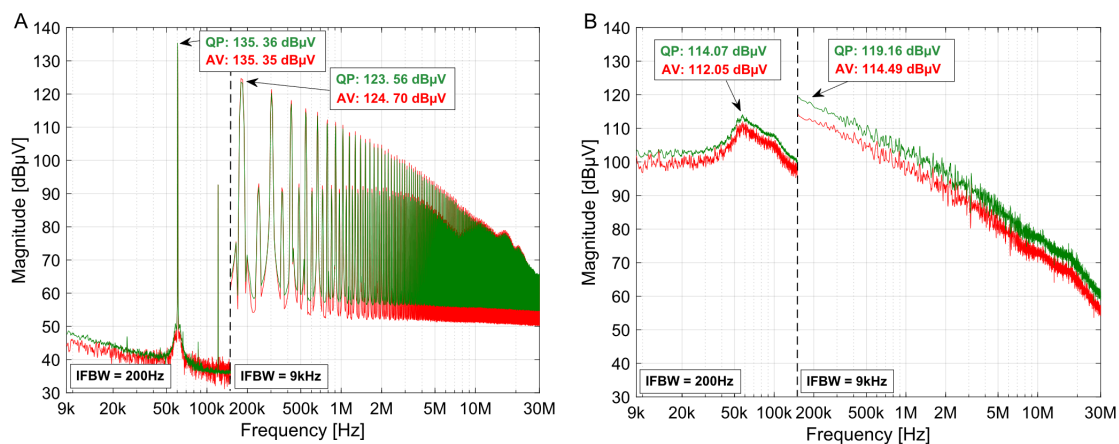


Figure 1. Electromagnetic interference (EMI) measurement of DC/DC converter with the $f_{sw} = 60$ kHz and $d = 0.5$: (A) for deterministic modulation (DetM) and (B) for random modulation (RanM). Results obtained through the FPGA-based system proposed in [20].

The novelty of this paper lies in the presentation of the comparative analysis concerning aggregated interference generated by converters with DetM and RanM. This approach allows us to comprehend the behavior of low-frequency envelopes phenomena beyond the traditional knowledge related with DetM and RanM, i.e., the absence of f_{sw} variation means high disturbance values for the f_{sw} and its harmonics. On the other hand, through the introduction of f_{sw} variation means reduced of disturbances levels. The analyses presented in this paper consider simulations and experimental results based on a standardized testing setup.

2. Simulation Results of Aggregated EMI Generated by DC/DC Converters with Deterministic and Random Modulation

The simulations of DC/DC buck converters with deterministic and random modulation have been run on MatLab software. The function spectrogram was used, and it returns the Short-Time Fourier Transform (STFT) of the aggregated signal with a Hamming window.

Figure 2 shows the results of the simulation in the form of 3D spectrograms. Simulations have been performed for the $f_{sw} = 80$ kHz and $d = 0.5$. The spectrogram (A) shows results for one interference signal generated by a single converter with DetM, while spectrogram (B) shows the aggregated interference introduced by two converters operating in parallel. Since the superimpositions of the switching frequency harmonics can be related to the summation of sinusoidal signals of similar frequency. This process of aggregating sinusoidal components with similar frequencies causes modulation of their amplitudes with low frequency envelopes. This phenomenon is well-known in acoustics as frequency beat. The theory of frequency beats [24] highlights that the sum of the harmonic vibrations with the frequencies f_1 and f_2 of amplitudes equal to 1 can be expressed by:

$$S_2(t; \{f_1, f_2\}) = \sin(2\pi f_1 t) + \sin(2\pi f_2 t) = 2 \cos\left(2\pi \frac{f_1 - f_2}{2} t\right) \sin\left(2\pi \frac{f_1 + f_2}{2} t\right). \quad (1)$$

The frequency beat effect appears when $|f_1 - f_2| \ll f_1 + f_2$. In such conditions, the absolute value

$$\text{Env}_2(t; \{f_1, f_2\}) = \left| 2 \cos\left(2\pi \frac{f_1 - f_2}{2} t\right) \right| \quad (2)$$

is the envelope of the aggregated signal. It is also possible to observe that the period of the envelope does not depend on the frequencies of the components, but on the difference between the frequencies of the aggregated signals [24].

The appearance of low frequency envelopes in the case of aggregated interference might cause significant measuring problems.

Additionally, the comparison between spectrograms (A) and (B) in Figure 2 reveals that the maximum observed amplitude is lower in the case of the aggregated interference. However, it should be noted that the power spectral density in a sufficiently wide frequency range and measuring time is higher in the case of aggregated interferences.

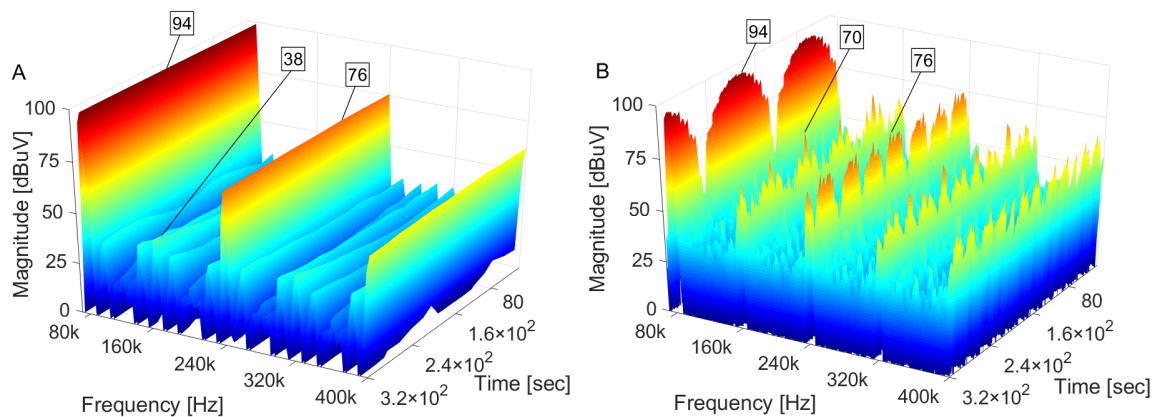


Figure 2. Simulation 3D spectrograms of interference caused by one DC/DC converter with DetM (A), and two DC/DC converters with DetM (B).

Figure 3 shows the spectrograms corresponding to those presented in Figure 2 with the same parameters, but for random modulation. In both cases of Figure 3, item (A) and (B), the interference

power has been spread over the frequency range, and is more even in comparison with DetM, Figure 2. As a result of a more even distribution of interference power, the maximum measured levels have been significantly decreased.

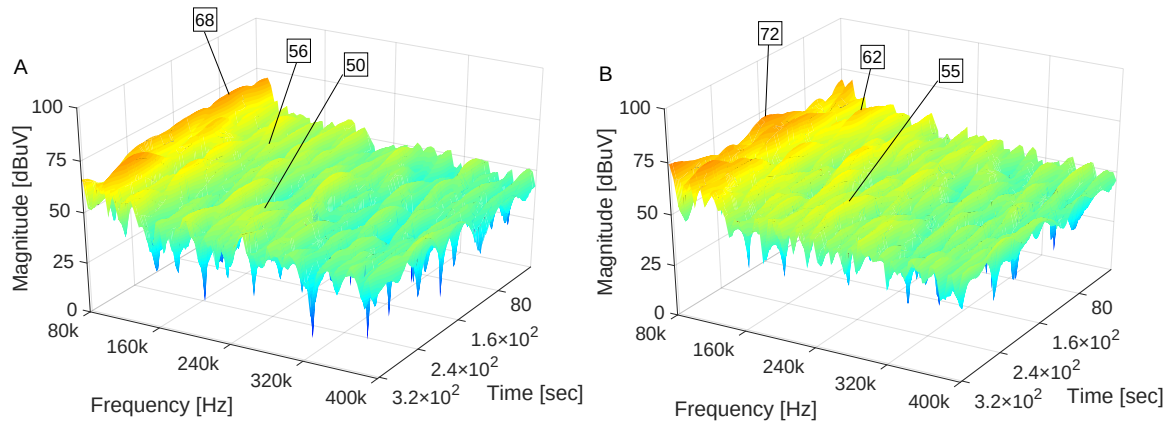


Figure 3. Simulation 3D spectrograms of interference caused by one DC/DC converter with RanM (A), and two DC/DC converters with RanM (B).

3. Measurements of Aggregated EMI Generated by DC/DC Converters with Deterministic and Random Modulation

In order to confirm the results of the simulation, standardized EMI measurements have been obtained from a laboratory setup fully compliant with EN 55011 based on a voltage probe. Two DC/DC buck-converters constitute the Equipment Under Test (EUT). Both converters are based on a C2-class high speed insulated-gate bipolar transistor (IGBT). The hardware interface for signal and ground are made by the R-Series Multifunction RIO (FPGA PXI-7854R), with VIRTEX-5 LX110. The control signal output (RanM and DetM) is provided at the hardware level by the shielded connector block NI SCB-68A. Figure 4 illustrates the scheme for the measuring testbed.

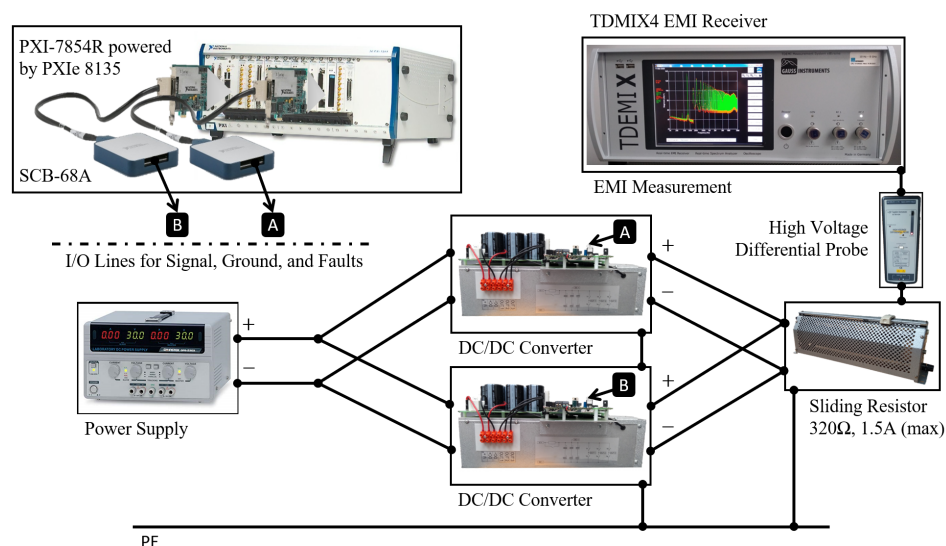


Figure 4. Schematic diagram of measuring testbed.

The schematic diagram presented in Figure 4 shows that both buck-converters are powered by the same regulated laboratory power supply by means of the cables of equal length. In addition, two FPGA control boards were used, and both were powered by controller PXIe 8135 to avoid additional couplings through the power source. A 1.5 A Leybold sliding resistor $320\ \Omega$, was connected as the load on the

output of buck-converters (24 V) connected in parallel. In addition, equal length of cables has been applied. The most important parameters of the buck-converter topology have been summarized in Table 1.

Table 1. The main parameters of buck-converter topology.

Component/Function	Specification
Transistors type	IXGH40N60C2D1
$I_C(\text{max})$	40 A
t_{on}	40 ns
t_{off}	180 ns
Transistor Gate Drivers	HCPL-316J
Converter Power	1800 W (max)
DC capacitors	1500 μF
Max DC voltage	450 V
Load	sliding resistor 320 Ω (max), 1.5 A (max)

The output voltage was measured by a differential voltage probe SI-9010A from Sapphire Instruments (with a 40 dB attenuation level). In both cases, for all presented experimental results, the $f_{sw} = 80$ kHz and $d = 0.5$ remained unchanged. Figures 5 and 6 show the measurements obtained using a digital receiver type TDMIX6 EMI, which provides a 3D spectrogram for both Quasi Peak (QP) and Average (AV) detector and CISPR 16-1-1 compliant measurements. In order to increase readability of the figures, measurements have been taken up to 6th harmonic with IFBW = 200 Hz. The experimental results presented in Figure 5 have confirmed the presence of the frequency beat phenomenon observed in simulations. In a case of two converters low frequency envelopes resulting from frequency beat are superimposed on the interference harmonics.

The use of random modulation to disperse interference over the frequency range prevents the frequency beating phenomenon, which appears during aggregation of sinusoidal components of similar frequencies. Thus, in the case of RanM presented in Figure 6 the low frequency envelopes do not appear for aggregated interference introduced by two DC/DC converters connected in parallel Figure 6B.

Generally, the shapes of experimental results, presented in the form of 3D spectrograms, based on data from a laboratory setup, fit well with corresponding 3D spectrograms obtained by simulations. Both simulation and experimental results confirm the theoretical assumptions concerning aggregation of interference for deterministic and random modulation. The obtained results encouraged us to perform multiple measurements according to standard requirements.

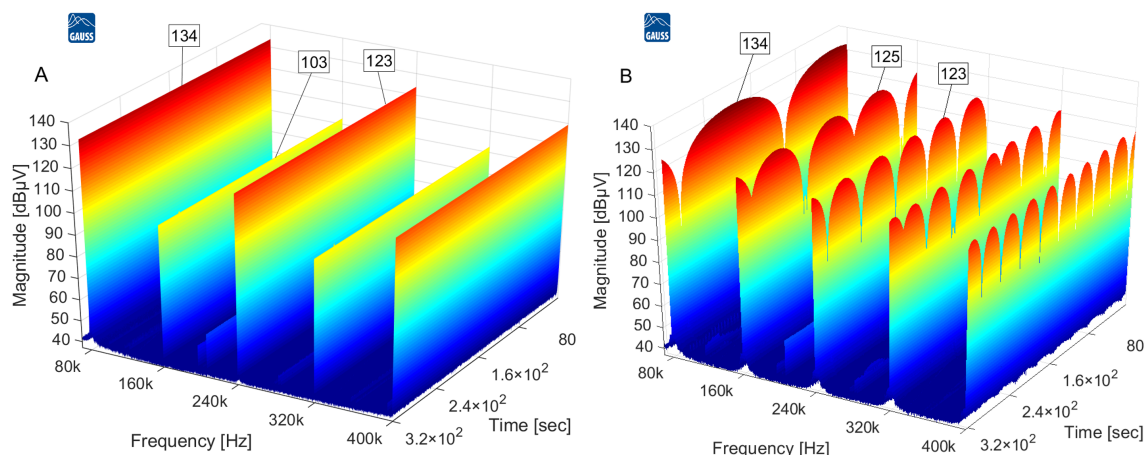


Figure 5. Experimental 3D spectrograms of interference measured using AV detector, caused by one DC/DC converter with DetM (A), and two DC/DC converters with DetM (B).

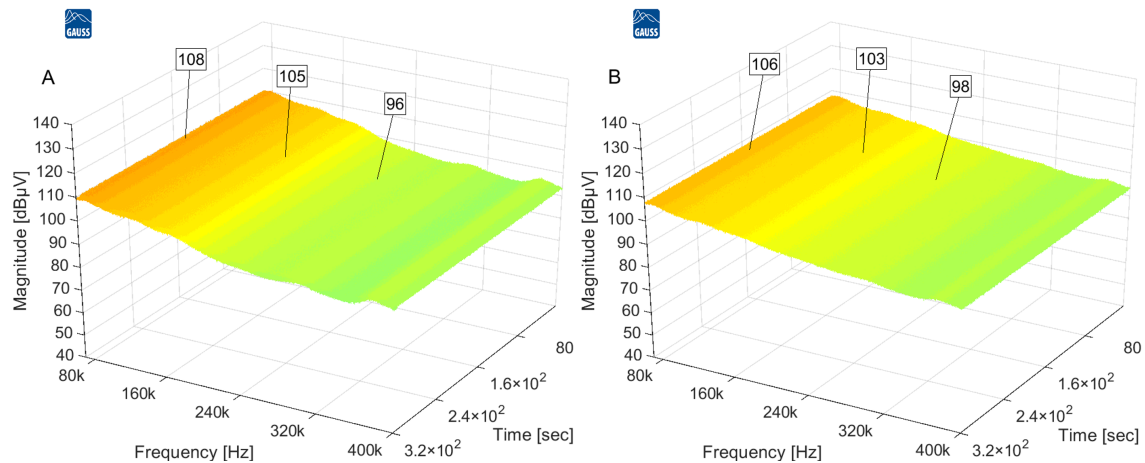


Figure 6. Experimental 3D spectrograms of interference measured using AV detector, caused by one DC/DC converter with RanM (A), and two DC/DC converters with RanM (B).

4. Statistical Analyses of Aggregated EMI Generated by Converters with Deterministic and Random Modulation Measured According to Standards

In order to present measurement problems connected with the frequency beat phenomenon multiple measurements of the frequency linked with the highest emission were taken. The results of the measurements have been presented in the form of box-and-whisker plots, supplemented with individual values of measured EMI depicted as points. According to standard requirements [28], one final measurement taken during a measuring period equal to 1 s can be compared with the limit line for a presumption of conformity based on harmonized standards. The standards require measurements using QP as well as AV detector. Since the results obtained for both detectors did not differ significantly the presented analyses were based on AV detector measurements only. For each investigated case, 1000 final measurements during 1 s were taken [29].

Figure 7 shows distributions of the results obtained for single DC/DC converters with DetM (A) and RanM (B). The dispersion of the 1000 results in the case of DetM (A) is lower than 0.1 dB. The randomization of the switching frequency caused an increase of the dispersion up to 2 dB. Such distributions of the results confirm that a case of EMI generated by a single DC/DC converter is sufficient for EMI evaluation.

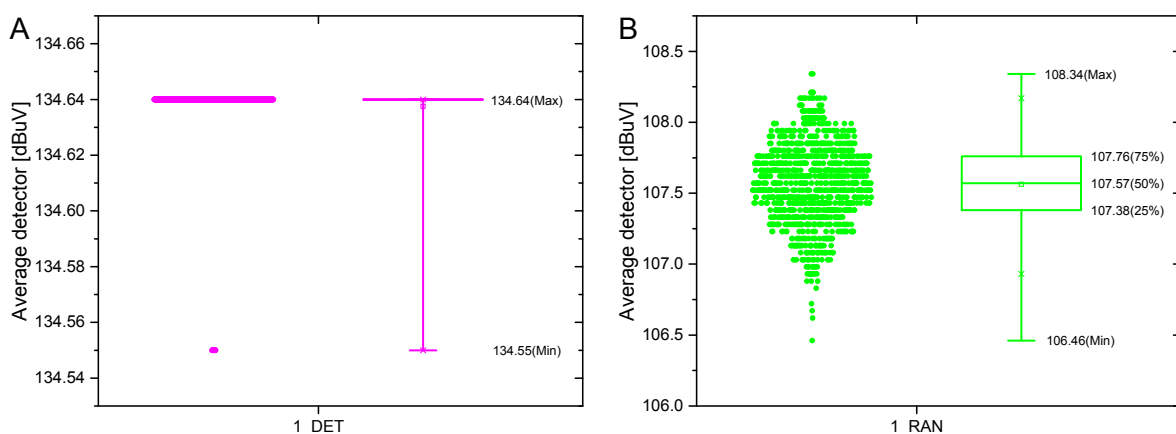


Figure 7. Box-and-whisker plots of 1000 average detector 1 s measurements for one DC/DC converter with: (A) deterministic modulation and (B) random modulation

The 2 dB dispersion remained unchanged in the case of aggregated interference introduced by two DC/DC converters with random modulation, Figure 8B. However, low frequency envelopes, linked with the frequency beat phenomenon and accompanying aggregation of EMI introduced by

converters with deterministic modulation, caused a significant increase in the range of measured levels. The observed differences reached 25 dB (18 times), Figure 8A.

The observations based on the Figures 7 and 8 are confirmed by statistical parameters determined for empirical distributions presented in the figures. The values of variance and standard deviation of measurements in an arrangement consisting of two DC/DC converters are much greater than in other investigated cases (Table 2). The variance and standard deviation calculation, from the EMI measurement viewpoint, represent the dispersion of the measurements of the AV detector, indicating “how far” in general its values are from the expected value. In fact, such dispersion of the results makes evaluation of aggregated EMI, based on one final measurement, in arrangement consisting converters with deterministic modulation unreliable.

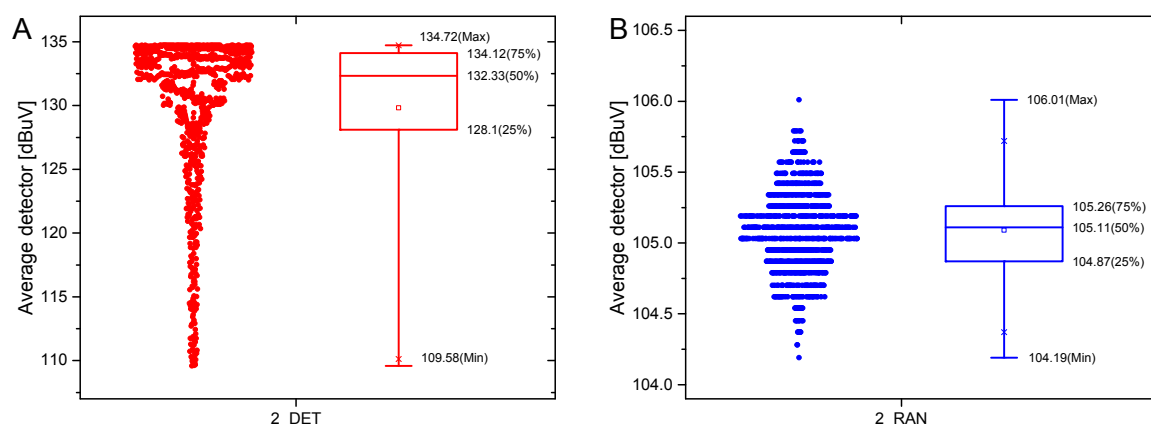


Figure 8. Box-and-whisker plots of 1000 average detector 1 s measurements for two DC/DC converters with: (A) deterministic modulation and (B) random modulation

Table 2. Statistical parameters of empirical distributions of 1000 final measurements using AV detector.

	Mean	Standard Deviation	Variance	Median	Minimum	Maximum
1_DET	134.64	0.01	0.0002	134.64	134.55	134.64
1_RAN	107.56	0.29	0.08	107.57	106.46	108.34
2_DET	129.82	6.02	36.25	132.33	109.58	134.72
2_RAN	105.09	0.28	0.08	105.11	104.19	106.01

5. Conclusions

In the paper both simulation and experimental results concerning aggregated conducted electromagnetic interference generated by DC/DC converters with deterministic and random modulation have been presented. In the case of deterministic modulation the obtained results have shown that the amplitudes of aggregated interference are modulated with low frequency envelopes caused by the frequency beat phenomenon accompanying summation of sinusoidal components of close frequencies.

The investigation presented in this paper, despite consisting of two identical DC/DC converters, is corroborated by conducted electromagnetic interference in multiconverter systems, as recently investigated by [24], through a real 1 MW photovoltaic power plant. Furthermore, the statistical analyses of large series of final measurement data has confirmed assumptions that low-frequency envelopes might make the standardized EMI tests unreliable.

The research presented has revealed that in the case of random modulation a blurring of instantaneous values of switching frequency contributes to the decreasing of maximum EMI values as well as to the prevention of the frequency beat phenomenon.

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Abbreviations

The following abbreviations are used in this manuscript:

AV	Average
CISPR	International Special Committee on Radio Interference
DetM	Deterministic Modulation
EM	ElectroMagnetic
EMC	ElectroMagnetic Compatibility
EMI	ElectroMagnetic Interference
EUT	Equipment Under Test
FPGA	Filed-Programmable Gate Array
IEC	International Electrotechnical Commission
IFBW	Intermediate Frequency Band Width
PDF	Probability Density Function
QP	Quasi Peak
RanM	Random Modulation
STFT	Short-Time Fourier Transform

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